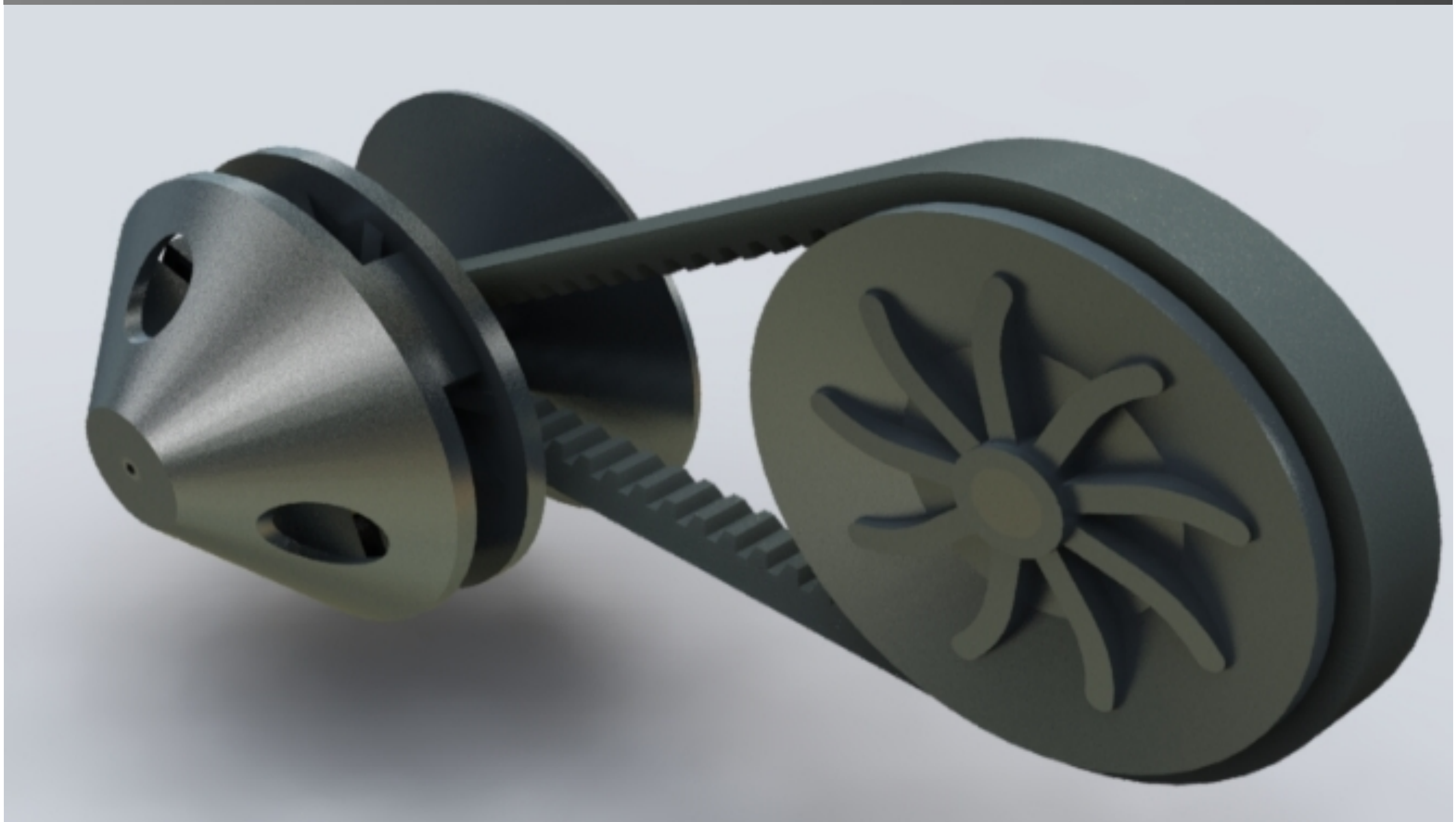

FSAE Continuously Variable Transmission

PHASE 2

Team 13

October 27, 2017

Trysten den Hartog
FSAE University of Alberta
9211-116 Street NW
Edmonton, AB T6G 1H9

Re: FSAE Continuously Variable Transmission – Phase 2 Deliverables

Dear Mr. den Hartog,

Team 13 is excited to present our Phase 2 report contained herein. The topics addressed include the following

- Update project status including design problem statement and specifications
- Summary of 3 design concepts
- Key analyses and comparison of concepts
- Cost analysis of concepts
- Project Management and Scheduling

The updated total time and cost estimates for the project are $52,673. Phase 2 required 256 hours to complete at a cost of $23,040. Phase 3 projections have been updated yielding a projection of 237 hours remaining.

Sincerely,

Colin Reimer, Project Lead

enlcosed.

cc.

Dr. Mohtada Sadrzadeh P.Eng	Dr. Michael Lipsett P.Eng.
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1 Executive Summary

Team 13 has been contracted to design a continuously variable transmission (CVT) for the University of Alberta's Formula SAE (FSAE) team. The goal of the proposed CVT design is to maintain peak acceleration during competitions without the need to shift gears.

A Dual Clutch design, a Variator-Clutch design and an Electronically Controlled CVT were proposed for further analysis. The Dual-Clutch system uses a primary clutch with spinning weights to produce a centrifugal upshifting force, while the secondary clutch uses a torque-sensing element, or torque cam, to downshift the CVT based on the torque transmitted through the system. The Variator-Clutch system uses a variator with roller weights to create a centrifugal upshifting force, without the need to monitor the applied torque with a cam. The Electronically controlled system uses an Arduino as a Proportional Integral-Derivative (PID) controller to control the CVT ratio in an effort to optimize engine speed.

After reviewing the physical dimensions, costs, installation and maintenance requirements, and performance specifications from the client, Team 13 recommends Concept 2 – the Variator-Clutch design. The simplicity in the numerical analysis for this design reduces the uncertainty in its expected performance. The total mass of the CVT is approximately 4.1 kg and the cost, including machined and custom of the shelf (COTS) parts, is $1,223 USD, with an approximate total number of machining hours of 10.

After completing the second phase of this project, the engineering design cost totaled $33,883 with Phase 2 making up for $23,040. Phase 3 is projected to cost an additional $22,080 upon completion. After reviewing the project schedule, Team 13 are projecting have a final design proposal completed along with all project deliverables by December 8, 2017.

2 Design Concepts

2.1 Background and Project Update

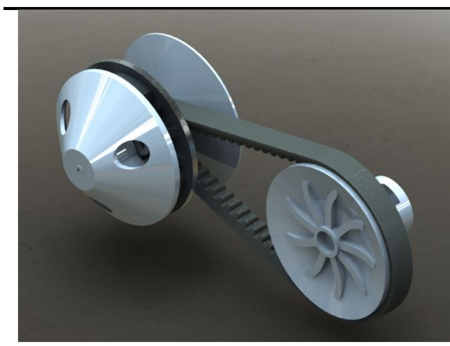
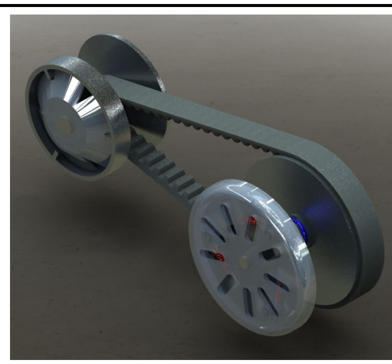
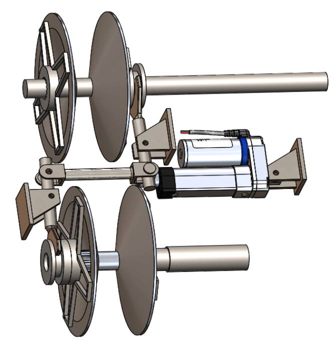
University of Alberta’s Formula SAE (FSAE) team would like to implement a continuously variable transmission (CVT) in their vehicle for the 2018 competition year. Team 13 has been contracted to design a CVT that is lightweight, inexpensive, and achieves maximum acceleration capabilities for the vehicle’s competition operation.

The transmission is required to mount to the existing transmission/engine assembly output and take advantage of the current gearbox output ratios. It must transmit power to the vehicle output - the rear axle differential, ideally without any additional shafts.

2.2 Description of Proposed Concepts

The three proposed concepts developed focus on using the Reeve’s Variable Pulley design for transmitting power, but significantly vary in terms of the method with which they are controlled, and as such, have some significantly different functional characteristics. The commonly used design rule for Reeve’s designs is to use a 3.5:1 minimum gear ratio and a 1:1 maximum gear ratio. There is some flexibility with respect to these ratios but there are limitations primarily due to belt flexibility. A brief introduction of the three proposed concepts can be seen in Table 1.

Table 1 Proposed Concepts

		
Dual Clutch/Torque Sensing	Variator-Bell Clutch	Electronically Controlled
• Shifting depends on angular velocity of engine and power output of engine • Extremely difficult to numerically model entire performance • Application of system is well known - tuning parameters remove need to fully predict performance	• Shifting depends only on angular velocity of engine • Relatively easy to numerically predict actual performance • Lightest design • Least expensive	• Shifting controlled electronically through Arduino PID and linear electric actuator • Most Expensive • Requires controller tuning and selection to ensure expected performance is achieved

2.3 Concept 1: Dual Clutch/Torque Sensing

The dual clutch CVT, also referred to as a torque sensing CVT, transmits power from the engine to the wheels using two sets of angled sheaves with a rubber belt under tension between them. The dual clutch CVT responds to the forces between the primary and secondary clutch to vary the transmission gear ratio. There are three primary components/sub-assemblies that make up this concept as seen in Figure 1.

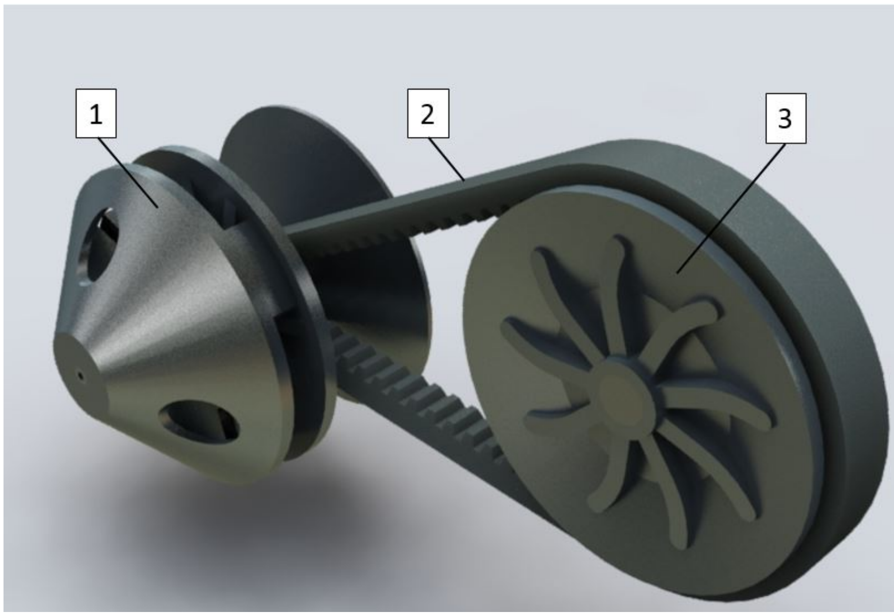


Figure 1 Concept 1 Full Assembly

Table 2 Bill of Materials (BOM) for Concept 1 Full Assembly

Item	Component	Description
1	Primary Clutch	Drive pulley/angular velocity shifting clutch. Mounted to power output shaft of vehicle
2	Rubber V-Belt	Brass centrifugal weights that roll outwards during rotation that provide an axial force to the movable sheave
3	Secondary Clutch	Driven pulley/torque-sensing clutch. Mounted to vehicle differential

For the following description it is important to understand a few terms:

- **Upshifting -** when the CVT transmission shifts to a higher gear ratio, corresponding to a greater vehicle speed for a given engine speed
- **Downshifting -** when the CVT transmission shifts to a lower gear ratio
- **Upshifting Force -** axial forces on the CVT pulley sheaves that induce upshifting
- **Downshifting Force -** axial forces on the CVT pulley sheaves that induce downshifting

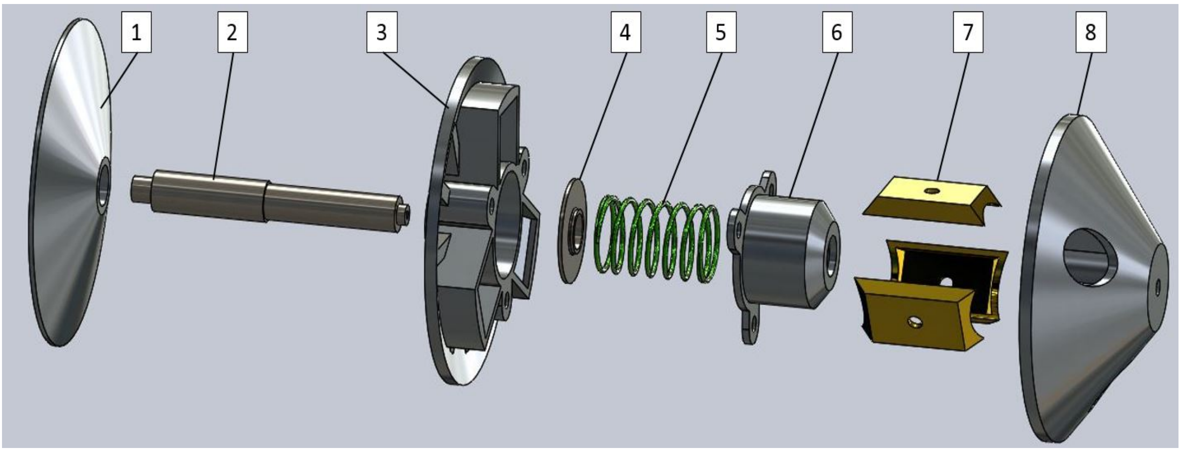


Figure 2 Concept 1 Primary Clutch exploded view

Table 3 BOM for Concept 1 Primary Clutch

Item	Component	Description
1	Fixed Sheave	Aluminum, fixed pulley sheave, permanently installed on the clutch shaft
2	Primary Clutch Stepped Shaft	Steel, stepped shaft for primary clutch - integrated into existing engine/transmission output
3	Primary Clutch Moveable Sheave	Aluminum, moveable pulley sheave, position dictated by compression spring clutch weights
4	Spring Shoulder	Steel shoulder contacts stepped shaft and creates dynamic relationship between spring compression and moveable sheave
5	Primary Spring	Preloaded compression spring
6	Spring Cap	Transmits spring force to moveable sheave and maintains spring preload during assembly
7	Clutch Weights	Sliding weights that shift radially outward during shifting
8	Spider	Contains sliding weights. Fixed to shaft. As weights move radially forces axial movement of moveable sheave

The primary clutch operation is relatively simple. It takes advantage of the radial acceleration of spinning weights, commonly referred to as centrifugal force, to induce an upshifting force. It also contains a compression spring that is installed with a specific amount of preload and is designed induce a downshifting force that increases as the primary shifts and compresses the spring. The FBD for the shifting forces can be seen in Figure 3. Note that the belt force on the sheave has been neglected.

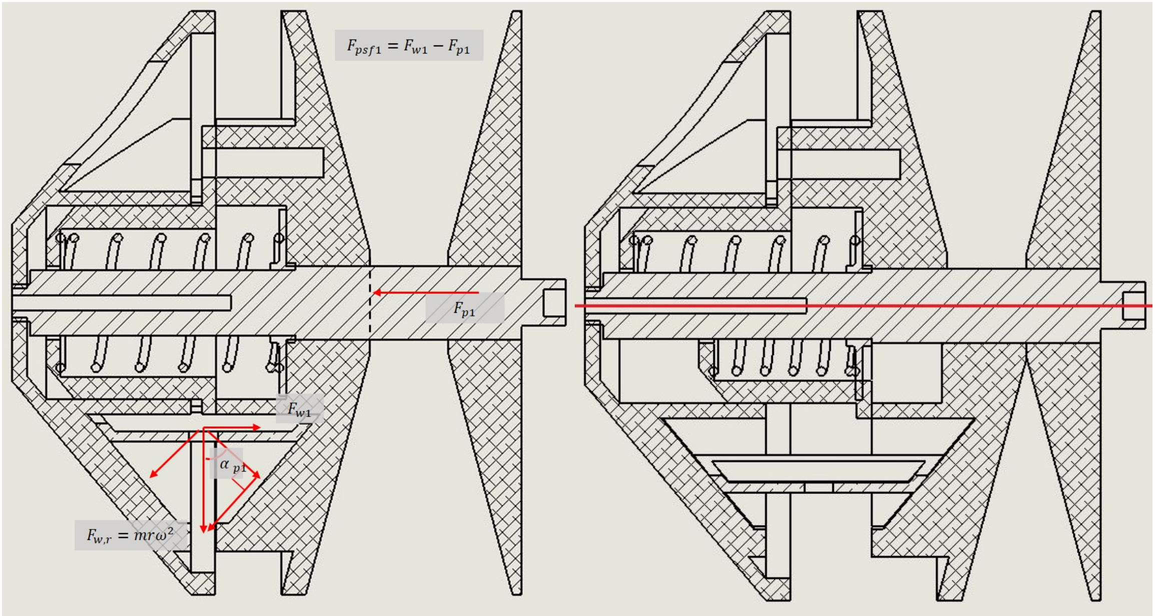


Figure 3 Left: Free body diagram of shifting forces in primary clutch. F.w1, axial force on moveable sheave due to centrifugal force; F.p1, axial force of compression spring. Right: Open (top) and closed (bottom) positions of the primary clutch

While the belt is key to the transmission of power between the primary and secondary clutch, it is conceptually simple and common to each design concept therefore it will not be discussed in detail. The third key component is the secondary clutch. An exploded assembly view of it can be seen in the following figure.

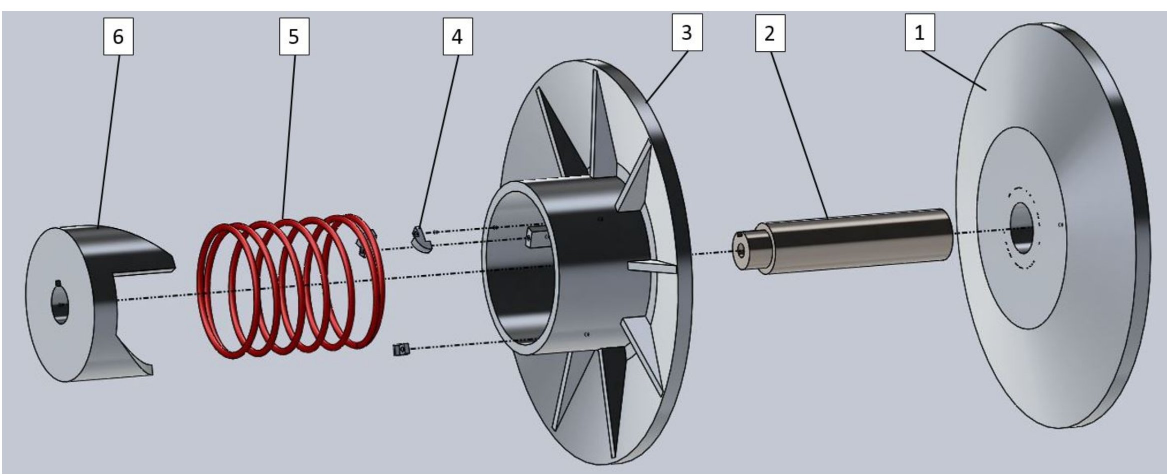


Figure 4 Concept 1 Secondary Clutch Exploded view

Table 4 BOM for Concept 1 Secondary Clutch

Item	Component	Description
1	Fixed Sheave	Aluminum, pulley sheave that is permanently installed on the clutch shaft
2	Secondary Clutch Stepped Shaft	Steel, stepped shaft for secondary clutch - either additional transmission shaft or integrated into differential
3	Secondary Clutch Moveable Sheave	Aluminum, pulley sheave that slides on shaft based on forces from helix and spring
4	Helix Slider	Sliding contact point between helix and moveable sheave
5	Secondary compression Spring	Compression spring
6	Helix	Torque sensing cam, pushes against moveable helix when under load

The secondary clutch, despite fewer components is more conceptually complex. It too contains a compression spring like the primary, however it is designed to cause a downshifting force. It also contains a helix, commonly referred to as a torque cam, which is the torque-sensing element that makes this concept so unique. The helix generates a downshifting force that is a function of the amount of torque being transmitted through the system. The forces can be seen in the FBD in Figure 5.

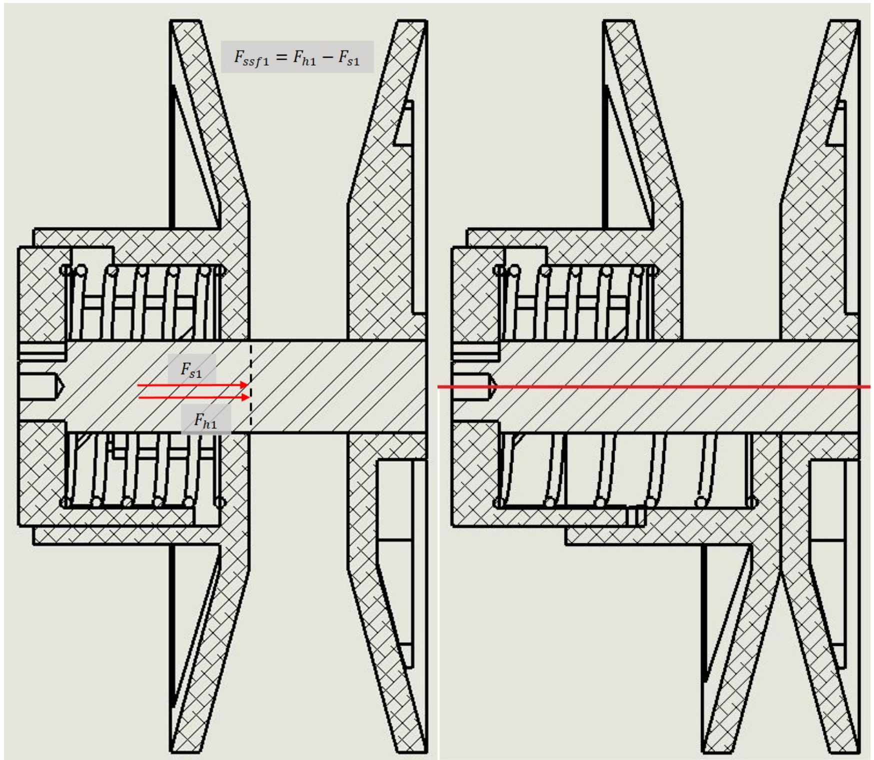


Figure 5 Left: Free body diagram of shifting forces in secondary clutch. F.h1, axial force on moveable sheave due to helix; F.s1, axial force of compression spring. Right: Open (top) and closed (bottom) positions of the secondary clutch

To understand how the system functions, an ideal shift curve was developed to show the vehicle speed as a function of engine speed for the dual clutch CVT.

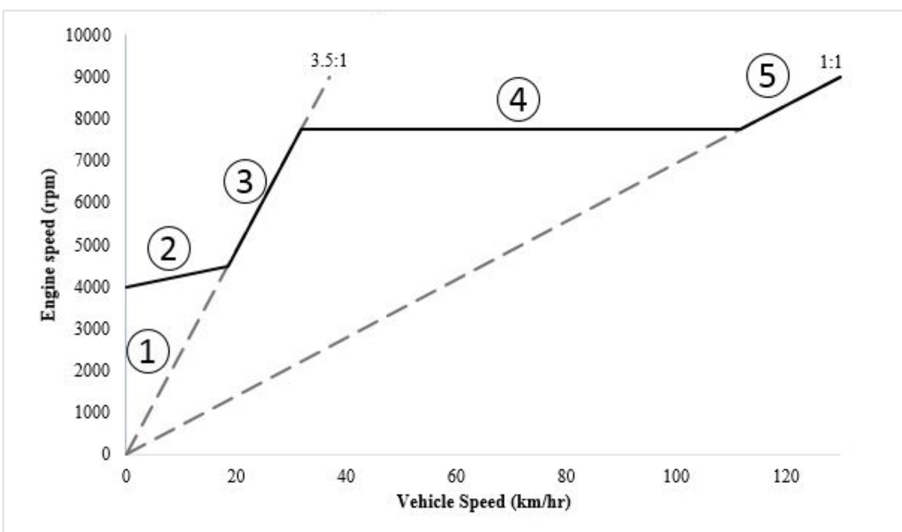


Figure 6 Concept 1 ideal shift curve using design standard CVT ratios (3.5:1 to 1:1). Assume gearbox is fixed in first gear with no additional transmission shaft

Table 5 Concept 1 ideal shift curve stages

Stage	Description
Stage 1 (0 to *4000 rpm)	Engine speed is not enough to engage transmission. The vehicle remains stationary.
Stage 2 (4000 to ~4500 rpm)	Primary clutch begins to engage and power transmission begins. The belt slips until engine speed and vehicle speed are equivalent. The duration of this shift phase is highly dependent on how the vehicle is operated therefore the upper limit of ~4500 rpm is an approximation based on known transmission characteristics
Stage 3 (~4500 to 7750 rpm)**	Upshifting forces are not enough to overcome downshifting forces therefore vehicle operates in CVT minimum ratio
Stage 4 (7750 rpm)	Upshifting and downshifting forces are equivalent and vehicle operation is maintained at approximately ideal power output engine speed of 7750 rpm.
Stage 5 (>7750rpm)	Referred to as "shift out" or when transmission has reached the maximum gear ratio and the vehicle revs to redline rpm. Upshifting forces indefinitely overcome downshifting forces

*4000 rpm was arbitrarily decided upon as the engagement rpm and is subject to change
**7750 rpm was selected based on the peak power curve for previous year's dyno curve - subject to change based on current vehicle peak power engine speed

The shift curve in Figure 6 is a rough approximation of how the system works and is highly sensitive to the tuning design parameters of a dual clutch CVT. There are many design parameters that influence this curve, though the four that are designed to be adjustable or "tuneable" are as follows:

1. Spring preload/spring constant of primary clutch spring
2. Mass of clutch weights
3. Spring preload/spring constant of secondary clutch spring
4. Helix angle

Numerically modelling the entire system operation proved to be extremely complex and became dependent on variables that could not be defined. However, the transition points between the shift stages were able to be determined based on the physical characteristics of the system (see Appendix A for calculations).

2.4 Concept 2: Variator-Bell Clutch

The Variator-Bell Clutch concept uses a variator to adjust the gear ratio as a function of the engine's angular speed. The variator contains roller weights situated between a moveable sheave and a cap fixed to the shaft. This is much like the Concept 1 Primary Clutch but uses roller weights instead of sliding weights. The major distinction is that the variator does need a spring. The CAD assembly and a description of its parts can be seen in Figure 7, Figure 8, and Table 6.

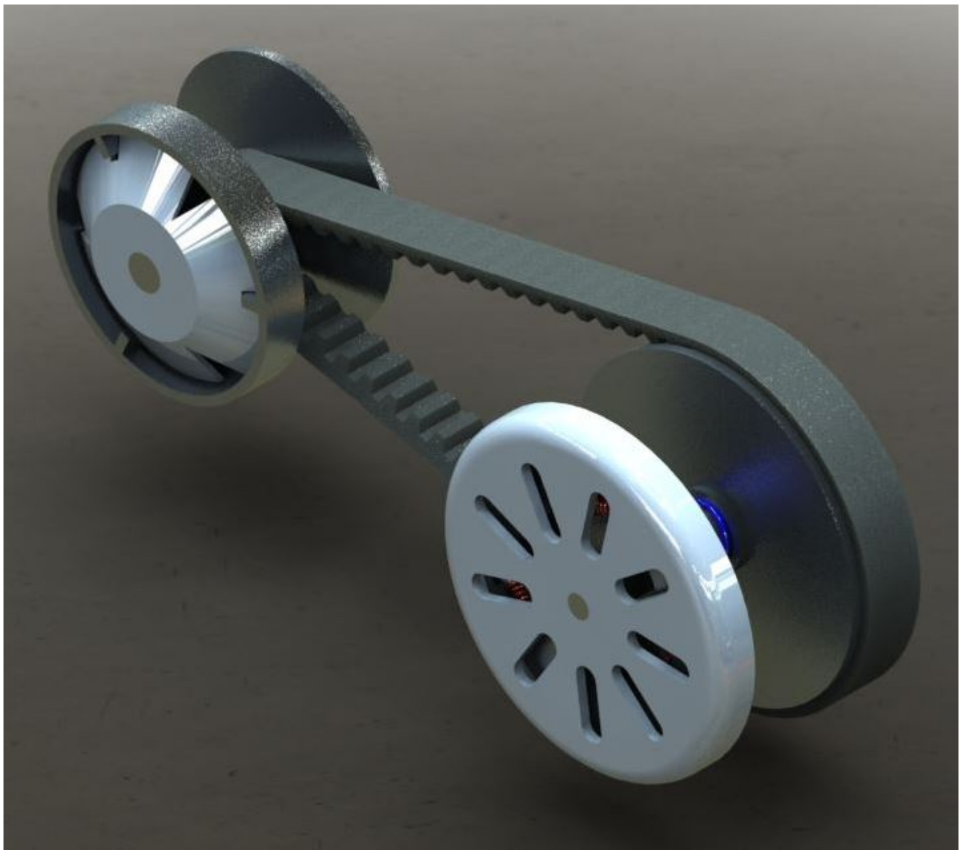


Figure 7 Concept 2 full Assembly – Variator (top left) and clutch (bottom right)

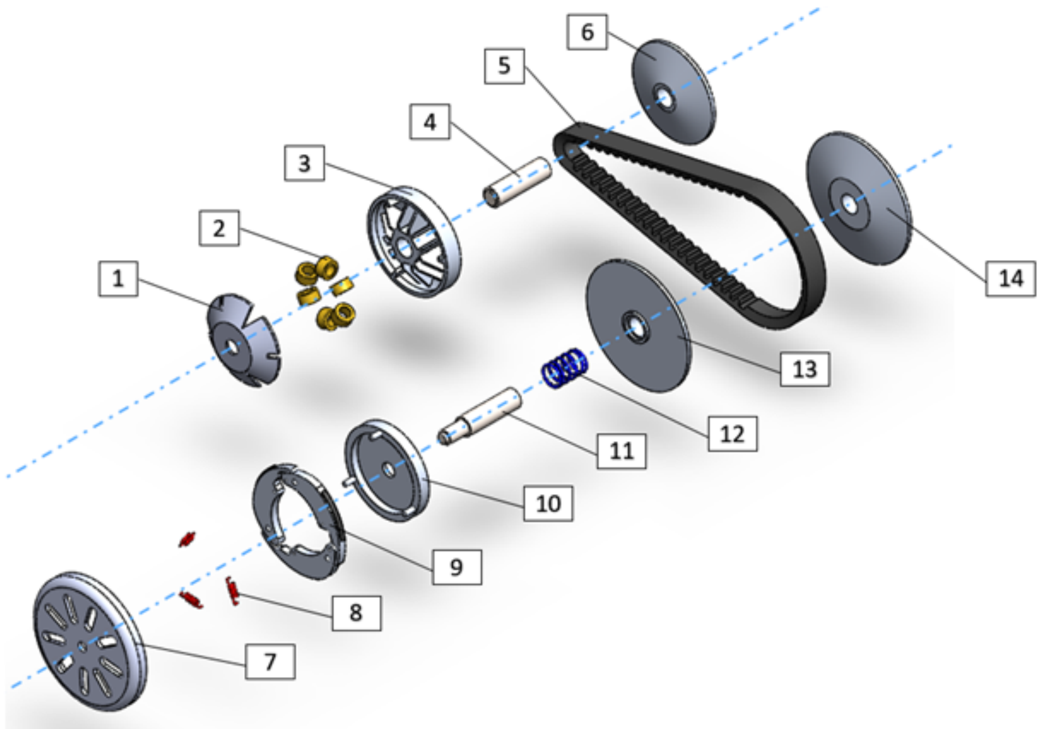


Figure 8 Concept 2 Full Assembly Exploded View

Table 6 BOM for Concept 2

Item	Component	Description
1	Roller House Cap	Fixed aluminum plate needed to push roller weights into movable sheave
2	Clutch Weights	Brass centrifugal weights that roll outwards during rotation that provide an axial force to the movable sheave
3	Variator Moveable Sheave	Aluminum sheave that houses the clutch weights
4	Input shaft to CVT	Steel shaft that connects to the output shaft from the FSAE engine
5	CVT Belt	V ribbed Belt used to transmit power from conical sheaves
6	Variator Fixed Sheave	Aluminum sheave that does not move axially
7	Clutch Bell	Steel Cap that encases the clutch weights
8	Clutch Springs	Springs that resist radial acceleration of clutch arms

9	Clutch arms	Steel arms that provide a clutching force during rotation to engage the CVT – manufactured with clutching surface on one side
10	Clutch Plate	Steel plate that houses clutch arms and situates clutch arms onto the CVT output shaft
11	Output Shaft	Steel shaft that connects to the differential of the FSAE vehicle
12	Clutch Compression Spring	Spring used to provide tension in the V-belt during shifting operations
13	Clutch Movable Sheave	Aluminum sheave that can move axially allowing for belt tension to develop from secondary clutch spring
14	Clutch Fixed Sheave	Aluminum sheave that is fixed to the output shaft of the CVT

As the variator spins faster, the weights climb the ramp in the cage, forcing the front pulley halves together from the centrifugal force and raising the effective gearing as shown in Figure 9.

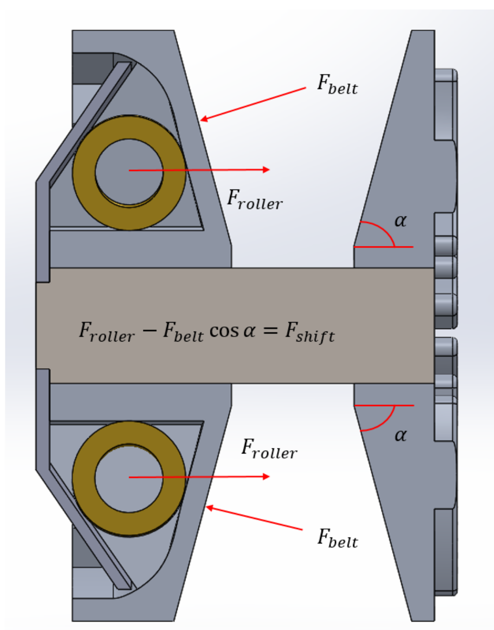


Figure 9 Free Body Diagram of shifting forces in Variator

By using a variator, the CVT only depends on the angular velocity and no longer on torque. This simplification allows a numerical model to be developed with relative ease and the transition from design to implementation typically smoother since the model better represents the real system than the model for the other concepts. However, since the CVT system only depends on angular velocity, the shifting process results in a slope between the CVT minimum and maximum gear ratios reducing the time spent at the ideal engine rpm power output speed. The shift curve for concept 2 can be seen in Figure 10.

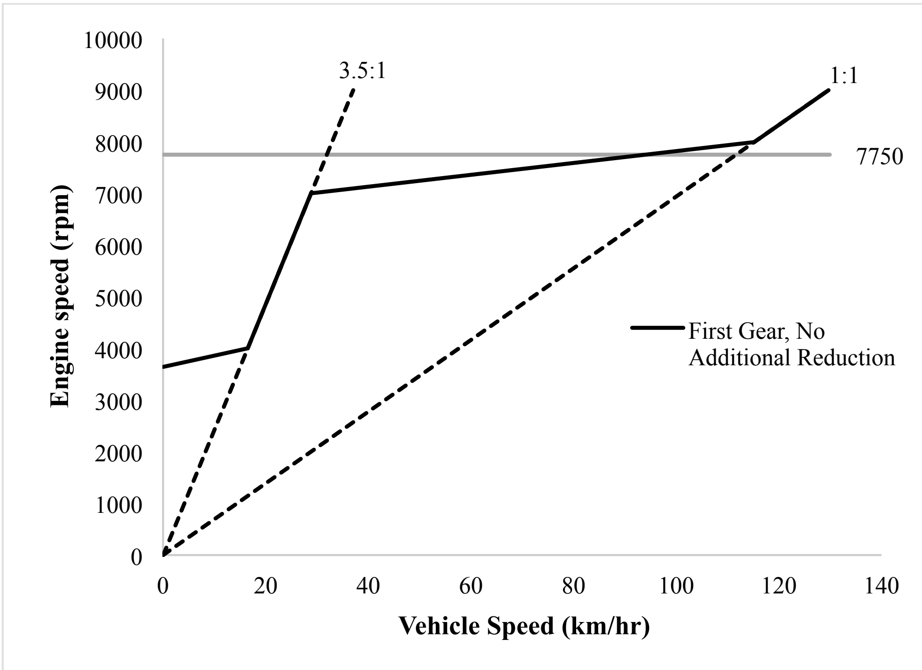


Figure 10 Shift curve for Variator-Bell Clutch design

Adjusting the mass of the roller weights and the compression spring can reduce the slope in the shift curve. However, due to physical limitations the slope cannot be reduced indefinitely resulting in a range of rpm operation throughout the CVT shift generally greater than 1000 rpm.

The clutch in this concept functions similarly to the clutch in an automatic transmission. While at idle the clutch arms do not have enough angular velocity to overcome the spring force. Adjusting the weight and spring tension of the bell clutch adjusts the engagement speed and the amount of torque that can be transmitted.

2.5 Concept 3: Electronically Controlled

The electrically controlled CVT uses an Arduino as a Proportional Integral-Derivative (PID) controller to change the rate at which gearing shifts.

The third CVT concept is the most complicated from a design perspective. It utilizes an electro-mechanical system to accomplish the CVT ratio actuation. This concept has the potential to be the highest performing design by allowing total control over the CVT ratio actuation. This is accomplished by using a computational based PID controller that drives an electronic servo actuator as shown in Figure 11.

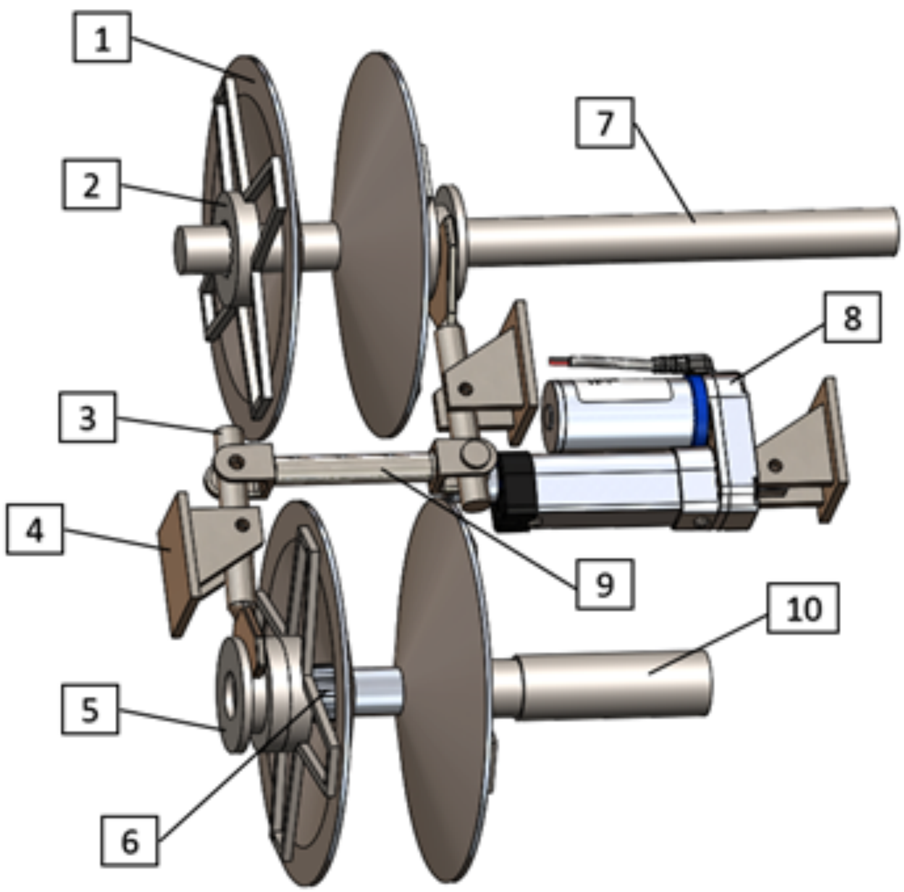


Figure 11 Concept 3 Full Assembly

Table 7 BOM for Concept 3

Item	Component	Description
1	Belt Sheave	Lightweight Aluminum sheave designed for low rotational Inertia
2	Backing Plate	Steel spokes designed to transmit torque from transmission shafts to the sheaves
3	Shift Fork	Steel fork used to move sheaves axially for CVT ratio adjustment
4	Transmission Mount	Steel mounts used to fixate the transmission onto the frame of the FSAE vehicle
5	Thrust Bearing	Bearing used to transmit force from the shift fork to the backing plate
6	Splined Shaft	Steel shaft with splined sections used for torque transmission to the backing plate
7	Transmission Output Shaft	Steel shaft that mounts to the differential of the FSAE vehicle
8	Linear Actuator	Electronic servo that provides force to the shifting forks in order to adjust the CVT ratio
9	Connecting Rod	Steal link used to synchronize motion between input and output sheaves during CVT ratio adjustments
10	Transmission Input Shaft	Steel shaft that is a part of the engine of the FSAE vehicle

The transmission alters its gear ratios by extending or retracting the linear actuator. This motion causes the belt sheaves to move axially thereby changing the belt position and transmission ratio. Figure 12 shows the transmission in the fully retracted, midpoint position and the fully extended position (left to right).

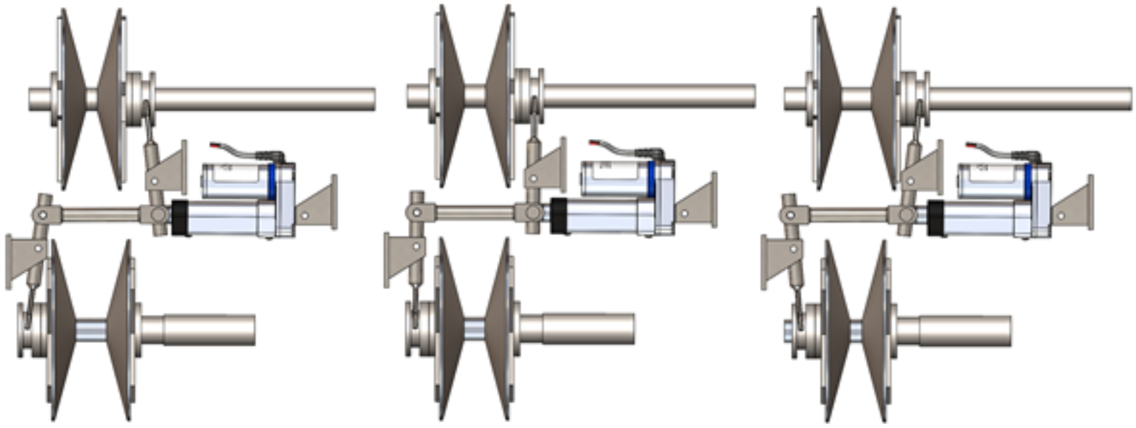


Figure 12 Concept 3 Position 1 (Left); Position 2 (Middle); Position 3 (Right)

This concept uses an electronic Proportional Integral Derivative (PID) controller to vary its transmission ratio. This PID controls the movement of the linear actuator to accomplish a desired ratio adjustment. The PID controller maintains maximum engine power over the ratio range of the CVT by keeping the engine RPM at its maximum value. This process is detailed in Figure 13 where the PID minimizes the error between the input engine RPM and the desired set point RPM by adjusting the output CVT ratio.

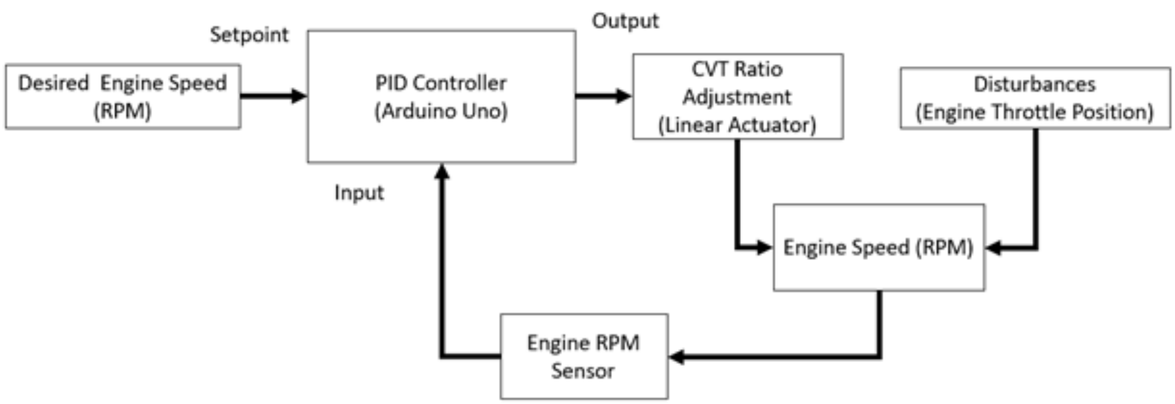


Figure 13 Concept 3 PID Process Diagram

By minimizing the error between the desired and measured engine speed, an approximately flat curve can be assumed for region three on this concepts CVT shift curve outlined in Figure 14.The PID function can be accomplished with an Arduino Uno R3 programmed to operate as a PID controller. Where the engine RPM sensor can be routed from the existing engine control unit to provide input to the controller.

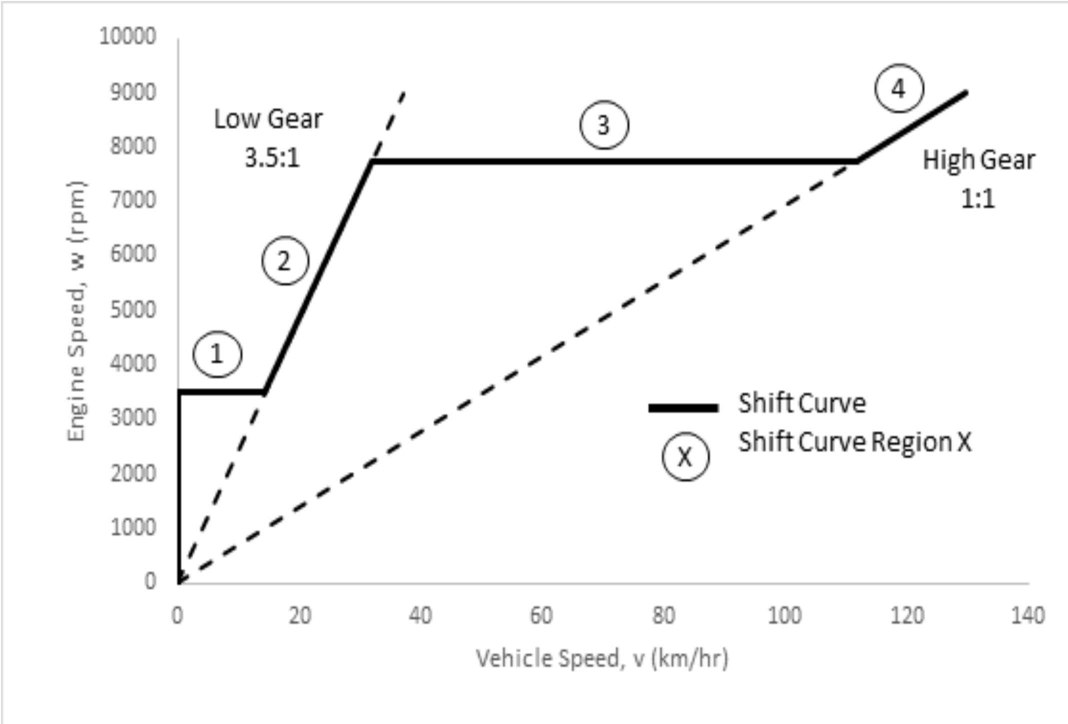


Figure 14 Ideal Concept 3 Shift Curve without an intermediary shaft/reduction

Concept 3 has a shift curve nearly identical to Concept 1. The only difference is Region 1 where this concept is dependent on the vehicle's existing clutch to determine engagement speed and engine speed/vehicle speed synchronization. Concept 3 differs in that it uses a PID controller to produce region 3, shifting the CVT to maintain a specific engine speed determined by the reference input for the system.

Concept 3 has the lowest rotational inertia of the three concepts with a value of 14.1 g*m^2. However, this CVT weighs the most due to its external linkages weighing in at 6.3 kg. This concept also requires the largest amount of space to fit into the FSAE vehicle's chassis with three special transmission mounts being required for installation. It also requires a 12V power source routed from the vehicles battery to power the linear actuator. Concept 3 has the greatest cost of all three designs due to the number of custom components used. This transmission carries a price of $1800 USD.

3 Key Design Analyses

Specific design analyses for each system were selected for the purpose of comparing the concepts and developing the design evaluation matrix in . These key analyses were done on the concept mass, rotational inertia, overall dimensions, and performance numerically. A qualitative assessment was also completed with respect to the team capability, tune-ability, and physical limitations for each of the design concepts.

In terms of mass the Variator-Clutch design is the lightest while the Electronically Actuated design is the heaviest. However, with respect to rotational inertia Concept 3 is the lowest while Concept 1 is the highest. The values for the dimensional characteristics of the concepts are shown in Table 8**.** These values were determined using SolidWorks mass properties and measurements and comparing to typical industry values.

Table 8 Measured Physical parameters for Each concept

Key Analysis	Concept 1	Concept 2	Concept 3
Mass (kg)	4.5	4.1	6.3
Rotational Inertia (kg*m^2)	0.023	0.016	0.014
*Size (width, mm)	225	140	200

*Only compare width of each design since pulley diameter and belt length/distance between pulleys remains constant.

With available space in the chassis being very limited for the transmission being selected, Concept 2 has a sizeable advantage over both Concept 1 and 3 being the smallest design by a significant margin. Measured at only 140 mm in width, Concept 2 is only 62% and 70% of the width of Concepts 1 and 3 respectively.

Two key analyses completed for each concept were determining the shift curve for each concept – a graphical representation of engine speed versus the vehicle speed and a ground force versus vehicle speed evaluation that directly correlates to the vehicle acceleration.

Based strictly on the shift curves in Figure 15, all three concepts clearly outperform the sequential gearbox. Concept 1 and 3 are both able to achieve a constant engine speed throughout the majority of the shift curve and consequently can be tuned/designed to ensure maximum engine power is maintained. Concept 2, due to its physical parameters, will always have a non-horizontal slope throughout the shift curve. However, it is still able to hold the engine much closer to the optimal speed for power output than the sequential gearbox.

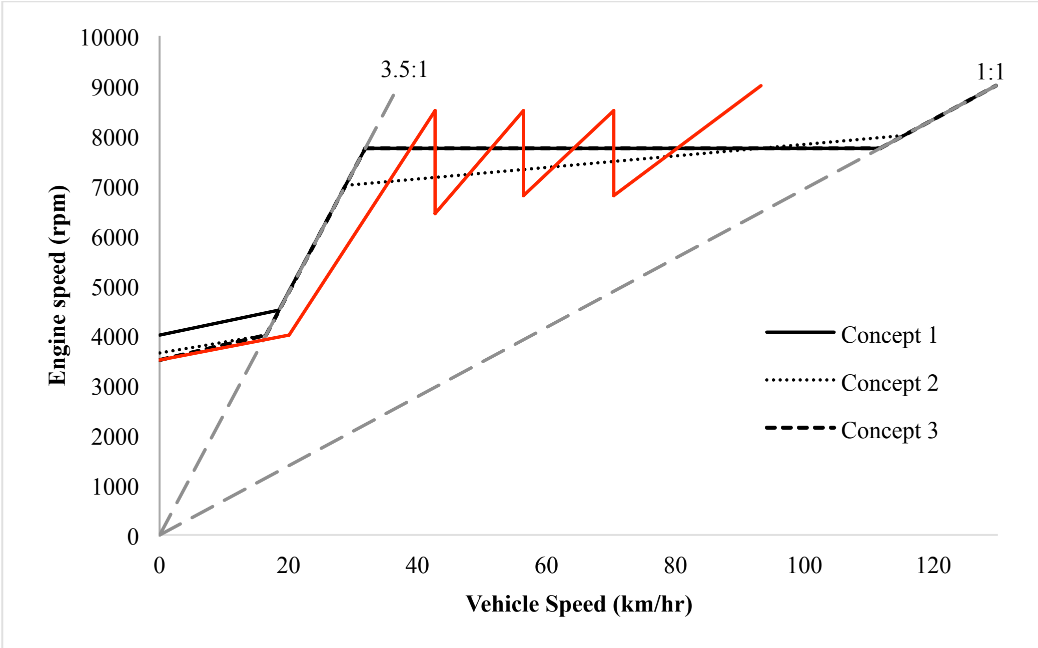


Figure 15 Shift Curve Comparison

Estimates for the power losses through a CVT transmission, based on typical industry standards, are roughly 5%. This is greater than the typical value of 2% for a sequential gearbox. Considering a dyno curve approximation for the vehicle engine (Appendix A**)** the ground force output of the CVT can be compared to the Sequential Gearbox. For this curve the first shifting stage was neglected while the engine speed and vehicle speed are not synchronized. The ground force applied to the road is defined by the expression:

$$F_{ground} = \eta_{transmission} \frac{HP_{engine}}{v_{vehicle}} \quad \textbf{Equation 1}$$

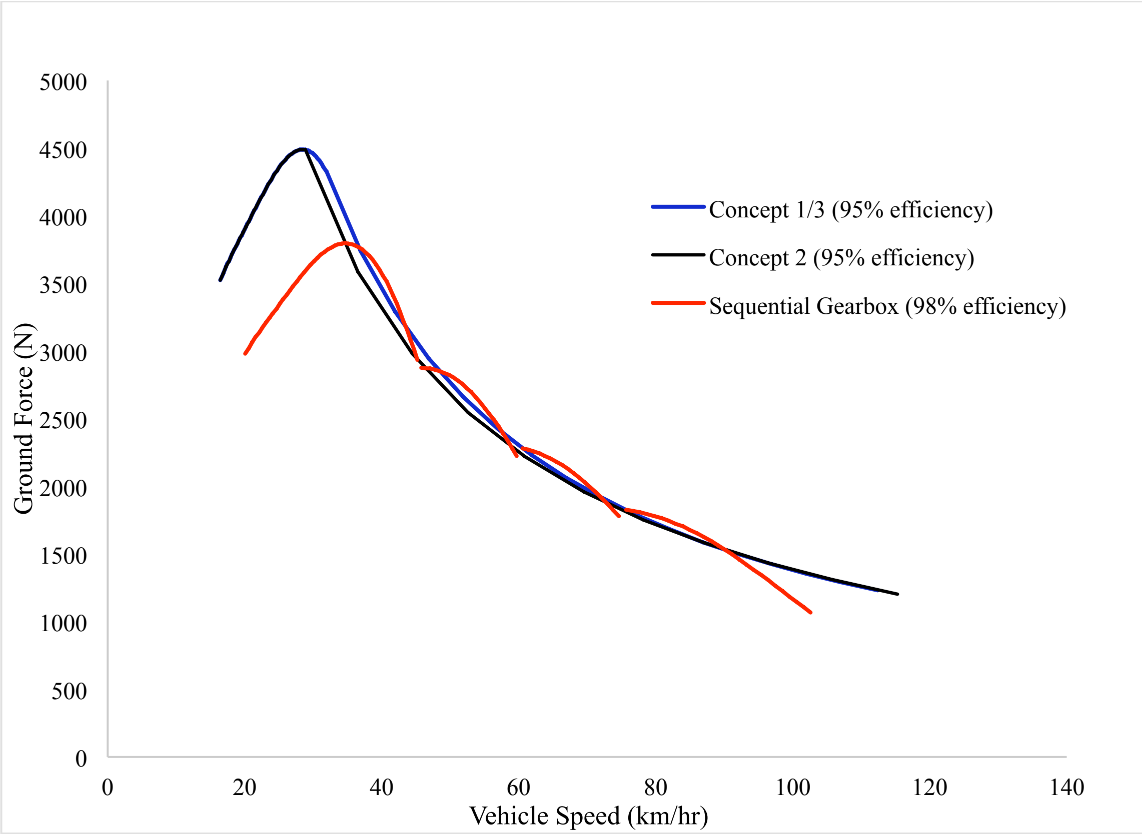


Figure 16 Ground force for each transmission compared versus vehicle speed. The ground force is the force applied to the ground by the wheels assuming that no slip occurs.

From Figure 16 it can be seen that Concept 1 and 3 achieve a slightly greater ground force than Concept 2. A more difficult comparison is that between the sequential gear box and the CVT's. If not for the discrepancy in mechanical efficiency's the CVT transmission would clearly provide the greater acceleration according to Newton's first law.

$$\Sigma F = ma \qquad \textbf{Equation 2}$$

One additional factor that cannot be graphically accounted for is the shift delay introduced by the driver and the inability to consistently shift at the ideal engine speed. Despite the reduced mechanical efficiency for CVT's, the errors introduced by human operation still result in faster acceleration rates for each of the CVT design concepts.

4 Cost Analysis

The majority of the components in each concept can be sourced from local suppliers, namely McMaster-Carr, EPI Performance, CVtech and ServoCity (Referred to as COTS-Custom Off the Shelf). Quotes for custom parts were obtained from Proto Labs and Solidworks, which can be found in Appendix B. Estimates for the shaft adapter have been omitted for each concept analysis list, but are included in the total cost. The cost of a shaft adapter for mounting to the engine ranges from $300 to $400 based on preliminary estimates. All concepts are well under the required budget of $2500 USD. Each of the designs takes advantage of numerous existing COTS parts available. The machine hours estimated for each concept were 1 hour, 10 hours, and 12 hours for concepts 1 through 3 respectively. Concept 3 is the only design that exceeds the desired limit of 10 hours though only by a 2-hour margin.

Table 9 Cost analysis of Concept 1: Dual Clutch Design

Subassembly	Part	Part No.	Mfg	Cost (USD)	Qty	Total Cost (USD)
Primary Clutch	Drive Clutch	0400-0204	CVTech	$500	1	$500
	Clutch Weights (Pack of 6)	0901-7101	CVTech	$27	1	$27
	Drive Pulley Spring (Replacement)	0451-1104	CVTech	$35	0	$35
Secondary Clutch	Secondary Clutch	6000-032	CVTech	$507	1	$507
	Secondary Pulley Spring (Replacement)	X-5218304	CVTech	$35	0	$35
	Rubber V-Belt	DC52-2208-T	CVTech	$83	1	$83
	Tuning Tools	-	CVTech	$165	1	$165
*Total cost indicated does not include replacement parts					**Total Cost:**	**$1282 ($1117 less Tools)**

Table 10 Cost analysis of Concept 2: Variator-Bell Clutch Design

Subassembly	Part	Part No.	Mfg	Cost (USD)	Qty	Total Cost (USD)
Variator Clutch	Roller House Cap	-	SW	$80	1	$80
	Clutch Weights (Pack of 8)	WE240000	EPI	$50	1	$50
	Variator Roller House	-	SW	$90	1	$90
	Input Shaft to CVT	-	SW	$45	1	$45
	Fixed Variator Sheave	6204K372	MC	$50	1	$50
Secondary Clutch	Clutch Bell	-	SW	$140	1	$140
	Secondary Clutch Springs	1330K57	MC	$5	3	$15
	Secondary Clutch Arms	-	SW	$40	3	$120
	Secondary Clutch Weight Plate	-	PL	$255	1	$255
	CVT Output Shaft	8641T1	MC	$20	1	$20
	Secondary Clutch Spring	9657K379	MC	$10	1	$10
	Secondary Moveable Sheave	6204K372	MC	$50	1	$50
	Secondary Fixed Sheave	6204K372	MC	$50	1	$50
	Rubber V-Belt	DC52-2208-T	CVTech	$83	1	$83
	Tuning Tools	-	CVTech	$165	1	$165
* MC – McMaster-Carr, EPI – EPI Performance **Parts without “Part No.” quoted using SolidWorks (SW) or ProtoLabs (PL) indicated in “Mfg” column.					**Total Cost:**	**$1223 ($1058 less Tools)**

Table 11 Cost analysis of Concept 2: Variator-Bell Clutch Design

Part	Part No.	Mfg	Cost (USD)	Qty	Total Cost (USD)
Fixed Sheave	278112	Kimpex	$300	2	$600
Movable Sheave	-	SW	$280	2	$560
Shift Fork	-	SW	$40	2	$80
Fork Mount	-	SW	$30	3	$90
Fork Connecting Rod	-	SW	$70	1	$70
Connector Pin	98480A019	MC	$7	5	$35
Linear Actuator	HDLS-2-50-12V	SC	$300	1	$300
Rubber V-Belt	DC52-2208-T	CVTech	$83	1	$83
* MC – McMaster-Carr, SC – ServoCity **Parts without “Part No.” quoted using SolidWorks (SW) indicated in “Mfg” column.				Total Cost:	**$1818**

5 Design Evaluation

The design specification matrix from Phase 1 has been updated significantly in Table 13. The rating system has been revised as well from a 1-10 scale to a 1-5 scale. A number of the design specifications that were unclear such as net mass decrease have been simplified to improve clarity. The design specs that were removed include Failure Mechanism, Lubricants/Seals, Fuel Efficiency, Operating Temperature, assembly and installation time, and shape. These specifications were deemed irrelevant or lacked sufficient importance to justify validation. The effective difficulty of tuning the performance of each transmission post-assembly was added to the matrix. The rating system for the design specifications in Table 12 was created to establish a definitive meaning for each rating.

Table 12 Design Specification matrix rating system

Rating of Importance	Description
5	Vital
4	Important
3	Desirable
2	Nice to have
1	Not important

A rating of 5 means that without meeting the specification the design is unusable. A rating of 4 is a high priority, but could potentially be worked around if other benefits are great enough. A rating of 3 carries significant weight but is not no longer vital, a rating of 2 means it is a nice feature though not technically necessary, and a rating of 1 implies that while the specification exists and is still applicable, it is not a significant factor for design success.

The design evaluation matrix in Table 14 was developed based on the rating system as a weight for each of the design specifications and a normalized score for each of the concepts. Multiplying the weight by the score and summing determined the total design specification scores for the three concepts.

Table 13 Updated Design Specification matrix

Item	Description	Specification	Design Authority	Rating
A		**Dimensions**		
A1	Mass	Minimum total mass	Client	4
A2	Size	Fit into chassis/within FSAE body parameters	Client/FSAE rules	5
A3	Rotational Inertia	Minimum possible rotational inertia	Client/Design Team	2
A4	Fasteners	Fasteners must be metric	Client	4
B		**Safety**		
B1	Reliability	Component safety factor of 1.2 under competition operation	Design Team	4
B2	Durability	50 engine hours operation	Client	4
B3	Shielding	Finger guard must cover all moving parts. Guard must prevent passage of 12mm diameter object through guard	Client	
C		**Cost**		
C1	Machinability Hours	Less than 10 total machining hours	Client	4
C2	Total Cost	$2500 limit for sourced components	Client	5
D		**Function**		
D1	Power	Range of veichle speed oprating at max power 7750rpm ~50HP	Design Team	5
D2	Stationary Operation	Capable of maintaining neutral for vehicle noise test in competition. Engine speed of 9000 rpm without moving	Client/Design Team	3
D3	Max Vehicle Speed	Sustained transmission operation at 110km/hour	Client	4
D4	Transmission Tunability	Minimum number of design variables that can be readily adjusted after transmission assembly to effectively tune transmission	Design Team	3

Item	Description	Specification	Design Authority	Rating
E		**Installation/Manufacturing**		
E1	Mounting	Minimum number of necessary mounts on chassis	Client	5
E2	Material	Use readily available from local suppliers	Client	5
F		**Maintenance**		
F1	Simplicity	Minimum number of electrical parts possible	Client	1
F2	Part Sourcing	Available for purchase in typical Canadian/American suppliers	Client	4
F3	Serviceability	Belt accessible and interchangeable within 30 minutes	Client	4

Table 14 Design Evaluation Matrix

Item	Concept Rating						
	Concept 1		Concept 2		Concept 3		Justification
	Value	Rating	Value	Rating	Value	Rating	
A1	4.5kg	7	4.1kg	8	6.3kg	4	Total weight for each concept
A2	225mm	4	140mm	8	200mm	5	Maximum Size (width)
A3	$0.023\ kg * m^2$	5	$0.016\ kg * m^2$	7	$0.014\ kg * m^2$	8	Total Rotational Inertia of the Drive Clutch and Secondary Clutch for each design.
A4	1	10	1	10	1	10	Fasteners must be compatible with the vehicles unit system (1 for possible, 0 for not possible)
B1	8	7	8	7	8	7	Number of moving parts subject to fatigue and wear
B2	N/A	N/A	N/A	N/A	N/A	N/A	Not applicable until detail calculation completed
B3	1	10	1	10	1	10	All concepts need to have shielding (1 for possible, 0 for not possible)
C1	1	9	10	2	12	0	Number of total machining hours, $100/hour
C2	1255 USD	8	985 USD	10	1800 USD	7	Cost
D1	7750RPM (32-112 km/h)	10	7k-8k RPM (29-115 km/h)	7	7750RPM (32-112km/h)	10	Speed range at approximately optimal engine speed (7750 RPM)
D2	1	4	0	10	0	10	Number of steps needed to disengage drive train
D3	1	10	1	10	1	10	110 km/hour (or greater) maximum speed (1 for achievable, 0 for not achievable)
D4	4	8	2	9	4	7	Number of Tuning Parameters

Item	Concept Rating						
	Concept 1		Concept 2		Concept 3		Justification
	Value	Rating	Value	Rating	Value	Rating	
E1	0	10	0	10	3	5	Number of necessary transmission mounts needed on chassis
E2	1	10	1	10	1	10	Aluminum and steel materials used for all concepts (1 for used, 0 for other materials used)
F1	0	10	0	10	1	5	Number of electrical components
F2	1	10	1	10	1	10	All concepts can use Canadian/American suppliers (1 for possible, 0 for impossible)
F3	1	9	1	9	4	4	Number of steps needed to remove belt
Overall Score		514		530		437	

6 Design Recommendation

For the dimensions of each design, only the width (i.e. the maximum dimension of the transmission measured along the shaft axis) changes. Therefore, Concept 2 has the smallest width, followed by Concept 3 then Concept 1. Also, Concept 2 is the lightest with a mass of 4.1 kg, followed by Concept 1, then Concept 3. Concept 2 best satisfies the client's dimensional requirements. Including the cost of the required tools and the shaft adapter, the total comes to $1223 USD – approximately $60 less than Concept 1 and $600 less than Concept 3.

All three concepts use aluminum and steel, which are easily available and can be sourced from local suppliers. However, three chassis mounts are needed for Concept 3, whereas Concepts 1 and 2 require none. Concept 3 also has more electrical components, and the belt is more difficult to remove than the other two concepts for servicing. Concepts 1 and 2 are most suitable for maintenance and installation since they have no electrical components and need only one step to remove the belt.

After comparing the 3 conceptual designs using the decision matrix (Table 14), Team 13 proposes Concept 2 best fulfills the requirements specified by the client. With minimal mass and size both being key dimensions, Concept 2 performs best in these criteria compared to the other CVT designs with a mass of only 4.1 kg and a width of 140 mm. It is the least expensive and does not exceed the machining time limit. Concept 2 provides the benefit of mechanical simplicity compared to the other designs and is easier to mechanically tune, resulting in more predictable and reliable results. The small discrepancy in performance expectations between Concept 2 and Concepts 1 and 3 was not enough to sway the design recommendation based on the other benefits.

7 Project Management

The original projections for Phase 2 hours proved to be a slightly low and as a result the team was back loaded with work near the end of the phase. While many of the tasks for Phase 3 have been updated, adjusted in terms of expected time demand, and more detailed descriptions have been developed, the overall projection has not changed significantly since the original. The original and updated projections along with the actual values for Phase 1 and 2 have been tabulated and a graphical representation developed to show the project status and development (Table 15 and Figure 17)

Total design cost up to date is $33,883 with Phase 2 making up for $23,040. The projected and actual costs for each of the phases are recorded in Figure 18. Additionally see Appendix C for LiquidPlanner schedule and Timesheets.

Table 15 Summary of Engineering Design Hours (Junior and Intermediate)

		Junior	Intermediate
Phase 1	Original Projection	94.5	2
	Updated Projection	94.5	2
	Actual	98.25	2
Phase 2	Original Projection	225	4
	Updated Projection	262	4
	Actual	256	2
Phase 3	Original Projection	234	5
	Updated Projection	237	5

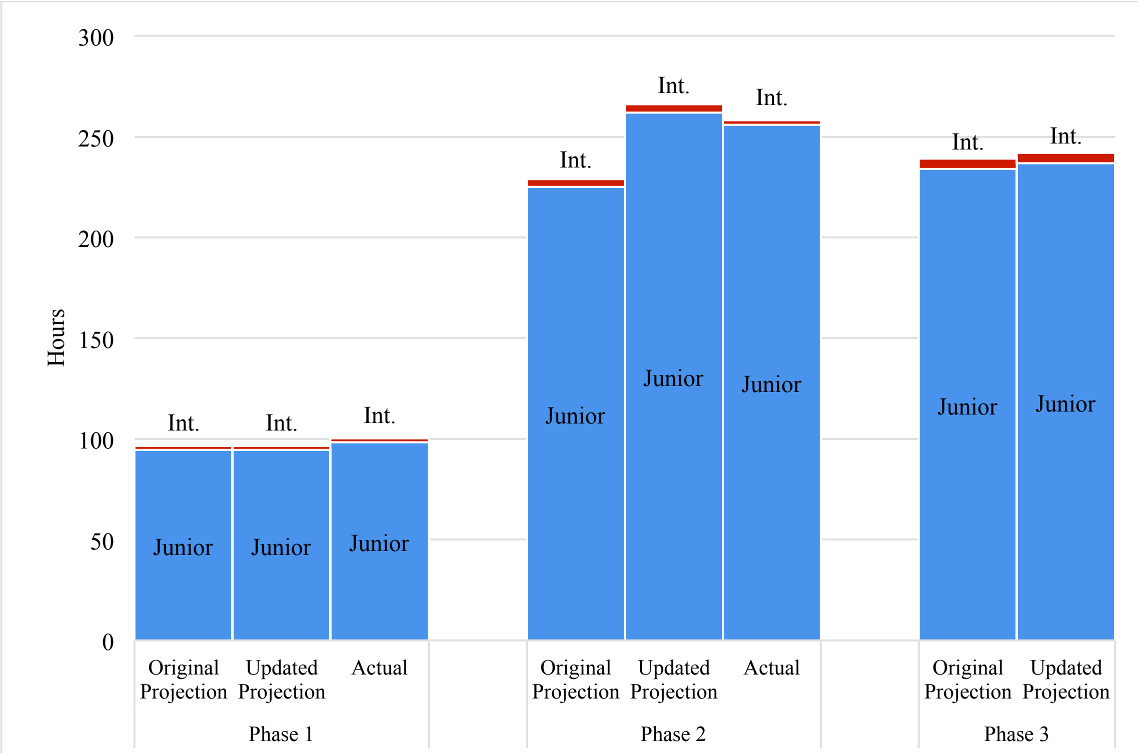


Figure 17 Engineer Design hours for Junior and Intermediate engineers for each phase

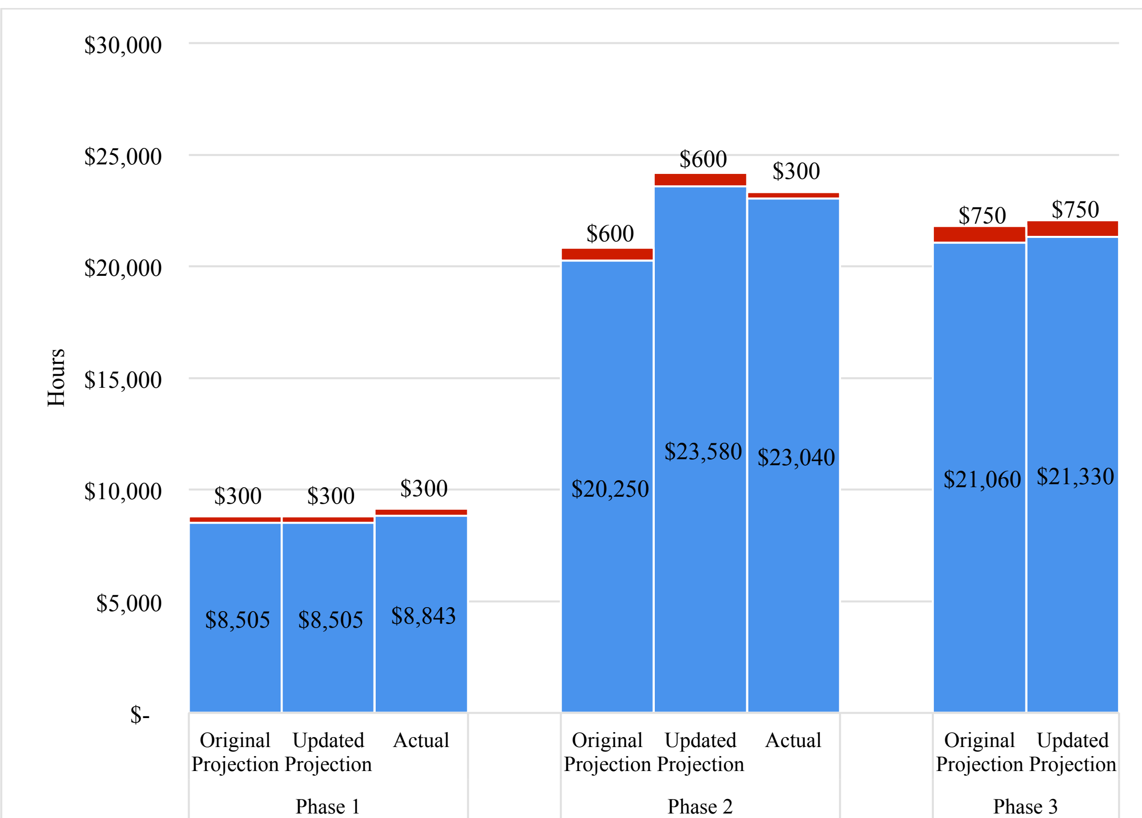


Figure 18 Engineer Design Cost for Junior and Intermediate engineers for each phase

8 References

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Appendix A. Calculations

A.1. Concept 1

Concept 1 Calculations

Existing Vehicle Gear Ratios

Gear Ratios

Primary Reduction

$pr := \frac{22}{62}$

First $g_1 := \frac{12}{29}$

Second $g_2 := \frac{15}{26}$

Third $g_3 := \frac{16}{21}$

Fourth $g_4 := \frac{20}{21}$

Fifth $g_5 := \frac{25}{21}$

CVT Ratios

Low gear $c_1 := \frac{1}{3.5}$

High Gear $c_2 := \frac{1}{1}$

Gear Reductions for Various Gear Options

	Low Gear Reduction	High Gear Reduction
First Gear	$r1_{min} := pr \cdot g_1 \cdot c_1 = 0.042$	$r1_{max} := pr \cdot g_1 \cdot c_2 = 0.1468$
Second Gear	$r2_{min} := pr \cdot g_2 \cdot c_1 = 0.0585$	$r2_{max} := pr \cdot g_2 \cdot c_2 = 0.2047$
Third Gear	$r3_{min} := pr \cdot g_3 \cdot c_1 = 0.0772$	$r3_{max} := pr \cdot g_3 \cdot c_2 = 0.2704$
Fourth Gear	$r4_{min} := pr \cdot g_4 \cdot c_1 = 0.0966$	$r4_{max} := pr \cdot g_4 \cdot c_2 = 0.3379$
Fifth Gear	$r5_{min} := pr \cdot g_5 \cdot c_1 = 0.1207$	$r5_{max} := pr \cdot g_5 \cdot c_2 = 0.4224$

Engine/Vehicle Parameters

Rotational Speed

$\omega_{max} := 9000\ rpm$

$\omega_{opt} := 7750\ rpm$

$\omega_{eg} := 4000\ rpm$ (Engagement RPM)

Power

$HP_{opt} := 50\ hp$

Tire Diameter

$d_T := 20.5\ in$

Speed and Torque Calculations for Gear Reductions
(No additional Reduction ie sheaves on diff)

First Gear

-Engagement $v1_{eg} = r1_{min} \cdot \omega_{eg} \cdot \frac{d_T}{2} = 16.47 \frac{km}{hr}$

-Low Gear optimal rpm $v1_L := r1_{min} \cdot \omega_{opt} \cdot \frac{d_T}{2} = 31.9107 \frac{km}{hr}$

-High Gear optimal rpm $v1_H := r1_{max} \cdot \omega_{opt} \cdot \frac{d_T}{2} = 111.6875 \frac{km}{hr}$

-Shift Out $v1_S = r1_{max} \cdot \omega_{max} \cdot \frac{d_T}{2} = 129.7016 \frac{km}{hr}$

Second Gear

-Engagement $v2_{eg} := r2_{min} \cdot \omega_{eg} \cdot \frac{d_T}{2} = 22.963 \frac{km}{hr}$

-Low Gear optimal rpm $v2_L := r2_{min} \cdot \omega_{opt} \cdot \frac{d_T}{2} = 44.4909 \frac{km}{hr}$

-High Gear optimal rpm $v2_H := r2_{max} \cdot \omega_{opt} \cdot \frac{d_T}{2} = 155.7182 \frac{km}{hr}$

-Shift Out $v2_S = r2_{max} \cdot \omega_{max} \cdot \frac{d_T}{2} = 180.834 \frac{km}{hr}$

Fourth Gear

-Engagement $v4_{eg} := r4_{min} \cdot \omega_{eg} \cdot \frac{d_T}{2} = 37.9073 \frac{km}{hr}$

-Low Gear $v4_L = r4_{min} \cdot \omega_{opt} \cdot \frac{d_T}{2} = 73.4453 \frac{km}{hr}$

-High Gear $v4_H := r4_{max} \cdot \omega_{opt} \cdot \frac{d_T}{2} = 257.0586 \frac{km}{hr}$

-Shift Out $v4_S := r4_{max} \cdot \omega_{max} \cdot \frac{d_T}{2} = 298.5196 \frac{km}{hr}$

Third Gear

-Engagement $v3_{eg} := r3_{min} \cdot \omega_{eg} \cdot \frac{d_T}{2} = 30.3258 \frac{km}{hr}$

-Low Gear $v3_L = r3_{min} \cdot \omega_{opt} \cdot \frac{d_T}{2} = 58.7562 \frac{km}{hr}$

-High Gear $v3_H := r3_{max} \cdot \omega_{opt} \cdot \frac{d_T}{2} = 205.6469 \frac{km}{hr}$

-Shift Out $v3_S := r3_{max} \cdot \omega_{max} \cdot \frac{d_T}{2} = 238.8157 \frac{km}{hr}$

Fifth Gear

-Engagement $v5_{eg} = r5_{min} \cdot \omega_{eg} \cdot \frac{d_T}{2} = 47.3841 \frac{km}{hr}$

-Low Gear $v5_L := r5_{min} \cdot \omega_{opt} \cdot \frac{d_T}{2} = 91.8066 \frac{km}{hr}$

-High Gear $v5_H = r5_{max} \cdot \omega_{opt} \cdot \frac{d_T}{2} = 321.3232 \frac{km}{hr}$

-Shift Out $v5_S = r5_{max} \cdot \omega_{max} \cdot \frac{d_T}{2} = 373.1495 \frac{km}{hr}$

From these speed calculations it is apparent some additional reduction must be achieved

Assume using shift out speed (top speed) of 110 km/hr
solve for required additonal gear reduction. Assume additional gear reduction occurs
AFTER the CVT reduction.

$$v_{ts} := 110 \frac{km}{hr}$$

First Gear

$$gr_{a2} = \frac{2 \cdot v_{ts}}{r2_{max} \cdot \omega_{max} \cdot d_T} = 0.6083$$

Assume approximate gear reduction as:

$$gr_{a2} := \text{round}\left(gr_{a2}, 1\right) = 0.6$$

$$v_{ts2} := \frac{gr_{a2} \cdot r2_{max} \cdot \omega_{max} \cdot d_T}{2} = 108.5004 \frac{km}{hr}$$

Second Gear

$$gr_{a1} := \frac{2 \cdot v_{ts}}{r1_{max} \cdot \omega_{max} \cdot d_T} = 0.8481$$

Assume approximate gear reduction as:

$$gr_{a1} := \text{round}\left(gr_{a1}, 1\right) = 0.8$$

$$v_{ts1} := \frac{gr_{a1} \cdot r2_{max} \cdot \omega_{max} \cdot d_T}{2} = 144.6672 \frac{km}{hr}$$

-Engagement $v2_{ega} := r2_{min} \cdot gr_{a2} \cdot \omega_{eg} \cdot \frac{d_T}{2} = 13.7778 \frac{km}{hr}$ $v1_{ega} := r1_{min} \cdot gr_{a1} \cdot \omega_{eg} \cdot \frac{d_T}{2} = 13.176 \frac{km}{hr}$

-Low Gear optimal rpm $v2_{La} := r2_{min} \cdot gr_{a2} \cdot \omega_{opt} \cdot \frac{d_T}{2} = 26.6945 \frac{km}{hr}$ $v1_{La} := r1_{min} \cdot gr_{a1} \cdot \omega_{opt} \cdot \frac{d_T}{2} = 25.5286 \frac{km}{hr}$

-High Gear optimal rpm $v2_{Ha} := r2_{max} \cdot gr_{a2} \cdot \omega_{opt} \cdot \frac{d_T}{2} = 93.4309 \frac{km}{hr}$ $v1_{Ha} := r1_{max} \cdot gr_{a1} \cdot \omega_{opt} \cdot \frac{d_T}{2} = 89.35 \frac{km}{hr}$

-Shift Out $v2_{Sa} := r2_{max} \cdot gr_{a2} \cdot \omega_{max} \cdot \frac{d_T}{2} = 108.5004 \frac{km}{hr}$ $v1_{Sa} := r1_{max} \cdot gr_{a1} \cdot \omega_{max} \cdot \frac{d_T}{2} = 103.7613 \frac{km}{hr}$

Third Gear

$$gr_{a3} := \frac{2 \cdot v_{ts}}{r3_{max} \cdot \omega_{max} \cdot d_T} = 0.4606$$

Assume approximate gear reduction as:

$$gr_{a3} := \text{round}\left(gr_{a3}, 2\right) = 0.46$$

$$v_{ts3} := \frac{gr_{a3} \cdot r3_{max} \cdot \omega_{max} \cdot d_T}{2} = 109.8552 \frac{km}{hr}$$

-Engagement $v3_{ega} := r3_{min} \cdot gr_{a3} \cdot \omega_{eg} \cdot \frac{d_T}{2} = 13.9499 \frac{km}{hr}$

-Low Gear optimal rpm $v3_{La} := r3_{min} \cdot gr_{a3} \cdot \omega_{opt} \cdot \frac{d_T}{2} = 27.0279 \frac{km}{hr}$

-High Gear optimal rpm $v3_{Ha} := r3_{max} \cdot gr_{a3} \cdot \omega_{opt} \cdot \frac{d_T}{2} = 94.5976 \frac{km}{hr}$

-Shift Out $v3_{Sa} := r3_{max} \cdot gr_{a3} \cdot \omega_{max} \cdot \frac{d_T}{2} = 109.8552 \frac{km}{hr}$

Fourth Gear

$$gr_{a4} := \frac{2 \cdot v_{ts}}{r4_{max} \cdot \omega_{max} \cdot d_T} = 0.3685$$

Assume approximate gear reduction as:

$$gr_{a4} := \text{round}\left(gr_{a4}, 2\right) = 0.37$$

$$v_{ts4} := \frac{gr_{a4} \cdot r4_{max} \cdot \omega_{max} \cdot d_T}{2} = 110.4523 \frac{km}{hr}$$

$v4_{ega} := r4_{min} \cdot gr_{a4} \cdot \omega_{eg} \cdot \frac{d_T}{2} = 14.0257 \frac{km}{hr}$

$v4_{La} := r4_{min} \cdot gr_{a4} \cdot \omega_{opt} \cdot \frac{d_T}{2} = 27.1748 \frac{km}{hr}$

$v4_{Ha} := r4_{max} \cdot gr_{a4} \cdot \omega_{opt} \cdot \frac{d_T}{2} = 95.1117 \frac{km}{hr}$

$v4_{Sa} := r4_{max} \cdot gr_{a4} \cdot \omega_{max} \cdot \frac{d_T}{2} = 110.4523 \frac{km}{hr}$

Fifth Gear

$$gr_{a5} := \frac{2 \cdot v_{ts}}{r5_{max} \cdot \omega_{max} \cdot d_T} = 0.2948$$

Assume approximate gear reduction as:

$$gr_{a5} := \text{round}\left(gr_{a5}, 2\right) = 0.29$$

$$v_{ts5} := \frac{gr_{a5} \cdot r5_{max} \cdot \omega_{max} \cdot d_T}{2} = 108.2134 \frac{km}{hr}$$

-Engagement $v5_{ega} := r5_{min} \cdot gr_{a5} \cdot \omega_{eg} \cdot \frac{d_T}{2} = 13.7414 \frac{km}{hr}$

-Low Gear optimal rpm $v5_{La} := r5_{min} \cdot gr_{a5} \cdot \omega_{opt} \cdot \frac{d_T}{2} = 26.6239 \frac{km}{hr}$

-High Gear optimal rpm $v5_{Ha} := r5_{max} \cdot gr_{a5} \cdot \omega_{opt} \cdot \frac{d_T}{2} = 93.1837 \frac{km}{hr}$

-Shift Out $v5_{Sa} := r5_{max} \cdot gr_{a5} \cdot \omega_{max} \cdot \frac{d_T}{2} = 108.2134 \frac{km}{hr}$

Fifth Gear Using Current Sprocket to Diff Reduction

$$gr_a := \frac{1}{4}$$

$$v_{ts} := \frac{gr_a \cdot r5_{max} \cdot \omega_{max} \cdot d_T}{2} = 93.2874 \frac{km}{hr}$$

$v_{eg} := r5_{min} \cdot gr_a \cdot \omega_{eg} \cdot \frac{d_T}{2} = 11.846 \frac{km}{hr}$

$v_L := r5_{min} \cdot gr_a \cdot \omega_{opt} \cdot \frac{d_T}{2} = 22.9517 \frac{km}{hr}$

$v_H := r5_{max} \cdot gr_a \cdot \omega_{opt} \cdot \frac{d_T}{2} = 80.3308 \frac{km}{hr}$

$v_S := r5_{max} \cdot gr_a \cdot \omega_{max} \cdot \frac{d_T}{2} = 93.2874 \frac{km}{hr}$

Engagement speed represents the relative vehicle speed difference with respect to the engine when the vehicle is accelerating from a standstill. Up to this speed the belt will be forced to "slip" in order to accomodate the speed difference between the two systems. For design it is important to make this speed below the typical vehicle operation speed to avoid excessive wear on the bel

Piecewise Function for Shifting

(First Gear, No additional reduction)

Piece 1

$$\omega_{eng1}(v_v) = \omega_{eg} + v_v \cdot \frac{(500\ rpm)}{v_{node1}} \qquad v_{node1} = r1_{min} \cdot (\omega_{eg} + 500\ rpm) \cdot \frac{d_T}{2} = 18.5288\ \frac{km}{hr}$$

$$\omega_{eg.u} := \frac{\omega_{eg}}{rpm}$$

$$v_{node1.u} := v_{node1} \frac{hr}{km} = 18.5288$$

$$\omega_{eng1.u}(v_v) = \omega_{eg.u} + v_v \cdot \left(\frac{500}{v_{node1.u}}\right)$$

*Make into unitless function for plot

Piece 2

$$\omega_{eng2}(v_v) := \frac{2 \cdot v_v}{r1_{min} \cdot d_T} \qquad v1_L := r1_{min} \cdot \omega_{opt} \cdot \frac{d_T}{2} = 31.9107\ \frac{km}{hr}$$

$$d_{T.u} := \frac{d_T}{km} = 0.0005$$

$$v1_{L.u} := v1_L \frac{hr}{km} = 31.9107$$

$$\omega_{eng2.u}(v_v) := \frac{2 \cdot v_v}{60 \cdot 2 \cdot \pi \cdot r1_{min} \cdot d_{T.u}}$$

1

Piece 3

$$\omega_{eng3}(v_v) := \omega_{opt}$$

$$v1_{H.u} := v1_H \frac{hr}{km} = 111.6875 \qquad v1_H = 111.6875\ \frac{km}{hr}$$

$$\omega_{opt.u} := \frac{\omega_{opt}}{rpm}$$

$$\omega_{eng3.u}(v_v) = \omega_{opt.u}$$

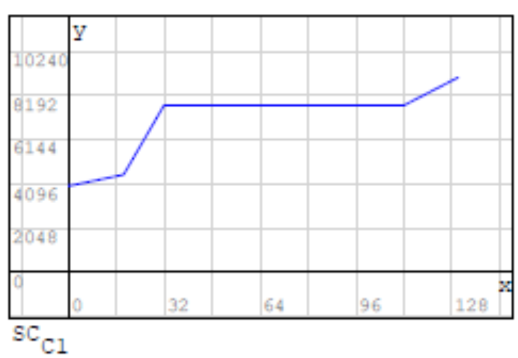
Piece 4

$$\omega_{eng4}(v_v) = \frac{2 \cdot v_v}{r1_{max} \cdot d_T}$$

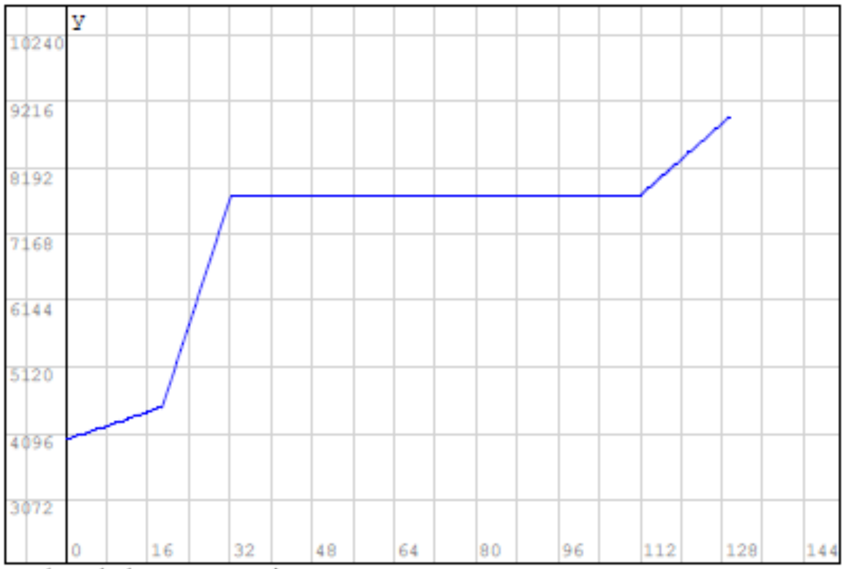
$$v1_{S.u} := v1_S \frac{hr}{km} \qquad \omega_{eng4}(v1_H) = 7750\ rpm$$

$$\omega_{eng4.u}(v_v) := \frac{2 \cdot v_v}{60 \cdot 2 \cdot \pi \cdot r1_{max} \cdot d_{T.u}}$$

$$SC_{C1} := \begin{bmatrix} 0 & \frac{\omega_{eg}}{rpm} \\ v_{node1} \frac{hr}{km} & \frac{\omega_{eg}}{rpm} + 500 \\ v1_L \frac{hr}{km} & \frac{\omega_{opt}}{rpm} \\ v1_H \frac{hr}{km} & \frac{\omega_{opt}}{rpm} \\ v1_S \frac{hr}{km} & \frac{\omega_{max}}{rpm} \end{bmatrix} = \begin{bmatrix} 0 & 4000 \\ 18.5288 & 4500 \\ 31.9107 & 7750 \\ 111.6875 & 7750 \\ 129.7016 & 9000 \end{bmatrix}$$



Shift curve assuming 1st gear from transmission is used and no additional gear reduction



if $(x \geq 0) \wedge (x \leq v_{node1.u})$

$\quad \omega_{eng1.u}(x)$

else

$\quad$ if $(x \geq v_{node1.u}) \wedge (x \leq v1_{L.u})$

$\qquad \omega_{eng2.u}(x)$

$\quad$ else

$\qquad$ if $(x \geq v1_{L.u}) \wedge (x \leq v1_{H.u})$

$\qquad\quad \omega_{eng3.u}(x)$

$\qquad$ else

$\qquad\quad$ if $(x \geq v1_{H.u}) \wedge (x \leq v1_{S.u})$

$\qquad\qquad \omega_{eng4.u}(x)$

$\qquad\quad$ else

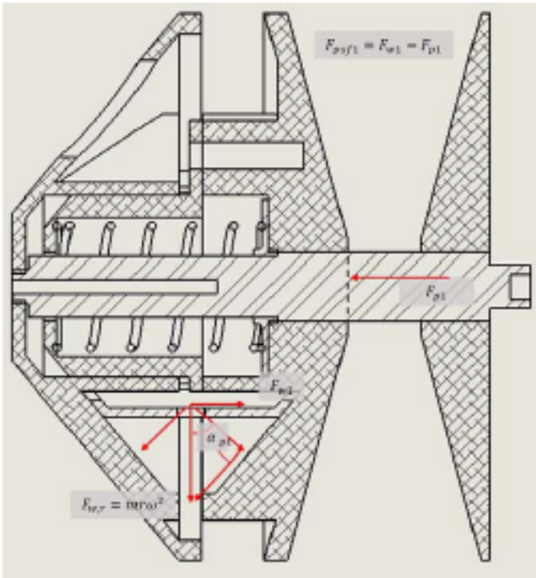
$\qquad\qquad$ "not defined"

The above shift curve is theoretically possible using the primary and secondary clutches, however, achieving this exact curve requires precise design optimization to determine each of the physical parameters. If this concept is selected these parameters will be evaluated based on the ideal curve and than adjusted after assemlby to try and match the real shift curve to the ideal one - this is the process of tuning which requires much trial and error and experience to accomplish it effectively and efficiently

Shift Forces

(neglect belt forces for these calculations)

Primary Clutch



The shifting force is a function of the weights in the primary clutch and the compression spring force (primary shifting force - psf)

$$\boxed{F_{psf1}(x_p, \omega_p) := F_{w1}(x_p, \omega_p) - F_{p1}(x_p)}$$

where x_p is the axial displacement of the primary clutch moveable sheave

ω_p is the angular speed of the primary clutch

$$F_{w1}(x_p, \omega_p) := \frac{r_1(x_p) \cdot m_{w1} \cdot \omega_p^{\,2}}{2 \cdot \cos(\alpha_{p1})}$$

Force due to the angular acceleration of the clutch weights

where r_1 is the radial position of the clutch weights

m_{w1} is the total mass of the clutch weights

α_{p1} is the slide angle of the clutch weights

However the radial position of the weights is a function of the position of the clutch

$$r_1(x) = r_o + \frac{x}{\cos(\alpha_{p1})}$$

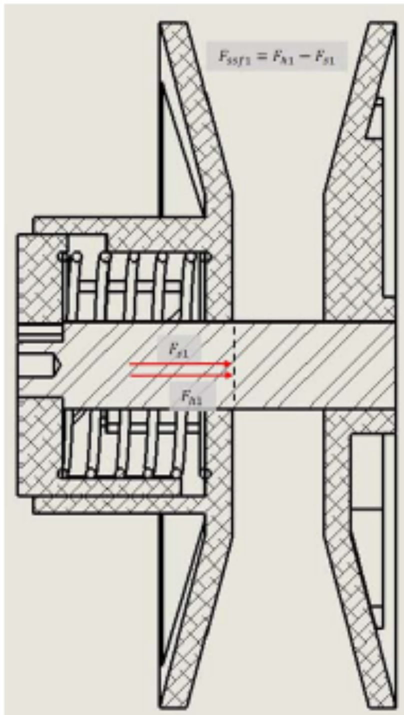
r_o is the neutral position of the weights

$$F_{p1}(x) := k_{p1} \cdot x + F_{peg1}$$

Force due to the primary clutch compression spring

F_{peg1} is the engagment preload of the primary clutch

Secondary Clutch



The shifting force of the secondary clutch is a function of the compression spring force and the torque applied to the helix

$$\boxed{F_{ssf1}\left(T_{s1}, x_s\right) := F_{s1}\left(x_s\right) + F_{h1}\left(T_{s1}\right)}$$

where T_{s1} is the torque experienced by the secondary clutch

x_s is the axial displacement of the secondary clutch moveable sheave

$$F_{h1} = T_{s1} \cdot \frac{\sin\left(\alpha_{s1}\right)}{r_{h1}}$$

α_{s1} is the helix angle

r_{h1} is the helix radius

$$F_{p2}\left(x_s\right) := \left(F_{seg1} + k_{s1} \cdot x_s\right)$$

F_{seg1} is the preload compression of the secondary clutch spring

k_{s1} is the spring stiffness of the secondary clutch

There is a complex relationship between these two shifting forces that takes into account the physical characteristics of the pulley sheaves, belt, and coefficients of friction. The numberical analysis of this relationship is not well known but the shift behavior of this type of a system is, as was characterized above

Power versus Speed Comparison

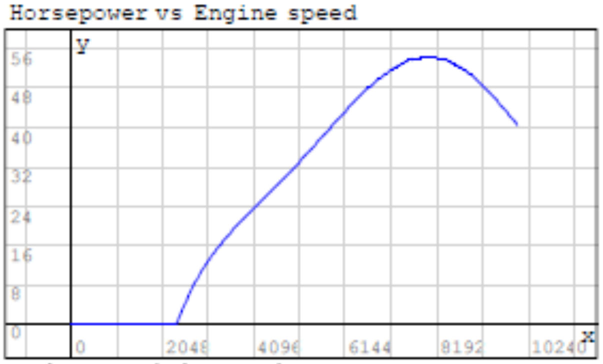
Create approximate engine horsepower curve using 7750rpm and 50hp as the peak and assuming it takes the shape of a fifth order polynomial - approximated from dyno curve of similar engine

$a_5 := 2.44244 \cdot 10^{-17} \frac{hp}{rpm^5}$ $a_3 := 9.83752 \cdot 10^{-9} \frac{hp}{rpm^3}$ $a_1 := 0.168498 \frac{hp}{rpm}$

$a_4 := 8.0189 \cdot 10^{-13} \frac{hp}{rpm^4}$ $a_2 := 5.72013 \cdot 10^{-5} \frac{hp}{rpm^2}$ $a_0 := 185.332\,hp$

$$HP_{eng}(\omega_{eng}) := \left(a_5 \cdot \omega_{eng}^5 - a_4 \cdot \omega_{eng}^4 + a_3 \cdot \omega_{eng}^3 - a_2 \cdot \omega_{eng}^2 + a_1 \cdot \omega_{eng} - (a_0)\right)$$

Horsepower vs Engine speed




```
if (x ≤ 10000) ∧ (x ≥ 2360)
  HP_eng(x rpm) · 1/hp
else
  if (x ≤ 2360) ∧ (x ≥ 0)
    0
  else
    "not defined"
```

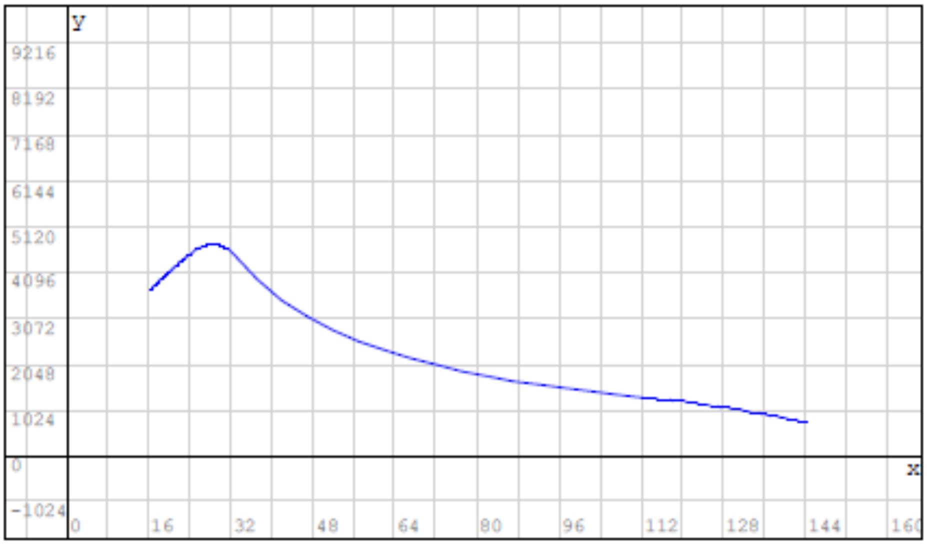
```
v_v1(ω_eng) := if (ω_eng ≥ ω_eg) ∧ (ω_eng < ω_opt)
                 pr · g_1 · c_1 · ω_eng · d_T/2
               else
                 if (ω_eng = ω_opt)
                   v_temp := v1_L
                   for i := 1 , (v_temp < v1_H) , i := i + 1
                     v_matrix_(i 1) := v_temp
                     v_temp := v_temp + 5 km/hr
                   v_matrix
                 else
                   if (ω_eng > ω_opt)
                     pr · g_1 · c_2 · ω_eng · d_T/2
                   else
                     "not defined"
```

Create piecewise function for velocity of vehicle as function of engine speed. Because engine speed is constant while the vehicle speed increases for a section of the curve a for loop was used to generate a matrix for plotting this section of the curve

Create matrix of vehicle speeds and ground force using the following script.

```
ω_eng ≔ ω_eg
counter ≔ 1
for i ≔ 1 , (ω_eng ≤ ω_opt + 1 rpm) , i ≔ i + 1
  if (ω_eng < ω_opt − 1 rpm)
    GF_C1[i 2 ≔ HP_eng(ω_eng) / v_v1(ω_eng) · 1/N
    GF_C1[i 1 ≔ v_v1(ω_eng) · hr/km
    ω_eng ≔ ω_eng + 50 rpm
    dummy ≔ 50
  else
    for j ≔ i , counter ≤ length(v_v1(ω_opt)) , j ≔ j + 1
      GF_C1[j 2 ≔ HP_eng(ω_opt) / v_v1(ω_opt)[j − i + 1] · 1/N
      GF_C1[j 1 ≔ v_v1(ω_opt)[j − i + 1] · hr/km
      dummy1 ≔ i
      dummy2 ≔ j
      counter ≔ counter + 1
    ω_eng ≔ ω_eng + 50 rpm
for i ≔ 92 , ω_eng ≤ 10000 rpm , i ≔ i + 1
  GF_C1[i 2 ≔ HP_eng(ω_eng) / v_v1(ω_eng) · 1/N
  GF_C1[i 1 ≔ v_v1(ω_eng) · hr/km
  ω_eng ≔ ω_eng + 50 rpm
  dummy ≔ 20
```

Concept 1 Force applied to ground vs speed curve



GF_{C1}

A.2. Concept 2

Concept 2 Calculations

Existing Vehicle Gear Ratios

Gear Ratios

Primary Reduction

$pr = \frac{22}{62}$

First $g_1 = \frac{12}{29}$

Second $g_2 = \frac{15}{26}$

Third $g_3 = \frac{16}{21}$

Fourth $g_4 = \frac{20}{21}$

Fifth $g_5 = \frac{25}{21}$

CVT Ratios

Low gear $c_1 = \frac{1}{3.5}$ High Gear $c_2 = \frac{1}{1}$

Gear Reductions for Various Gear Options

	Low Gear Reduction	High Gear Reduction
First Gear	$r1_{min} := pr \cdot g_1 \cdot c_1 = 0.042$	$r1_{max} := pr \cdot g_1 \cdot c_2 = 0.1468$
Second Gear	$r2_{min} := pr \cdot g_2 \cdot c_1 = 0.0585$	$r2_{max} := pr \cdot g_2 \cdot c_2 = 0.2047$
Third Gear	$r3_{min} := pr \cdot g_3 \cdot c_1 = 0.0772$	$r3_{max} := pr \cdot g_3 \cdot c_2 = 0.2704$
Fourth Gear	$r4_{min} := pr \cdot g_4 \cdot c_1 = 0.0966$	$r4_{max} := pr \cdot g_4 \cdot c_2 = 0.3379$
Fifth Gear	$r5_{min} := pr \cdot g_5 \cdot c_1 = 0.1207$	$r5_{max} := pr \cdot g_5 \cdot c_2 = 0.4224$

Using the same two cases as were used for concept 1

Case 1: No additional reductoin, 1st gear used $\quad v_{v1}(\omega_{eng}) := pr \cdot g_1 \cdot gr_{cvt2}(\omega_{eng}) \cdot \frac{d_T}{2} \cdot \omega_{eng}$

Case 2: Additional reduction of gr.a $\quad v_{v2}(\omega_{eng}) := pr \cdot g_5 \cdot gr_{a5} \cdot gr_{cvt2}(\omega_{eng}) \cdot \frac{d_T}{2} \cdot \omega_{eng}$

Engine/Vehicle Parameters

Rotational Speed

$\omega_{max} := 9000\ rpm$

$\omega_{opt} := 7750\ rpm$

$\omega_{eg} := 4000\ rpm$ Full Engagement RPM

Power

$HP_{opt} := 50\ hp$

Tire Diameter

$d_T := 20.5\ in$ $\quad gr_{a5} := \frac{1}{4}$

Assume the goal is to have the system in Low gear at 6000 rpm and high gear at 9000 rpm

$\omega_L := 7000\ rpm$

$\omega_H := 8000\ rpm$

For this concept, the gear ratio of the cvt is strictly a function of the engine speed and can be defined as a piecewise function given the high and low gear engine speeds that were previously defined.

$$gr_{cvt2}(\omega_{eng}) := \begin{array}{l} \text{if } (\omega_{eng} \ge 0) \wedge (\omega_{eng} \le \omega_L) \\ \quad c_1 \\ \text{else} \\ \quad \text{if } (\omega_{eng} \ge \omega_L) \wedge (\omega_{eng} \le \omega_H) \\ \quad \quad c_1 + \frac{(c_2 - c_1)}{(\omega_H - \omega_L)} \cdot (\omega_{eng} - \omega_L) \\ \quad \text{else} \\ \quad \quad c_2 \end{array}$$

Given this gear ratio function for the cvt and the gear ratios defined above, the angular speeds of the variator, driven pulley, and bell clutch can be defined as functions of the engine speed (case 1 and 2 are the same since the additional gear reduction would be added after the pulley

$\omega_{var}(\omega_{eng}) := \omega_{eng} \cdot pr \cdot g_1$ Variator speed

$\omega_{bc}(\omega_{eng}) := \omega_{eng} \cdot pr \cdot g_1 \cdot gr_{cvt2}(\omega_{eng})$ Bell Clutch speed

$\omega_{dp}(\omega_{eng}) = \omega_{bc}(\omega_{eng})$ Driven pulley speed

The design paraemeters for concept 2 are as follows

$\boxed{\text{Variator}}$

Variator Weights

Weights (assume constant) m_{w2}

Weight movement Angle (measured relative to shaft axis) $\alpha_{p2} := 50\ deg$

Weight Radius (starting postion) $r_{w2o} = 30\ mm$

Shift Length $L_{s2} := 27\ mm$

$\boxed{\text{Driven Pulley}}$

Axial spring

Preload $F_{d2} = 300\ N$

Load at Shift Out F_{ds2}

Spring constant $k_{d2} = \frac{F_{ds2} - F_{dp2}}{L_{s2}}$

$\boxed{\text{Bell Clutch}}$

Clutch Spring

Bell clutch spring constant $k_{bc2} := 500\ \frac{N}{m}$

Bell clutch weights m_{bc2}

Weights starting radius $r_{bcs2} = 75\ mm$

Weights contact radius $r_{bcc2} = 80\ mm$

Clutch coefficient of friction $\mu_{bc2} := 1$

Since having this many variables is unnecessary to design the system to the desired engine speeds for shifting (engagement, low gear, and high gear engine speeds). All but the 3 variables that are typically adjusted have been predefined based on common industry standards

To solve for the mass of the bell clutch weights consider the vehicle engagement speed

The engagement speed represents the engine speed that the system is designed for the clutch to no longer slip. Note that the exact point this occurs depends on the vehicle acceleration rate which is a function of how much the operator depresses the accelerator pedal. So, this speed will be solved for as a steady state speed where vehicle load is equivalent to the torque output of the clutch

$$T_{bc2} = L_v \quad \boxed{1}$$

Torque of the bell clutch is equal to the vehicle load

For steady state operation, the vehicle load is simply the drag force on the vehicle estimated by the following equation

Vehicle Mass $m_v := 260\ kg$

Drag Coefficient $C_D := 0.8$

Vehicle Area $A_v := 1\ m^2$

Air Density $\rho_a := 1.00\ \frac{kg}{m^3}$

Vehicle Drag Force

$$F_{Drag}(v_v) := \frac{1}{2} \cdot \rho_a \cdot {v_v}^2 \cdot C_D \cdot A_v$$

Approximate force to overcome mechanical losses

$$F_m := 40\ N$$

Consider 2 cases: Case 1 where there is no additional reduction and use first gear from the sequential gearbox. Case 2 where there is an additional reduction after the sequential gearbox of gr_a

Case 1:

$$L_{v1}(\omega_{eng}) := \left(F_{drag}(v_{v1}) + F_m\right) \cdot \frac{d_T}{2} \quad \boxed{2.1}$$

Case 2:

$$L_{v2}(\omega_{eng}) := gr_a \cdot F_{drag}(v_{v2}) \cdot \frac{d_T}{2} \quad \boxed{2.2}$$

Note that since we are assuming the clutch is no longer slipping at this point, the vehicle speed is a function of the engine speed

$$v_{v1} = v_{v1}(\omega_{eng}) \qquad v_{v2} = v_{v2}(\omega_{eng})$$

Therefore, the torque of the bell clutch given the desired vehicle speed can be solved by combining $\boxed{1}$ and $\boxed{2}$ for both cases

$$T_{bc2.1}(\omega_{eng}) := \left(F_{Drag}(v_{v1}(\omega_{eng})) + F_m\right) \cdot \frac{d_T}{2} \qquad T_{bc2.2}(\omega_{eng}) := gr_{a5} \cdot \left(F_{Drag}(v_{v2}(\omega_{eng})) + F_m\right) \cdot \frac{d_T}{2}$$

$$T_{bc.case1} := T_{bc2.1}(\omega_{eg}) = 12.5937\ N\ m \qquad T_{bc.case2} := T_{bc2.2}(\omega_{eg}) = 2.8854\ N\ m$$

Using these values for the torque applied to the bell clutch, the mass of the bell clutch weights can be evaluated

$$T_{bc2}(\omega_{eng}, m_{bc2}) := \mu_{bc2} \cdot \left(m_{bc2} \cdot r_{bcc2} \cdot \left(\omega_{bc}(\omega_{eng})\right)^2 - k_{bc2} \cdot (r_{bcc2} - r_{bcs2})\right) \cdot r_{bcs2}$$

Solving the above equation for the mass of the bell yields

$$m_{bc2}(\omega_{eng}, T_{bc2}) := \frac{1}{r_{bcc2} \cdot \left(\omega_{bc}(\omega_{eng})\right)^2} \cdot \left(\frac{T_{bc2}}{\mu_{bc2} \cdot r_{bcs2}} + k_{bc2} \cdot (r_{bcc2} - r_{bcs2})\right)$$

Solving this equation for both cases using the engagement speed of the engine yields

$$m_{bc2.1} := \left(m_{bc2}(\omega_{eg}, T_{bc.case1})\right) = 6.8985\ kg \qquad m_{bc2.2} := \left(m_{bc2}(\omega_{eg}, T_{bc.case2})\right) = 1.6585\ kg$$

This mass is excessively large - it is a feasibility issue

Next, from the physical parameters of the bell clutch, solve for the engine speed at which the clutch weights initially contact the bell with sufficient force to start vehicle movement

Assuming the point at which this occurs is when the weights force is equivalent to the spring force when the spring is extended up to the bell

$$F_{spring} := k_{bc2} \cdot \left(r_{bcc2} - r_{bcs2} \right) = 2.5\ N$$

However, the above assumption neglects the mechanical losses throught the system that increase the force necessary to start movement. This value cannot be determined from the current physical data, so a initial movement speed was estimated as 40 N of force.

Which can be converted to a torque load on the bell clutch when the vehicle is stationary

$$T_{mbc.1} := T_{bc2.1}(0\ rpm) = 10.414\ N\ m \qquad T_{mbc.2} := T_{bc2.2}(0\ rpm) = 2.6035\ N\ m$$

$$\omega_{move}\left(m_{bc2}, T_{mbc} \right) := \frac{1}{pr \cdot g_1 \cdot c_1} \cdot \sqrt{\frac{1}{r_{bcc2} \cdot m_{bc2}} \cdot \left(\frac{T_{mbc}}{\mu_{bc2} \cdot r_{bcs2}} + k_{bc2} \cdot \left(r_{bcc2} - r_{bcs2} \right) \right)}$$

$$\omega_{move.1} := \left(\omega_{move}\left(m_{bc2.1}, T_{mbc.1} \right) \right) = 3642.9848\ rpm$$

$$\omega_{move.2} := \left(\omega_{move}\left(m_{bc2.2}, T_{mbc.2} \right) \right) = 3812.1115\ rpm$$

To solve for the variator weights consider the low gear (about to shift) speed

To achieve the set low gear speed the variator shifting force must overcome the preload on the spring in the drive pulley. Note that this value is the same regardless of an additional gear reduction (case 1 and case 2 are equivalent)

$$F_{vsf2}\left(\omega_{eng}, m_{w2} \right) = \omega_{eng}^{2} \cdot m_{w2} \cdot r_{w2}(x)$$

But, x is a function of the cvt gear ratio, which is a function of the engine speed

$$x\left(\omega_{eng} \right) := \frac{c_1 \cdot L_{s2}}{c_1 - c_2} - \frac{L_{s2}}{c_1 - c_2} \cdot gr_{cvt2}\left(\omega_{eng} \right)$$

Therefore the radius of the weight can be written as a function of the engine speed

$$r_{w2}\left(\omega_{eng} \right) := r_{w2o} + x\left(\omega_{eng} \right) \cdot \sin\left(\alpha_{p2} \right)$$

Thus the shifting forse of the variator can be written as:

$$F_{vsf2}\left(\omega_{eng} \right) := \omega_{eng}^{2} \cdot m_{w2} \cdot r_{w2}\left(\omega_{eng} \right)$$

Rearranging the equation and solving for when the shifting force is the equal to the preload on the drive pulley sping

$$m_{w2}\left(\omega_{eng} \right) := \frac{F_{d2}}{\omega_{eng}^{2} \cdot r_{w2}\left(\omega_{eng} \right)}$$

Solving the mass of the weights using the desired low gear shifting speed yields

$$m_{w2} := m_{w2}\left(\omega_L \right) = 0.0186\ kg$$ This value for the weights is physically reasonable

Lastly, consider the case of the high gear shifting speed and solve for the shift out load for the drive pulley spring - and the corresponding spring constant, and preload compression length

$$F_{ds2} := F_{vsf2}(\omega_H) = 661.9847\,N$$

$$k_{d2} := \frac{F_{ds2} - F_{d2}}{L_{s2}} = 13406.839\,\frac{N}{m}$$

$$L_{pcd2} := \frac{F_{d2}}{k_{d2}} = 22.3766\,mm$$

Given the physical parameters of this system are realistic, the shift curve can be plotted using the various engine speed values.

Case 1:

$$\omega_{move.1} = 3642.9848\,rpm$$

$$v_1 := v_{v1}(\omega_{eg}) = 16.47\,\frac{km}{hr}$$

$$v_2 := v_{v1}(\omega_L) = 28.8226\,\frac{km}{hr}$$

$$v_3 := v_{v1}(\omega_H) = 115.2903\,\frac{km}{hr}$$

$$v_4 := v_{v1}(\omega_{max}) = 129.7016\,\frac{km}{hr}$$

Case 2:

$$\omega_{move.2} = 3812.1115\,rpm$$

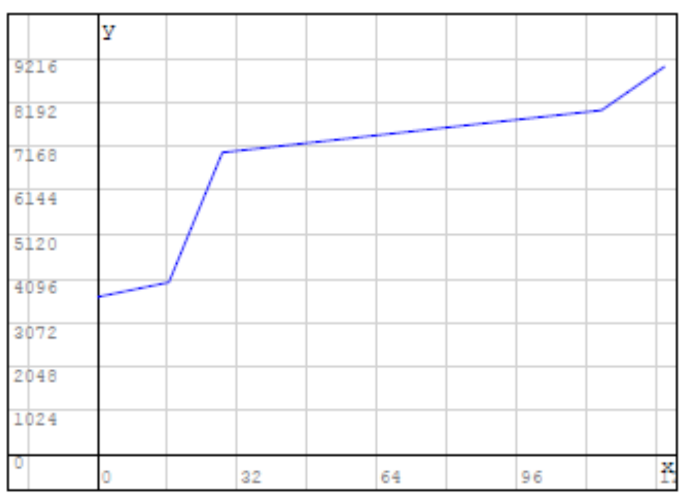
$$v_{v2}(\omega_{eg}) = 11.846\,\frac{km}{hr}$$

$$v_{v2}(\omega_L) = 20.7305\,\frac{km}{hr}$$

$$v_{v2}(\omega_H) = 82.9221\,\frac{km}{hr}$$

$$v_{v2}(\omega_{max}) = 93.2874\,\frac{km}{hr}$$

$$SC_{C2} := \begin{bmatrix} 0 & \frac{\omega_{move.1}}{rpm} \\ v_1\,\frac{hr}{km} & \frac{\omega_{eg}}{rpm} \\ v_2\,\frac{hr}{km} & \frac{\omega_L}{rpm} \\ v_3\,\frac{hr}{km} & \frac{\omega_H}{rpm} \\ v_4\,\frac{hr}{km} & \frac{\omega_{max}}{rpm} \end{bmatrix} = \begin{bmatrix} 0 & 3642.9848 \\ 16.47 & 4000 \\ 28.8226 & 7000 \\ 115.2903 & 8000 \\ 129.7016 & 9000 \end{bmatrix}$$



SC_{C2}

Power versus Speed Comparison

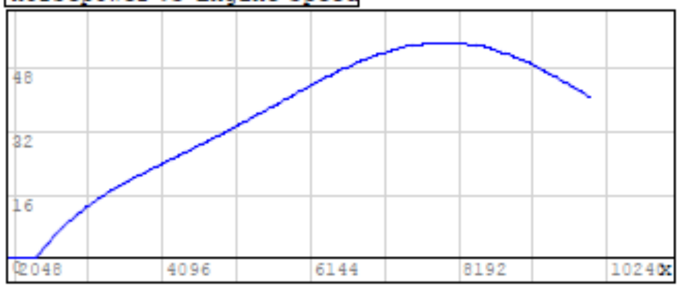
Create approximate engine horsepower curve using 7750rpm and 50hp as the peak and assuming it takes the shape of a fifth order polynomial - approximated from dyno curve of similar engine

$a_5 := 2.44244 \cdot 10^{-17} \dfrac{hp}{rpm^5}$ $\quad a_3 := 9.83752 \cdot 10^{-9} \dfrac{hp}{rpm^3}$ $\quad a_1 := 0.168498 \dfrac{hp}{rpm}$

$a_4 := 8.0189 \cdot 10^{-13} \dfrac{hp}{rpm^4}$ $\quad a_2 := 5.72013 \cdot 10^{-5} \dfrac{hp}{rpm^2}$ $\quad a_0 := 185.332\ hp$

$$HP_{eng}\left(\omega_{eng}\right) := \left(a_5 \cdot \omega_{eng}^{5} - a_4 \cdot \omega_{eng}^{4} + a_3 \cdot \omega_{eng}^{3} - a_2 \cdot \omega_{eng}^{2} + a_1 \cdot \omega_{eng} - \left(a_0\right)\right)$$

Horsepower vs Engine speed



$$GroundForce = \frac{BrakeHP}{VehicleSpeed}$$

$\omega_{eng} := \omega_{eg}$

for $i := 1, \left(\omega_{eng} \le 10000\ rpm\right), i := i + 1$

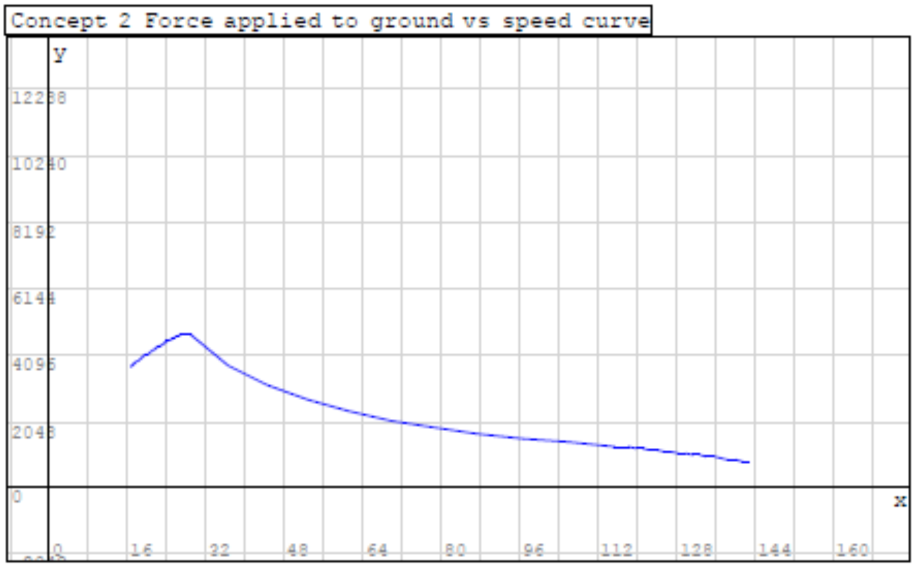
$\quad GF_{C2_{i\,2}} := \dfrac{HP_{eng}\left(\omega_{eng}\right)}{v_{v1}\left(\omega_{eng}\right)} \cdot \dfrac{1}{N}$

$\quad GF_{C2_{i\,1}} := v_{v1}\left(\omega_{eng}\right) \dfrac{hr}{km}$

$\quad \omega_{eng} := \omega_{eng} + 100\ rpm$

Create matrix of vehicle speeds and ground force using for loop and the horsepower curve above.

Concept 2 Force applied to ground vs speed curve



GF_{C2}

A.3. Concept 3

Each region along the shift curve of concept 3 had to be analyzed. The following is a detailed analysis of the four different regions.

Region 0:

- Initial engine speed is zero with the engine engagement clutch disengaged. Initial vehicle speed is zero.
- Final engine speed is 3500 rpm where the engine engagement clutch begins to engage the engine to the transmission with slipping. Vehicle speed at this point is still zero.

Region 1:

- Initial engine speed is 3500 rpm where clutch begins to engage with transmission.
- Final engine speed is maintained at 3500 rpm however; the engine and transmission are now fully engaged with no clutch slipping.

Region 2:

Initial engine speed is 3500 rpm with a vehicle speed calculated as:

$$v_{2i} = Gr_{primary} * Gr_{trans} * Gr_{CVT_{initial}} * w_{engine} * \frac{D_t}{2}$$

Where:

v represents the vehicles speed

$Gr_{primary}$ represents the primary reduction of the integrated sequential transmission

Gr_{trans} represents the secondary reduction of the integrates sequential transmission, in this case the selected reduction is for gear 1

Gr_{CVT} represents the low ratio reduction from the CVT

w_{engine} represents the engines rotational speed

D_t represents the diameter of the vehicles tires

In region 2 these variables evaluate to:

$$v_{2i} = \frac{22}{62} * \frac{12}{29} * \frac{1}{3.5} * 3500\ rpm * \frac{2\pi\ rad}{rev} * \frac{1\ min}{60\ s} * \frac{20.5"}{2} * \frac{25.4\ mm}{1"} * \frac{1\ km}{100\ 000\ mm} * \frac{3600\ s}{1\ hour}$$

$$v_{2i} = 14.4\ km/hr$$

Final engine speed for region two represents the start of the CVT ratio adjustment at the desired set point rpm. The vehicle speed would be calculated as:

$$v_{2f} = Gr_{primary} * Gr_{trans} * Gr_{CVT_{initial}} * w_{engine} * \frac{D_t}{2}$$

For example, if the set point rpm was 7750 rpm:

$$v_{2f} = \frac{22}{62} * \frac{12}{29} * \frac{1}{3.5} * 7750\, rpm * \frac{2\pi\, rad}{rev} * \frac{1\, min}{60\, s} * \frac{20.5"}{2} * \frac{25.4\, mm}{1"} * \frac{1\, km}{100\,000\, mm} * \frac{3600\, s}{1\, hour}$$

$$v_{2f} = 31.9\, km/hr$$

Region 3:

Initial engine speed in region three is controlled by the PID to be the set point speed. The initial vehicle speed as detailed above would be:

$$v_{3i} = v_{2f} = 31.9\, km/hr$$

Final engine speed would be maintained at the set point speed. However, the vehicle speed would change according to:

$$v_{3f} = Gr_{primary} * Gr_{trans} * Gr_{CVT_{final}} * w_{engine} * \frac{D_t}{2}$$

For an engine set point speed of 7750 rpm this vehicle speed would evaluate to:

$$v_{3f} = \frac{22}{62} * \frac{12}{29} * \frac{1}{1} * 7750\, rpm * \frac{2\pi\, rad}{rev} * \frac{1\, min}{60\, s} * \frac{20.5"}{2} * \frac{25.4\, mm}{1"} * \frac{1\, km}{100\,000\, mm} * \frac{3600\, s}{1\, hour}$$

$$v_{3f} = 111.7\, km/hr$$

Region 4:

Initial engine speed for the final region matches the final engine speed from region three:

$$v_{4i} = v_{3f}$$

The final engine speed represents the maximum governed speed for the engine. In the case of a WR450 engine this evaluates to roughly 9000 rpm. The final vehicle speed for this engine speed would be evaluated as:

$$v_{4f} = Gr_{primary} * Gr_{trans} * Gr_{CVT_{final}} * w_{engine} * \frac{D_t}{2}$$

$$v_{4f} = \frac{22}{62} * \frac{12}{29} * \frac{1}{1} * 9000\, rpm * \frac{2\pi\, rad}{rev} * \frac{1\, min}{60\, s} * \frac{20.5"}{2} * \frac{25.4\, mm}{1"} * \frac{1\, km}{100\,000\, mm} * \frac{3600\, s}{1\, hour}$$

$$v_{4f} = 129.7\, km/hr$$

A.4. Concept Comparison

Sequential Gearbox Analysis and Comparison to Concepts

Gear Ratios

Primary Reduction

$pr = \frac{22}{62}$

First $g_1 := \frac{12}{29}$

Second $g_2 = \frac{15}{26}$

Third $g_3 := \frac{16}{21}$

Fourth $g_4 := \frac{20}{21}$

Fifth $g_5 = \frac{25}{21}$

Final Reduction

$fr := \frac{1}{4}$

Engine/Vehicle Parameters

Engine Speeds

$\omega_{max} := 10000\ rpm$

$\omega_{shift} := 9000\ rpm$ approximate shift speed if powerband occurs at 7750 rpm

$\omega_{opt} := 7750\ rpm$

$\omega_{eg} := 3500\ rpm$ Existing initial clutch engagement rpm

$\omega_{feg} := 4000\ rpm$ Estimated fully engage clutch speed

Power

$HP_{opt} := 50\ hp$

Tire Diameter

$d_T := 20.5\ in$

Vehicle speed as function of engine speed for each gear

$v_{v.g1}(\omega_{eng}) := pr \cdot g_1 \cdot fr \cdot \frac{d_T}{2} \cdot \omega_{eng}$

$v_{v.g2}(\omega_{eng}) := pr \cdot g_2 \cdot fr \cdot \frac{d_T}{2} \cdot \omega_{eng}$

$v_{v.g3}(\omega_{eng}) := pr \cdot g_3 \cdot fr \cdot \frac{d_T}{2} \cdot \omega_{eng}$

$v_{v.g4}(\omega_{eng}) := pr \cdot g_4 \cdot fr \cdot \frac{d_T}{2} \cdot \omega_{eng}$

$v_{v.g5}(\omega_{eng}) := pr \cdot g_5 \cdot fr \cdot \frac{d_T}{2} \cdot \omega_{eng}$

*However, the current vehicle configuration does not use gear 1. Neglect this equation for shift curve

Determine shift speed in each gear using engine shift speed of 9000 rpm

$v_{v2.feg} := v_{v.g2}(\omega_{feg}) = 20.0927\ \frac{km}{hr}$

$v_{v2.shift} := v_{v.g2}(\omega_{shift}) = 45.2085\ \frac{km}{hr}$

$v_{v3.shift} := v_{v.g3}(\omega_{shift}) = 59.7039\ \frac{km}{hr}$

$v_{v4.shift} := v_{v.g4}(\omega_{shift}) = 74.6299\ \frac{km}{hr}$

$v_{v5.max} := v_{v.g5}(\omega_{max}) = 103.6527\ \frac{km}{hr}$

Solve for engine speed after shifting up for each gear

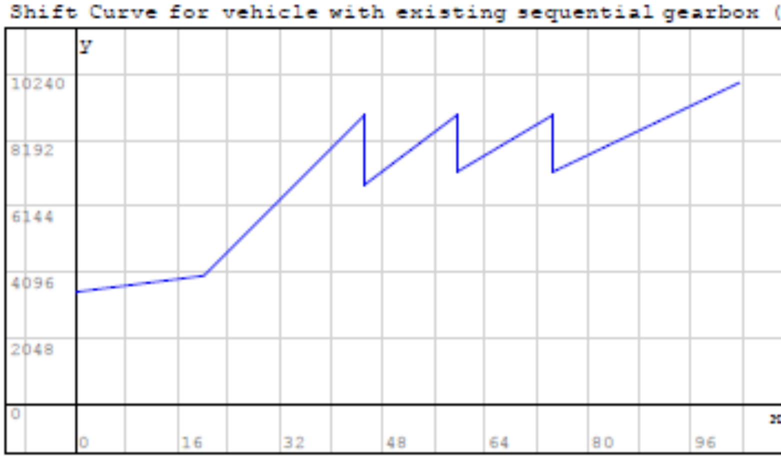
$$\omega_{eng.3} := \frac{2 \cdot v_{v2.shift}}{pr \cdot g_3 \cdot fr \cdot d_T} = 6814.9038\ rpm$$ Engine speed in third gear after shifting from second

$$\omega_{eng.4} := \frac{2 \cdot v_{v3.shift}}{pr \cdot g_4 \cdot fr \cdot d_T} = 7200\ rpm$$ Engine speed in fourth gear after shifting from third

$$\omega_{eng.5} := \frac{2 \cdot v_{v4.shift}}{pr \cdot g_5 \cdot fr \cdot d_T} = 7200\ rpm$$ Engine speed in fift gear after shifting from fourth

$$SC := \begin{bmatrix} 0 & \frac{\omega_{eg}}{rpm} \\ v_{v2.feg} \frac{hr}{km} & \frac{\omega_{feg}}{rpm} \\ v_{v2.shift} \frac{hr}{km} & \frac{\omega_{shift}}{rpm} \\ v_{v2.shift} \frac{hr}{km} & \frac{\omega_{eng.3}}{rpm} \\ v_{v3.shift} \frac{hr}{km} & \frac{\omega_{shift}}{rpm} \\ v_{v3.shift} \frac{hr}{km} & \frac{\omega_{eng.4}}{rpm} \\ v_{v4.shift} \frac{hr}{km} & \frac{\omega_{shift}}{rpm} \\ v_{v4.shift} \frac{hr}{km} & \frac{\omega_{eng.5}}{rpm} \\ v_{v5.max} \frac{hr}{km} & \frac{\omega_{max}}{rpm} \end{bmatrix} = \begin{bmatrix} 0 & 3500 \\ 20.0927 & 4000 \\ 45.2085 & 9000 \\ 45.2085 & 6814.9038 \\ 59.7039 & 9000 \\ 59.7039 & 7200 \\ 74.6299 & 9000 \\ 74.6299 & 7200 \\ 103.6527 & 10000 \end{bmatrix}$$ Shift Curve plot points

Shift Curve for vehicle with existing sequential gearbox (first gear removed)



SC

Power versus Speed Comparison

Create approximate engine horsepower curve using 7750rpm and 50hp as the peak and assuming it takes the shape of a fifth order polynomial - approximated from dyno curve of similar engine

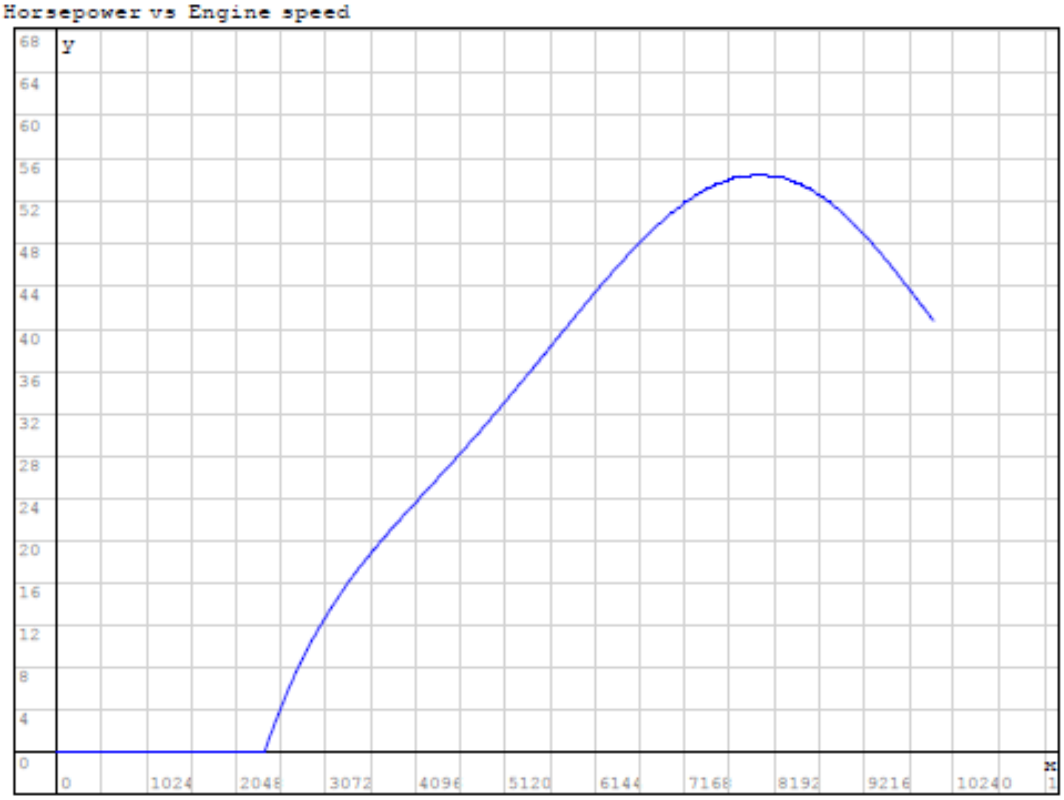
$a_1 = 0.168498 \frac{hp}{rpm}$

$a_5 = 2.44244 \cdot 10^{-17} \frac{hp}{rpm^5}$ $a_3 = 9.83752 \cdot 10^{-9} \frac{hp}{rpm^3}$ $a_0 = 185.332\, hp$

$a_4 = 8.0189 \cdot 10^{-13} \frac{hp}{rpm^4}$ $a_2 = 5.72013 \cdot 10^{-5} \frac{hp}{rpm^2}$

$$HP_{eng}(\omega_{eng}) := \left|a_5 \cdot \omega_{eng}^5 - a_4 \cdot \omega_{eng}^4 + a_3 \cdot \omega_{eng}^3 - a_2 \cdot \omega_{eng}^2 + a_1 \cdot \omega_{eng} - (a_0)\right|$$

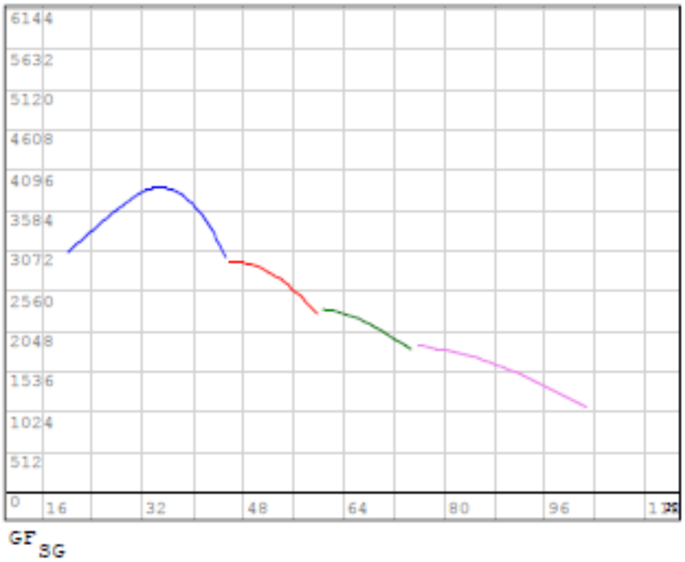
Horsepower vs Engine speed



Script for generating the 2 column matrix for plotting the Force-Speed diagram. Each if loop represents the shifting completed in the subscripts gear

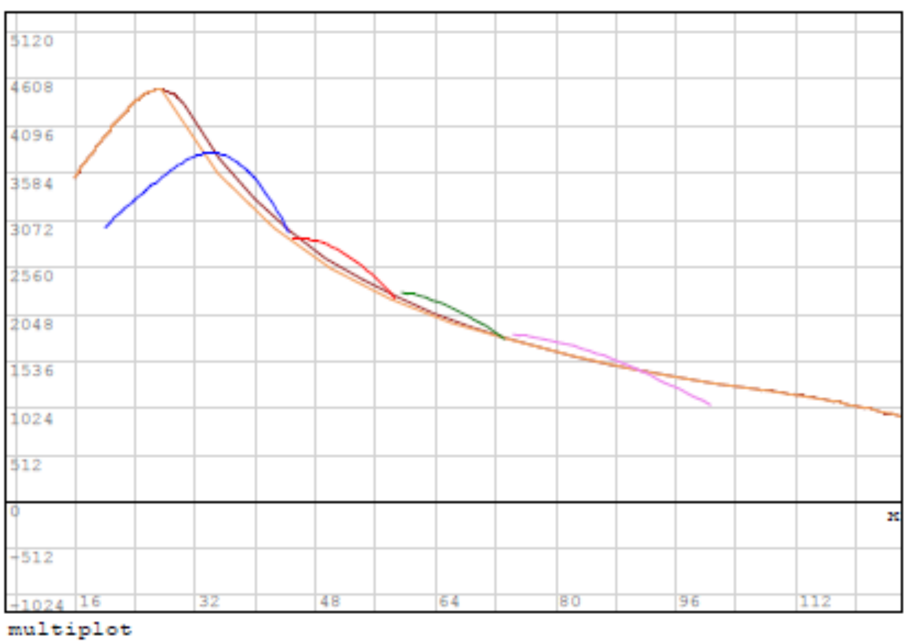
```
ω_eng := ω_feg
  i_3 := 1
  i_4 := 1
  i_5 := 1
for i := 1, (ω_eng ≤ 10000 rpm), i := i + 1
    if (ω_eng ≥ ω_feg) ∧ (ω_eng ≤ ω_shift)
        GF_G2[i,2] := HP_eng(ω_eng) / v_v.g2(ω_eng) · 1/N
        GF_G2[i,1] := v_v.g2(ω_eng) · hr/km
    else
        "not defined"
    if (ω_eng ≥ ω_eng.3) ∧ (ω_eng ≤ ω_shift)
        GF_G3[i_3,2] := HP_eng(ω_eng) / v_v.g3(ω_eng) · 1/N
        GF_G3[i_3,1] := v_v.g3(ω_eng) · hr/km
        i_3 := i_3 + 1
    else
        "not defined"
    if (ω_eng ≥ ω_eng.4) ∧ (ω_eng ≤ ω_shift)
        GF_G4[i_4,2] := HP_eng(ω_eng) / v_v.g4(ω_eng) · 1/N
        GF_G4[i_4,1] := v_v.g4(ω_eng) · hr/km
        i_4 := i_4 + 1
    else
        "not defined"
    if (ω_eng ≥ ω_eng.5)
        GF_G5[i_5,2] := HP_eng(ω_eng) / v_v.g5(ω_eng) · 1/N
        GF_G5[i_5,1] := v_v.g5(ω_eng) · hr/km
        i_5 := i_5 + 1
    else
        "not defined"
    ω_eng := ω_eng + 100 rpm
GF_SG := { GF_G2
           GF_G3
           GF_G4
           GF_G5 }
```

Force versus Speed for Sequential Gearbox



$$\text{multiplot} = \begin{cases} 0.98 \cdot GF_{SG} \\ 0.95 \cdot GF_{C2} \\ 0.95 \cdot GF_{C1} \end{cases}$$

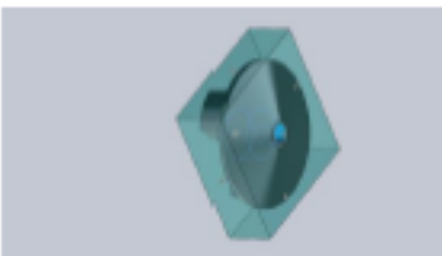
Force versus Speed for Concept 1&3, Concept 2, and Sequential Gearbox considering 98% efficiency for sequential and 95% for CVT designs. - see excel plot



Appendix B.Cost Analysis

B.1. Concept 1

SOLIDWORKS Costing Report



Model Name:	DriveClutch_MoveableSheave
Date and time of report:	10/26/2017 5:30:35 PM
Manufacturing Method:	Machining
Material:	Plain Carbon Steel
Stock weight:	21.32 kg
Stock Type	Block
Block Size:	68.43x199.91x199.82 mm
Material cost/weight:	3.50 USD/kg
Shop Rate:	N/A

Quantity to Produce

Total number of parts:	2
Lot size:	2

Estimated cost per part: 282.63 USD

Costing template used:	machiningtemplate_default(metric).sldctm
Costing mode used:	Manufacturing Process Recognition
Comparison:	2% Current 282.63 USD Previous 277.40 USD

Cost Breakdown

Material:	74.63 USD	26%
Manufacturing:	208.00 USD	74%
Markup:	0.00 USD	0%
Mold:	0.00 USD	0%

Estimated time per part: 06:56:00

Setups:	02:55:00
Operations:	04:01:00

Cost Report

1

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Model Name:	DriveClutch_Moveable Sheave	Material:	Plain Carbon Steel	Material cost: Manufacturing cost: Markup:	74.83 USD 208.00 USD 0.00 USD	Total cost /part: Total time /part:	282.83 USD 06:56:00

Manufacturing Cost Breakdown

Operation Setups	Time (hh:mm:ss)	Cost (USD / Part)
Setup Operation 1	00:30:00	15.00
Setup Operation 2	00:30:00	15.00
Setup Operation 3	00:30:00	15.00
Setup Operation 4	00:30:00	15.00
Setup Operation 5	00:30:00	15.00
Total	02:30:00	75.00

Load and Unload Setups	Time (hh:mm:ss)	Cost (USD / Part)
Setup Operation 1	00:05:00	2.50
Setup Operation 2	00:05:00	2.50
Setup Operation 3	00:05:00	2.50
Setup Operation 4	00:05:00	2.50
Setup Operation 5	00:05:00	2.50
Total	00:25:00	12.50

Operation	Surface Finish	Volume Removed (mm^3)	Time (hh:mm:ss)	Cost (USD / Part)	Tooling	Cost-per-Volume (USD/mm^3)
Slot 1	Roughing	44015.61	00:05:19	2.66	Flat End Mill	N/A
Slot 2	Roughing	44015.61	00:05:19	2.66	Flat End Mill	N/A
Slot 3	Roughing	44015.61	00:05:19	2.66	Flat End Mill	N/A
Circular Pocket 1	Roughing	1.30E+5	00:14:08	7.07	Flat End Mill	N/A
Circular Pocket 1	Finishing	16859.24	00:12:17	6.15	Flat End Mill	N/A
Volume 1	Roughing	1.82E+6	03:18:36	99.30	Flat End Mill	N/A
Total		2.10E+6	04:01:00	120.50		

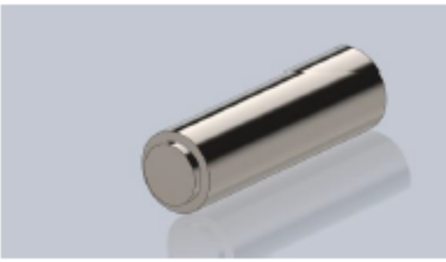
No Cost Features
Slot 4
Slot 5
Slot 6

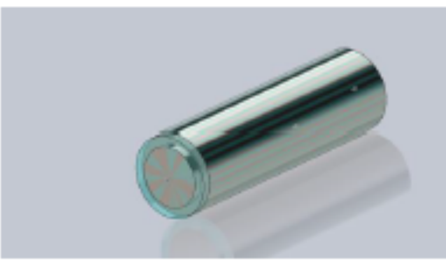
Setup Operations

1. Setup Operation 1
    a. Slot 1
2. Setup Operation 2
    a. Slot 2
3. Setup Operation 3
    a. Slot 3
4. Setup Operation 4
    a. Circular Pocket 1
5. Setup Operation 5
    a. Volume 1

B.2. Concept 2

SOLIDWORKS Costing Report





Model Name: VariatorClutch_Shaft

Date and time of report:	10/24/2017 7:00:10 PM

Manufacturing Method: Machining

Material:	Plain Carbon Steel
Stock weight:	0.35 kg
Stock Type	Cylinder
Cylinder Size:	25.40x87.67 mm
Material cost/weight:	3.58 USD/kg
Shop Rate:	N/A

Quantity to Produce

Total number of parts:	1
Lot size:	1

Estimated cost per part: 44.63 USD

Costing template used:	machiningtemplate_default(metric).sldctm
Costing mode used:	Manufacturing Process Recognition
Comparison:	0% Current 44.63 USD Previous 44.63 USD

Cost Breakdown

Material:	1.24 USD	3%
Manufacturing:	43.39 USD	97%
Markup:	0.00 USD	0%
Mold:	0.00 USD	0%

Estimated time per part: 01:05:05

Setups:	01:05:00
Operations:	00:00:05

Model Name:	VariatorClutch_Shaft	Material:	Plain Carbon Steel	Material cost: Manufacturing cost: Markup:	1.24 USD 43.39 USD 0.00 USD	Total cost /part: Total time /part:	44.63 USD 01:05:05

Manufacturing Cost Breakdown

Operation Setups	Time (hh:mm:ss)	Cost (USD / Part)
Setup Operation 1	01:00:00	40.00
Setup Operation 3	00:00:00	0.00
Total	**01:00:00**	**40.00**

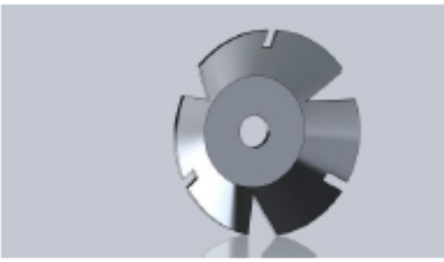
Load and Unload Setups	Time (hh:mm:ss)	Cost (USD / Part)
Setup Operation 1	00:05:00	3.33
Setup Operation 3	00:00:00	0.00
Total	**00:05:00**	**3.33**

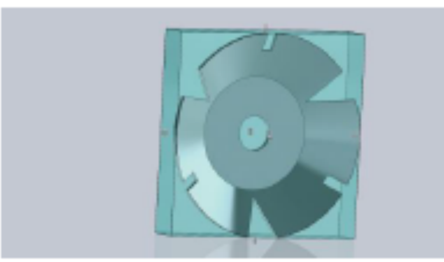
Turn Operation	Surface Finish	Volume Removed (mm^3)	Time (hh:mm:ss)	Cost (USD / Part)	Tooling	Cost-per-Volume (USD/mm^3)
OD Turn 1	Roughing	665.17	00:00:05	0.06	OD Turning	N/A
Total		**665.17**	**00:00:05**	**0.06**		

Setup Operations

1. Setup Operation 1
   a. OD Turn 1
2. Setup Operation 3

SOLIDWORKS Costing Report





Model Name:	VariatorClutch_RollerHouseCap
Date and time of report:	10/24/2017 6:58:29 PM

Manufacturing Method:	Machining
Material:	6061 Alloy
Stock weight:	0.76 kg
Stock Type	Block
Block Size:	115.90x115.18x21.00 mm
Material cost/weight:	10.10 USD/kg
Shop Rate:	N/A

Quantity to Produce

Total number of parts:	1
Lot size:	1

Estimated cost per part:	77.45 USD
Costing template used:	machiningtemplate_default(metric).sldctm
Costing mode used:	Manufacturing Process Recognition
Comparison:	0% Current 77.45 USD Previous 77.45 USD

Cost Breakdown

Material:	7.64 USD	10%
Manufacturing:	69.80 USD	90%
Markup:	0.00 USD	0%
Mold:	0.00 USD	0%

Estimated time per part:	02:19:36
Setups:	02:10:00
Operations:	00:09:36

Model Name:	VariatorClutch_RollerHouseCap	Material:	6061 Alloy	Material cost: Manufacturing cost: Markup:	7.64 USD 69.80 USD 0.00 USD	Total cost /part: Total time /part:	77.45 USD 02:19:36

Manufacturing Cost Breakdown

Operation Setups	Time (hh:mm:ss)	Cost (USD / Part)
Setup Operation 1	01:00:00	30.00
Setup Operation 2	01:00:00	30.00
Total	02:00:00	60.00

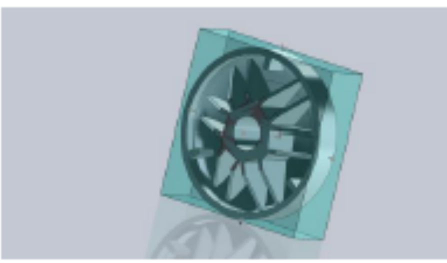
Load and Unload Setups	Time (hh:mm:ss)	Cost (USD / Part)
Setup Operation 1	00:05:00	2.50
Setup Operation 2	00:05:00	2.50
Total	00:10:00	5.00

Operation	Surface Finish	Volume Removed (mm^3)	Time (hh:mm:ss)	Cost (USD / Part)	Tooling	Cost-per-Volume (USD/mm^3)
Slot 1	Roughing	643.11	00:00:20	0.17	Flat End Mill	N/A
Slot 2	Roughing	189.91	00:00:05	0.05	Flat End Mill	N/A
Slot 3	Roughing	189.91	00:00:05	0.05	Flat End Mill	N/A
Slot 4	Roughing	643.11	00:00:20	0.17	Flat End Mill	N/A
Volume 1	Roughing	2.50E+5	00:08:44	4.37	Flat End Mill	N/A
Total		2.52E+5	00:09:36	4.80		

Setup Operations

1. Setup Operation 1
   a. Slot 1
   b. Slot 3
   c. Slot 4
   d. Slot 2
2. Setup Operation 2
   a. Volume 1

SOLIDWORKS Costing Report



Model Name: VariatorClutch_RollerHouse

Date and time of report:	10/24/2017 6:48:03 PM

Manufacturing Method: Machining

Material:	6061 Alloy
Stock weight:	1.82 kg
Stock Type	Block
Block Size:	129.89x129.94x40.00 mm
Material cost/weight:	10.10 USD/kg
Shop Rate:	N/A

Quantity to Produce

Total number of parts:	1
Lot size:	1

Estimated cost per part: 92.14 USD

Costing template used:	machiningtemplate_default(metric).sldctm
Costing mode used:	Manufacturing Process Recognition
Comparison:	100% Current 92.14 USD

Cost Breakdown

Material:	18.41 USD	20%
Manufacturing:	73.73 USD	80%
Markup:	0.00 USD	0%
Mold:	0.00 USD	0%

Estimated time per part: 02:27:27

Setups:	02:10:00
Operations:	00:17:27

Model Name:	VariatorClutch_RollerHouse	Material:	6061 Alloy	Material cost:	18.41 USD	Total cost /part:	92.14 USD
				Manufacturing cost:	73.73 USD	Total time /part:	02:27:27
				Markup:	0.00 USD		

Manufacturing Cost Breakdown

Operation Setups	Time (hh:mm:ss)	Cost (USD / Part)
Setup Operation 1	01:00:00	30.00
Setup Operation 2	01:00:00	30.00
Total	**02:00:00**	**60.00**

Load and Unload Setups	Time (hh:mm:ss)	Cost (USD / Part)
Setup Operation 1	00:05:00	2.50
Setup Operation 2	00:05:00	2.50
Total	**00:10:00**	**5.00**

Operation	Surface Finish	Volume Removed (mm^3)	Time (hh:mm:ss)	Cost (USD / Part)	Tooling	Cost-per-Volume (USD/mm^3)
Circular Pocket 1	Roughing	20268.30	00:00:42	0.35	Flat End Mill	N/A
Volume 1	Roughing	4.80E+5	00:16:44	8.37	Flat End Mill	N/A
Total		5.00E+5	**00:17:27**	8.73		

No Cost Features
Slot 1
Slot 2
Slot 3
Slot 4
Slot 5
Slot 6
Slot 7
Slot 8
Fillet 1
Fillet 2

2

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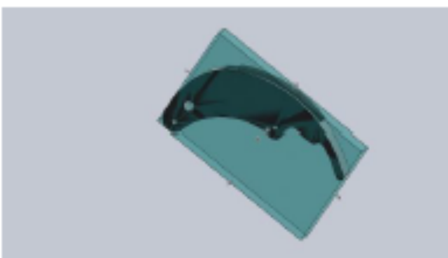
SOLIDWORKS Costing Report



Model Name:	SecondaryClutch_Weight
Date and time of report:	10/24/2017 6:37:21 PM
Manufacturing Method:	Machining
Material:	6061 Alloy
Stock weight:	0.23 kg
Stock Type	Block
Block Size:	73.30x115.48x10.00 mm
Material cost/weight:	10.10 USD/kg
Shop Rate:	N/A

Quantity to Produce

Total number of parts:	3
Lot size:	3

Estimated cost per part: 40.93 USD

Costing template used:	machiningtemplate_default(metric).sldctm
Costing mode used:	Manufacturing Process Recognition
Comparison:	100% Current 40.93 USD

Cost Breakdown

Material:	2.31 USD	6%
Manufacturing:	38.62 USD	94%
Markup:	0.00 USD	0%
Mold:	0.00 USD	0%

Estimated time per part: 01:17:14

Setups:	01:15:00
Operations:	00:02:14

Model Name:	SecondaryClutch_Weight	Material:	6061 Alloy	Material cost:	2.31 USD	Total cost /part:	40.93 USD
				Manufacturing cost:	38.62 USD	Total time /part:	01:17:14
				Markup:	0.00 USD		

Manufacturing Cost Breakdown

Operation Setups	Time (hh:mm:ss)	Cost (USD / Part)
Setup Operation 1	00:20:00	10.00
Setup Operation 2	00:20:00	10.00
Setup Operation 3	00:20:00	10.00
Total	**01:00:00**	**30.00**

Load and Unload Setups	Time (hh:mm:ss)	Cost (USD / Part)
Setup Operation 1	00:05:00	2.50
Setup Operation 2	00:05:00	2.50
Setup Operation 3	00:05:00	2.50
Total	**00:15:00**	**7.50**

Operation	Surface Finish	Volume Removed (mm^3)	Time (hh:mm:ss)	Cost (USD / Part)	Tooling	Cost-per-Volume (USD/mm^3)
Slot 1	Roughing	2544.41	00:00:09	0.08	Flat End Mill	N/A
Slot 1	Roughing	0.00	00:00:00	0.00	Ball End Mill	N/A
Volume 1	Roughing	40006.90	00:01:23	0.70	Flat End Mill	N/A
Volume 2	Roughing	11401.89	00:00:23	0.20	Flat End Mill	N/A
Volume 3	Roughing	173.28	00:00:00	0.00	Flat End Mill	N/A
Total		**54126.49**	**00:01:57**	**0.98**		

Hole Operation	Surface Finish	Volume Removed (mm^3)	Time (hh:mm:ss)	Cost (USD / Part)	Tooling	Cost-per-Volume (USD/mm^3)
Hole 1	Drill	384.85	00:00:07	0.06	HSS Drill	N/A
Hole 2	Drill	70.69	00:00:04	0.04	HSS Drill	N/A

Hole 3	Drill	70.69	00:00:04	0.04	HSS Drill	N/A
Total		526.22	00:00:16	0.14		

No Cost Features
Fillet 1

Setup Operations

1. Setup Operation 1
   a. Slot 1
2. Setup Operation 2
   a. Hole 1
   b. Hole 2
   c. Hole 3
3. Setup Operation 3
   a. Volume 1
   b. Volume 3
   c. Volume 2

3

SOLIDWORKS Costing Report

Model Name:	SecondaryClutch_Cap
Date and time of report:	10/24/2017 6:29:15 PM
Manufacturing Method:	Machining
Material:	6061 Alloy
Stock weight:	1.56 kg
Stock Type	Block
Block Size:	20.00x169.96x169.93 mm
Material cost/weight:	10.10 USD/kg
Shop Rate:	N/A

Quantity to Produce

Total number of parts:	1
Lot size:	1

Estimated cost per part: 140.03 USD

Costing template used:	machiningtemplate_default(metric).sldctm
Costing mode used:	Manufacturing Process Recognition
Comparison:	100% Current 140.03 USD

Cost Breakdown

Material:	15.75 USD	11%
Manufacturing:	124.28 USD	89%
Markup:	0.00 USD	0%
Mold:	0.00 USD	0%

Estimated time per part: 04:08:33

Setups:	02:10:00
Operations:	01:58:33

Model Name:	SecondaryClutch_Cap	Material:	6061 Alloy	Material cost: Manufacturing cost: Markup:	15.75 USD 124.28 USD 0.00 USD	Total cost /part: Total time /part:	140.03 USD 04:08:33

Manufacturing Cost Breakdown

Operation Setups	Time (hh:mm:ss)	Cost (USD / Part)
Setup Operation 1	01:00:00	30.00
Setup Operation 2	01:00:00	30.00
Total	02:00:00	60.00

Load and Unload Setups	Time (hh:mm:ss)	Cost (USD / Part)
Setup Operation 1	00:05:00	2.50
Setup Operation 2	00:05:00	2.50
Total	00:10:00	5.00

Operation	Surface Finish	Volume Removed (mm^3)	Time (hh:mm:ss)	Cost (USD / Part)	Tooling	Cost-per-Volume (USD/mm^3)
Pocket 1	Roughing	1.98E+5	01:43:50	51.92	Flat End Mill	N/A
Pocket 1	Roughing	0.00	00:00:00	0.00	Ball End Mill	N/A
Pocket 2	Roughing	2065.49	00:01:04	0.54	Flat End Mill	N/A
Pocket 3	Roughing	2065.49	00:01:04	0.54	Flat End Mill	N/A
Pocket 4	Roughing	2065.49	00:01:04	0.54	Flat End Mill	N/A
Pocket 5	Roughing	2065.49	00:01:04	0.54	Flat End Mill	N/A
Pocket 6	Roughing	2065.49	00:01:04	0.54	Flat End Mill	N/A
Pocket 7	Roughing	2065.49	00:01:04	0.54	Flat End Mill	N/A
Pocket 8	Roughing	2065.49	00:01:04	0.54	Flat End Mill	N/A
Pocket 9	Roughing	2065.49	00:01:04	0.54	Flat End Mill	N/A
Pocket 10	Roughing	2065.49	00:01:04	0.54	Flat End Mill	N/A

Volume 1	Roughing	1.35E+5	00:04:42	2.35	Flat End Mill	N/A
Total		3.52E+5	01:58:17	59.14		

Hole Operation	Surface Finish	Volume Removed (mm^3)	Time (hh:mm:ss)	Cost (USD / Part)	Tooling	Cost-per-Volume (USD/mm^3)
Hole 1	Drill	633.38	00:00:04	0.04	HSS Drill	N/A
Hole Pattern 1	Drill	577.27	00:00:11	0.09	HSS Drill	N/A
Total		1210.65	00:00:16	0.13		

No Cost Features
Fillet 1

Setup Operations

1. Setup Operation 1
   a. Hole Pattern 1 - 3
   b. Pocket 10
   c. Hole Pattern 1 - 2
   d. Pocket 5
   e. Pocket 4
   f. Hole Pattern 1 - 1
   g. Pocket 3
   h. Pocket 6
   i. Pocket 9
   j. Pocket 7
   k. Hole 1
   l. Pocket 8
   m. Pocket 1
   n. Pocket 2
2. Setup Operation 2
   a. Volume 1

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Real Parts. Really Fast.

ProtoQuote®

CNC Machining Quote

Prepared for: University of Alberta
Quote Number: 1068702
Quote Date: 10/23/2017
Part Name: SecondaryClutch_Custom_Parts / Secondary Clutch_WeightPlate.SLDPRT
Extents: 122 mm x 122 mm x 34 mm

Thank you for the opportunity to quote your parts. We look forward to working with you on this project. If you have any questions, please contact us at 877.479.3680.

① Confirm or Modify Specifications and Review Pricing

Material:	Aluminum - Gray (Aluminum 6061-T651)		
Machining Method:	Mill		
	Lathe	Lathe is not available due to part geometry.	
Quantity:	1	1 Part(s) @ $255.20 ea.	$255.20
Finish:	Edges broken (tool marks visible)		
Manufacturing Time:	Parts ship in 3 business days (standard price)		

Total USD: $255.20
currency calculator

② Manufacturability Analysis

As-Machined View

This view shows how your finished part will look after we machine it, including deviations from the desired shape. Note that colored indicators are representative, and not all machine artifacts may be shown.

No undercuts, radius issues, or thin areas were detected for this part.

Please zoom and rotate the image to check for any colored indicators, as they may be very small.

Be sure to review the Thin Areas and Thread Assignment tabs.

Secondary operations are not supported at this time.

If you have technical questions about this quote please contact our Customer Service Engineers at customerservice@protolabs.com or 877.479.3680.

If your feature is covered / skinned over by color, this feature will not be milled.
Cutter Radii Index:

Thin Areas

This view highlights any thin areas detected in your model. Thin areas may be machined thinner than designed and may chip, break out, bend or warp.

No thin areas were detected.

Secondary operations are not supported at this time.

If you have technical questions about this quote please contact our Customer Service Engineers at customerservice@protolabs.com or 877.479.3680.

Thread Assignment

We were unable to find any features to thread. Please see our Threading page for more information.

Secondary operations are not supported at this time.

Original Part

This view shows your part model as we received it.

Secondary operations are not supported at this time.

If you have technical questions about this quote please contact our Customer Service Engineers at customerservice@protolabs.com or 877.479.3680.

③ Summary

Order Pricing

Specifications Selected

Quantity:	1	1 Part(s) @ $255.20 ea.	$255.20
Manufacturing Time:	Parts ship in 3 business days (standard price)		
Material:	Aluminum - Gray (Aluminum 6061-T651)		
Machining Method	Mill		

Total USD: $255.20

currency calculator

You cannot order from this quote until you have reviewed the "Thread Assignment" tab in the viewer above.

Upload a Revised Model

Notes

- Customers are responsible for ensuring that the properties and performance of the material selected meet the requirements of their application.
- Tolerances of +/- 0.005inch (0.13mm) are expected and generally achieved.
- The estimated manufacturing time is the best estimate available at the time of quote for the part. Actual manufacturing times are dependent on part complexity, the number of part numbers being ordered, quantity, material availability, workload at the time the order is placed and other factors. Reasonable efforts will be made to deliver within or as close to estimated manufacturing times as possible; however there is no assurance that any estimated manufacturing time will be met.
- Secondary operations are not supported at this time. Threads that cannot be produced with the Proto Labs CNC machining process may not be highlighted correctly in the as-machined view due to the inconsistent methods by which they are represented in CAD models. Regardless of what is displayed in the as-machined view, threads will not be present in the finished part unless explicitly displayed in the Thread Assignment section of the ProtoQuote along with a corresponding thread type selection in the table. Please note there are limitations on the depths of threaded features and that in those instances where threads are cut from both sides of a given feature, the threads will not meet seamlessly. Thread selections will be listed in your order confirmation and should be reviewed for accuracy.

Terms and Conditions —ProtoQuote interactive quote

Terms and Conditions of Sale – Proto Labs, Inc.

Seller. As used herein, "Seller" means Proto Labs, Inc., a Minnesota corporation.

Proto Labs Quotes. Proto Labs provides a Quote for the Buyer's part(s) based on a 3D CAD model submitted by Buyer to Seller. Any change to the 3D CAD model requires an updated Quote. Quotes are valid for 30 days, after which pricing may change without notice. Seller reserves the right to correct clerical and other typographical errors in any quotation.

Offer and Contract Acceptance. These Terms and Conditions of Sale, together with a valid Quote, form a legally binding agreement (the "Agreement") and contains the entire understanding between Buyer and Seller for the goods and services provided by Seller and supersede any and all other agreements, representations and understandings of the parties, if any, whether oral or in writing. Buyer is deemed to have accepted this Agreement when it accepts a Quote or issues a purchase order or other writing expressing the Buyer's intent to proceed with the Agreement. This Agreement will govern any orders Seller accepts from Buyer and/or Buyer's authorized purchasers based on the Quote provided to Buyer. The terms and conditions contained herein shall be the only terms that shall govern the purchase and sale of the goods and services between Buyer and Seller, and no other terms and conditions shall apply and are hereby expressly excluded, including, without limitation, any terms contained in a request for quotation, purchase order, website, or elsewhere. The only additional terms in a request for quotation, purchase order, website or other writing that shall apply, if accepted by Seller, shall be terms regarding the description, price, quantity, and shipping destination for goods produced, and any and all other terms and conditions shall be excluded and deemed inapplicable. After Seller accepts an order, Buyer is responsible for any delivery delays or charges, in addition to the original price, due to a Buyer requested change that is agreed to in writing by Seller.

Termination for Convenience. Buyer may terminate an order in whole or in part at any time by written notice to customerservice@protolabs.com, effective upon receipt by Seller. In the event of termination, Seller reserves the right to invoice Buyer for all goods produced or services performed prior to receipt of notice of termination as well as for any resin purchased to make Buyer's parts which Seller is unable to return. This section shall not limit or affect the Buyer's right to cancel this order for breach by Seller.

Delivery; Quantity; Title. Any stated delivery time represents Seller's intended or typical delivery time, but actual delivery times may vary. Seller reserves the right to limit quantities at any time. Partial shipments may be delivered to Buyer. All parts are shipped FCA (Incoterms 2010) at Seller's facilities. Title passes to the Buyer at the time and place of delivery to the carrier.

B.3. Concept 3

SOLIDWORKS Costing Report

Model Name:	Concept 3 Shift Fork
Date and time of report:	10/26/2017 4:13:32 PM
Manufacturing Method:	Machining
Material:	Plain Carbon Steel
Stock weight:	1.23 kg
Stock Type	Block
Block Size:	70.00x150.00x15.00 mm
Material cost/weight:	0.50 USD/kg
Shop Rate:	N/A

Quantity to Produce

Total number of parts:	2
Lot size:	2

Estimated cost per part: 42.89 USD

Costing template used:	machiningtemplate_default(metric).sldctm
Costing mode used:	Manufacturing Process Recognition
Comparison:	100% Current 42.89 USD

Cost Breakdown

Material:	0.61 USD	1%
Manufacturing:	42.27 USD	99%
Markup:	0.00 USD	0%
Mold:	0.00 USD	0%

Estimated time per part: 01:24:32

Setups:	01:10:00
Operations:	00:14:32

Model Name:	Concept 3 Shift Fork	Material:	Plain Carbon Steel	Material cost:	0.81 USD	Total cost /part:	42.89 USD
				Manufacturing cost:	42.27 USD	Total time /part:	01:24:32
				Markup:	0.00 USD		

Manufacturing Cost Breakdown

Operation Setups	Time (hh:mm:ss)	Cost (USD / Part)
Setup Operation 1	00:30:00	15.00
Setup Operation 2	00:30:00	15.00
Total	**01:00:00**	**30.00**

Load and Unload Setups	Time (hh:mm:ss)	Cost (USD / Part)
Setup Operation 1	00:05:00	2.50
Setup Operation 2	00:05:00	2.50
Total	**00:10:00**	**5.00**

Operation	Surface Finish	Volume Removed (mm^3)	Time (hh:mm:ss)	Cost (USD / Part)	Tooling	Cost-per-Volume (USD/mm^3)
Volume 1	Roughing	1.30E+5	00:14:09	7.08	Flat End Mill	N/A
Total		**1.30E+5**	**00:14:09**	**7.08**		

Hole Operation	Surface Finish	Volume Removed (mm^3)	Time (hh:mm:ss)	Cost (USD / Part)	Tooling	Cost-per-Volume (USD/mm^3)
Hole 1	Drill	577.27	00:00:11	0.09	HSS Drill	N/A
Hole 2	Drill	577.27	00:00:11	0.09	HSS Drill	N/A
Total		**1154.54**	**00:00:22**	**0.19**		

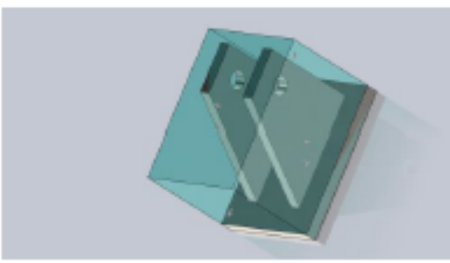
No Cost Features
Fillet 1

Setup Operations

1. Setup Operation 1
    a. Hole 1
    b. Hole 2
2. Setup Operation 2

a. Volume 1

SOLIDWORKS Costing Report



Model Name:	Concept 3 Fork Mount
Date and time of report:	10/26/2017 4:17:48 PM

Manufacturing Method:	Machining
Material:	Plain Carbon Steel
Stock weight:	1.05 kg
Stock Type	Block
Block Size:	60.00x45.00x50.00 mm
Material cost/weight:	0.50 USD/kg
Shop Rate:	N/A

Quantity to Produce

Total number of parts:	3
Lot size:	3

Estimated cost per part:	31.43 USD
Costing template used:	machiningtemplate_default(metric).sldctm
Costing mode used:	Manufacturing Process Recognition
Comparison:	100% Current 31.43 USD

Cost Breakdown

Material:	0.53 USD	2%
Manufacturing:	30.90 USD	98%
Markup:	0.00 USD	0%
Mold:	0.00 USD	0%

Estimated time per part:	01:01:47
Setups:	00:50:00
Operations:	00:11:47

Model Name:	Concept 3 Fork Mount	Material:	Plain Carbon Steel	Material cost:	0.53 USD	Total cost /part:	31.43 USD
				Manufacturing cost:	30.90 USD	Total time /part:	01:01:47
				Markup:	0.00 USD		

Manufacturing Cost Breakdown

Operation Setups	Time (hh:mm:ss)	Cost (USD / Part)
Setup Operation 1	00:20:00	10.00
Setup Operation 2	00:20:00	10.00
Total	**00:40:00**	**20.00**

Load and Unload Setups	Time (hh:mm:ss)	Cost (USD / Part)
Setup Operation 1	00:05:00	2.50
Setup Operation 2	00:05:00	2.50
Total	**00:10:00**	**5.00**

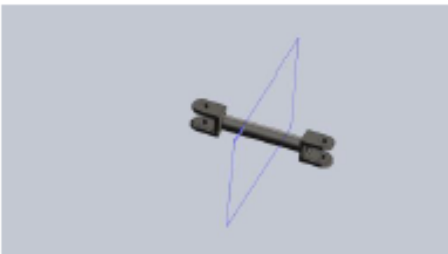
Operation	Surface Finish	Volume Removed (mm^3)	Time (hh:mm:ss)	Cost (USD / Part)	Tooling	Cost-per-Volume (USD/mm^3)
Volume 1	Roughing	1.07E+5	00:11:40	5.84	Flat End Mill	N/A
Total		**1.07E+5**	**00:11:40**	**5.84**		

Hole Operation	Surface Finish	Volume Removed (mm^3)	Time (hh:mm:ss)	Cost (USD / Part)	Tooling	Cost-per-Volume (USD/mm^3)
Hole 1	Drill	192.42	00:00:03	0.03	HSS Drill	N/A
Hole 2	Drill	192.42	00:00:03	0.03	HSS Drill	N/A
Total		**384.85**	**00:00:07**	**0.06**		

Setup Operations

1. Setup Operation 1
   a. Hole 1
   b. Hole 2
2. Setup Operation 2
   a. Volume 1

SOLIDWORKS Costing Report

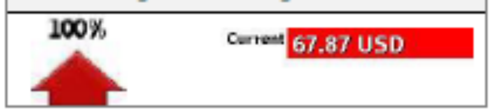


Model Name:	Concept 3 Fork Connecting Rod
Date and time of report:	10/26/2017 4:22:04 PM
Manufacturing Method:	Machining
Material:	Plain Carbon Steel
Stock weight:	0.59 kg
Stock Type	Block
Block Size:	20.00x151.00x25.00 mm
Material cost/weight:	0.50 USD/kg
Shop Rate:	N/A

Quantity to Produce

Total number of parts:	1
Lot size:	1

Estimated cost per part: 67.87 USD

Costing template used:	machiningtemplate_default(metric).sldctm
Costing mode used:	Manufacturing Process Recognition
Comparison:	

Cost Breakdown

Material:	0.29 USD	0%
Manufacturing:	67.57 USD	100%
Markup:	0.00 USD	0%
Mold:	0.00 USD	0%

Estimated time per part: 02:15:08

Setups:	02:10:00
Operations:	00:05:08

Cost Report

1

SOLIDWORKS

Model Name:	Concept 3 Fork Connecting Rod	Material:	Plain Carbon Steel	Material cost:	0.29 USD	Total cost /part:	87.87 USD
				Manufacturing cost:	67.57 USD	Total time /part:	02:15:08
				Markup:	0.00 USD		

Manufacturing Cost Breakdown

Operation Setups	Time (hh:mm:ss)	Cost (USD / Part)
Setup Operation 1	01:00:00	30.00
Setup Operation 2	01:00:00	30.00
Total	**02:00:00**	**60.00**

Load and Unload Setups	Time (hh:mm:ss)	Cost (USD / Part)
Setup Operation 1	00:05:00	2.50
Setup Operation 2	00:05:00	2.50
Total	**00:10:00**	**5.00**

Operation	Surface Finish	Volume Removed (mm^3)	Time (hh:mm:ss)	Cost (USD / Part)	Tooling	Cost-per-Volume (USD/mm^3)
Volume 1	Roughing	28038.54	00:03:03	1.53	Flat End Mill	N/A
Volume 2	Roughing	8629.62	00:00:56	0.47	Flat End Mill	N/A
Volume 3	Roughing	8629.62	00:00:56	0.47	Flat End Mill	N/A
Total		**45297.78**	**00:04:56**	**2.47**		

Hole Operation	Surface Finish	Volume Removed (mm^3)	Time (hh:mm:ss)	Cost (USD / Part)	Tooling	Cost-per-Volume (USD/mm^3)
Hole 1	Drill	251.33	00:00:03	0.03	HSS Drill	N/A
Hole 2	Drill	251.33	00:00:03	0.03	HSS Drill	N/A
Hole 3	Drill	251.33	00:00:03	0.03	HSS Drill	N/A
Hole 4	Drill	251.33	00:00:03	0.03	HSS Drill	N/A
Total		**1005.31**	**00:00:12**	**0.10**		

No Cost Features

Slot 1
Slot 2
Fillet 1
Fillet 2

Setup Operations

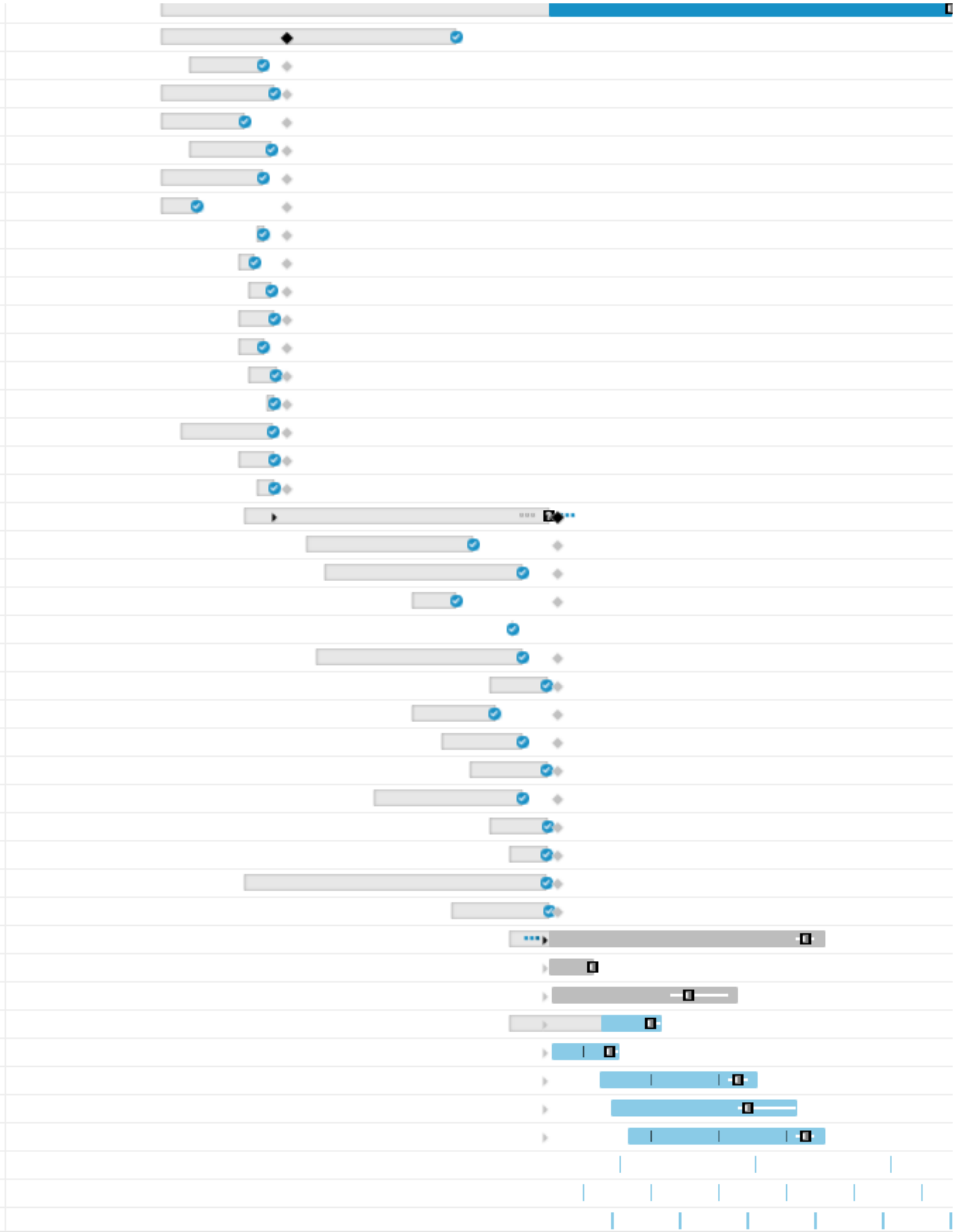
1. Setup Operation 1
    a. Hole 1
    b. Hole 3
    c. Hole 4
    d. Hole 2
2. Setup Operation 2
    a. Volume 1
    b. Volume 2
    c. Volume 3

3

Appendix C. Project Schedule/Timesheets

Person ▲	Week 43 90.50 h 10/22/17	Week 42 86.50 h 10/15/17	Week 41 66.50 h 10/08/17	Week 40 21.00 h 10/01/17	Week 39 72.50 h 09/24/17	Week 38 43.25 h 09/17/17
ZichengC	4.00 h	18.50 h	7.00 h	4.50 h	10.50 h	6.50 h
ToyaO	21.50 h	13.50 h	6.50 h	4.50 h	12.00 h	8.50 h
JoshM	20.00 h	19.00 h	22.00 h	4.00 h	15.00 h	5.50 h
ColinR	34.00 h	16.50 h	15.50 h	4.00 h	22.50 h	16.50 h
ChristianB	11.00 h	19.00 h	15.50 h	4.00 h	12.50 h	6.25 h

460 Design Project: FSAE CV Transmission ...	ColinR	340h - 355h	12/07/17
Phase 1	[ColinR]		
Design Spec Matrix	[ZichengC, ColinR, ChristianB, ToyaO...		
Market Research	[ChristianB, ToyaO, ColinR]		
Patents Research	[ToyaO, ChristianB]		
Applicable Rules/Standards Research	[ZichengC, JoshM, ColinR]		
Project Scheduling	[ColinR]		
Report Template	[ColinR]		
Writing: Report Letter	[ColinR]		
Writing: Introduction	[ToyaO]		
Writing: Design Objectives	[JoshM]		
Writing: Design Specifications	[JoshM, ZichengC, ToyaO, ColinR, Ch...		
Writing: Project Management Sections	[ColinR]		
Writing: Conclusion	[ToyaO]		
Appendices	[ColinR, ChristianB]		
Cost Analysis	[ColinR]		
Assemble Report	[ToyaO, ColinR]		
Edit Report	[ColinR, ToyaO, ChristianB, JoshM, Zi...		
Phase 2	ColinR	0h - 0h	10/27/17
Brainstorming	[ChristianB, ColinR, ToyaO, JoshM, Zi...		
Design Conceptualization	[ChristianB, ColinR, ToyaO, JoshM, Zi...		
C1 Solid Modelling	[ColinR, ChristianB]		
Conceptual Design Review	[ColinR, ChristianB, ToyaO, JoshM, Zi...		10/23/17
C1 Calculations	[ZichengC, ColinR]		
C1 Cost Analysis	[ColinR, ZichengC, ToyaO, ChristianB]		
C2 Solid Modelling	[ColinR, ChristianB, ToyaO]		
C2 Calculations	[ZichengC, ColinR]		
C2 Cost Analysis	[ZichengC, ToyaO, ChristianB]		
C3 Solid Modelling	[ColinR, JoshM]		
C3 Calculations	[ZichengC, JoshM]		
C3 Cost Analysis	[JoshM, ZichengC, ToyaO, ChristianB]		
Design Concept Matrix	[ZichengC, ColinR, ChristianB, ToyaO...		
Report 2	[ColinR, ChristianB, ToyaO, JoshM, Zi...		
Phase 3	ColinR	229h - 244h	11/22/17
Calculations	ColinR	18.84h - 25.16h	10/31/17
CAD	ColinR	51.73h - 61.27h	11/10/17
COTS Sourcing	ToyaO	10h - 12h	11/06/17
FEA Simulations	ZichengC, JoshM	24.88h - 29.12h	11/02/17
Poster	ToyaO, ChristianB, JoshM, ColinR, Zic...	31.68h - 38.32h	11/15/17
Presentation	ChristianB, ColinR, ToyaO, JoshM, Zic...	26.38h - 28.62h	11/16/17
Report 3	ToyaO, ColinR, ChristianB, ZichengC, ...	55h - 60h	11/22/17
Client Meeting in EVENTS (Out of Office)	ColinR, ChristianB, ToyaO, JoshM, Zic...	15h - 15h	11/03/17
Group meeting in EVENTS (Out of Office)	JoshM, ChristianB, ToyaO, ZichengC, ...	60h - 60h	10/30/17
Advisor Meeting in EVENTS (Out of Office)	ColinR, ChristianB, ToyaO, JoshM, Zic...	36h - 36h	11/02/17



	Owners	Remaining Effort	Finish [E]
MecE 460 Team 13	ColinR	363h - 381h	**01/01/18**
EVENTS (Out of Office)	ColinR	111h - 111h	**12/07/17**
ACTIVE PROJECTS	ColinR	340h - 355h	**12/07/17**
460 Design Project: FSAE CV Transmission …	ColinR	340h - 355h	**12/07/17**
Phase 1	[ColinR]		
Phase 2	ColinR	0h - 0h	**10/27/17**
Phase 3	ColinR	229h - 244h	**11/22/17**
Calculations	ColinR	18.84h - 25.16h	**10/31/17**
Secondary Shaft	ZichengC	4h - 8h	**10/28/17**
Sheaves/Pulleys	ColinR	4h - 8h	**10/28/17**
Belt	ChristianB	4h - 6h	**10/31/17**
Shaft Adapter/Engine Shaft	JoshM	4h - 6h	**10/28/17**
CAD	ColinR	51.73h - 61.27h	**11/10/17**
Solid Modelling	ChristianB	12h - 20h	**11/07/17**
Drawing Package	ColinR, ChristianB, ToyaO	37.9h - 43.1h	**11/10/17**
COTS Sourcing	ToyaO	10h - 12h	**11/06/17**
FEA Simulations	ZichengC, JoshM	24.88h - 29.12h	**11/02/17**
Poster	ToyaO, ChristianB, JoshM, ColinR, Zic…	31.68h - 38.32h	**11/15/17**
Presentation	ChristianB, ColinR, ToyaO, JoshM, Zic…	26.38h - 28.62h	**11/16/17**
Report 3	ToyaO, ColinR, ChristianB, ZichengC, …	55h - 60h	**11/22/17**
Client Meeting in EVENTS (Out of Office)	ColinR, ChristianB, ToyaO, JoshM, Zic…	15h - 15h	**11/03/17**
Group meeting in EVENTS (Out of Office)	JoshM, ChristianB, ToyaO, ZichengC, …	60h - 60h	**10/30/17**
Advisor Meeting in EVENTS (Out of Office)	ColinR, ChristianB, ToyaO, JoshM, Zic…	36h - 36h	**11/02/17**