Baja SAE Cost Reduction Report

Blue Jay Racing 2021 | 17XT | Johns Hopkins University

Introduction

Blue Jay Racing aims to improve upon our 2020 vehicle, the 16XT, by reducing cost throughout the entirety of the engineering design process. By surveying team members and critically analyzing our procedures, we have identified several actionable changes the team can make to decrease the overall cost of our vehicle. These methods are also rooted in our team's dedication to improving process standardization, emphasizing proper problem definition, and promoting thoughtful design. We present five ideas in this report, each researched as a cost reduction method and analyzed for integration into Blue Jay Racing's 2021 car: the 17XT.

1. Decrease Dependence on Off-the-Shelf Components

Historically, Blue Jay Racing has used a significant number of commercial, off-the-shelf components (COTS) in the design of our cars. The use of COTS components can be beneficial from a reliability standpoint, since commercial products are largely well tested, but they also typically cost more than their in-house counterparts, as can be seen from our team's previous Baja SAE cost reports. We can both reduce expenses and gain additional design freedom by decreasing our dependence on COTS parts.

Differentials

For the 2020 season, we chose to use COTS differentials in both the front and rear of our vehicle, in order to reduce manufacturing time and ensure the drivetrain was as durable as possible, despite the high cost of the components. The 16XT was Blue Jay Racing's first 4-wheel drive vehicle, so taking advantage of COTS components was essential in maximizing the probability of success in our unproven system. Despite offering robustness our system required and the capability to switch very easily between two/four wheel drive configurations, the 16XT differentials severely restricted our design choices, from both a monetary and performance standpoint. The team used a Hilliard Front Drive System (FDS) on the front axle and a Hilliard Auto-Lok differential on the rear axle, costing $1210 and $1275 respectively. For the 17XT, we identified the differentials as an ideal target for cost savings and additional performance improvements.

In the front of the vehicle, the FDS's relatively high output axis and large diameter limited the steering angle and severely restricted space in the footbox for the steering rack and pedals. For the 17XT, the team sought a more compact option that allowed for equal adjustability between drive configurations, at a lower price point. Our complete evaluation of different differential options in light of the criteria we considered is outlined in Appendix 1.1. The team ultimately opted for a mechanically-locking differential which can be switched from an open configuration to a locked configuration through the manual engagement of a dog clutch. An additional dog clutch was also added to the 17XT transfer case to enable the driver to control power output to the center driveshaft. Compared to the 16XT, the 17XT front differential weighs 14.5 lbs less, is 2" smaller in diameter, features a lower input shaft, and costs the team $500 to manufacture, saving approximately $710 from the purchased component.

As for the rear drivetrain system, the team opted to forgo a rear differential in favor of a rear spool, providing output to the wheels directly from the gearbox. Not only is this decision to completely eliminate the rear differential undeniably a significant cost saving measure, but it also drastically decreases the complexity of the system, improves packaging efficiency of our rear envelope (decreasing volume by 19%), and allows us to return to a legacy suspension point design that promotes tricycling instead of rear wheel differentiation.

As the 17XT has not yet been constructed, the success of this dual cost-saving and performance-enhancing measure stands unproven. Upon completion of the vehicle, the team has planned an extensive testing campaign to compare the efficiency (system losses), power (sled pull), and durability (lifetime testing) of our new design with that of the 16XT.

CVT

The team currently uses a COTS Gaged GX9 CVT system which costs $1225. In the past, the GX9 has adequately fulfilled our design requirements, but the high price has led us to explore different options. For the 17XT we identified two major CVT alternatives: switching to a CVTech CVT (around 40% cheaper) or developing our own custom unit. We identified a number of parameters by which to compare these two options with the GX9 (Appendix 1.2) and determined that a custom design would have significant benefits for both cost and performance. The CVTech, although cheaper, would require significant effort to integrate into the car, which led us to favor the custom design.

To mitigate the risks associated with a custom CVT, we are taking an incremental approach that targets marginal performance gains on the GX9, while maintaining backwards compatibility at first. The first custom components we develop will be drop-in replacements for COTS GX9 parts so as to maintain a backup option in case of failure. For example, while the GX9 has a theoretical ratio range of 3.9:1 at rest to 0.9:1 at top speed, the team has found, through dynamometer testing, that the standard GX9 flyweights do not have sufficient mass to provide the clamping force necessary to achieve the full 0.9:1 ratio. The team therefore designed an alternative flyweight (Appendix 1.3) with a teardrop-shaped brass body to both increase its mass and relocate the center of mass away from the pivot, improving its mechanical advantage against the ramps. These improved components will gradually replace the original GX9 parts, saving cost in future years as we make progress toward a fully custom CVT.

2. Design to Loading Conditions

Over the past year, Blue Jay Racing has placed a heavy emphasis on proper load determination, component testing, and analysis in order to design closer-to-optimal components, thus saving significant cost by reducing material and increasing design efficiency. By placing a concentrated effort into collecting live vehicle data during driving, the team can now empirically determine our maximum loading conditions. This, coupled with the team's vehicle proof-testing campaign and more mature analysis procedures, will enable component designers to confidently eliminate excess material, and could in the future even lead to reducing our global factor of safety with a better understanding of load propagation. This section reviews two steering components and the chassis, as well as appropriate fastener selection.

Case Study: Frame Design

The chassis of our Baja vehicle has undergone significant design changes this season, including a major switch to rear bracing from front bracing that had defined the design for several years. These design changes were facilitated by new found correlation between the data collected during driving and our methods of analysis, which have allowed us to refine our FEAs and produce more reliable simulations. One specific example of this involves our vehicle's front shock tab fixturing, which failed during a 2019 competition. After collecting shock loads with linear potentiometers post-competition, we found that the load was higher than originally anticipated. Re-running the 2019 FEA with new inputs, we were able to reconcile the simulation with the failure we saw on-car. This same interplay between data acquisition and simulation also helped improve confidence in multiple other areas of the frame analysis, allowing for an informed design change to rear bracing.

The 16XT's frame effectively used both front and rear bracing, adding structural members that are not required by SAE's rules. With the switch to only rear bracing, in addition to tighter drivetrain packaging and more optimal frame member sizing, the 17XT chassis weighs in at 62lbs, down 5lbs (7.5%) from the previous year's frame. The change saves approximately 5 linear feet of tubing stock, totally $49 in savings. This change is pictured in Appendix 2.2.

Fastener Selection

There has never been a bolt failure in recent Blue Jay Racing history, as the fasteners we select are oversized for the loads they are subjected to. In order to save cost in the future, we hope to purchase smaller and cheaper fasteners, through several methods. (1) In almost all locations on the car, high-strength grade 8 fasteners are not required and we should actively be opting for medium-strength grade 5 or even low-strength grade 2 fasteners. (2) For bolt size selection, we made a calculator for future designers to input loading conditions, fastener specifications, and desired factor of safety to receive the margin on the analysis. We will be better equipped to determine the exact forces on all fixtures as design simulations move from Solidworks to ANSYS. (3) All bolt shanks should be within the shear plane when a bolt is loaded in double shear. This utilizes the higher moment of inertia of the shank compared to the thread's minor diameter. Using partially threaded fasteners therefore not only reduces cost itself, but also enables even smaller bolt diameters if designed in this manner.

Using both the bolt calculator and design guidance, we can see the improvement in the suspension linkage's fixture to the frame as an example. Currently a ⅜"-24 bolt with threads loaded in shear, we can redesign this fastener for improved cost reduction, with the full specifications shown in Appendix 2.3. The presented design change to a ¼"-20 bolt with only its shank in the shear plane would result in a FOS reduction from 5.2 to 3.25, as well as a 44% reduction in cost. We can place an emphasis on fastener selection with this information, in order to confidently design closer to expected loads and reduce fastener cost.

Case Study: Clevis & Tie Rod Fastener Selection

The steering tie rods and clevis attachment to the rack body stand out as overbuilt among all 17XT components, with safety factors of 30 and 8, respectively. The rod end that fastens both components together has a safety factor of 49, as its own maximum misalignment angle has historically been the limiting design factor, requiring a large ⅜-24 thread size to be purchased to meet the angle requirement. The tie rod body and clevis size were therefore designed off of the rod end thread diameter, limiting how small they can be made, which is why they have such high safety factors.

However, in the search for cost savings, we determined a way to reduce the necessary operating angle and therefore use smaller rod ends. Switching from ⅜"-24 super swivel rod ends to ¼"-20 ball joint ones, allows for major reductions in clevis and tie rod material, as described in Appendix 2.1. For example, we can reduce the carbon fiber tube from 0.555" ID, 0.619" OD to 0.375" ID, 0.439" OD. The total cost savings for two new tie rods and clevises is $24.38, a 45% reduction, with the components now designed closer to their loading conditions.

3. Manufacturing Process Selection and Appropriate Tolerancing

Critical to cost effective manufacture is selecting the proper processes and adopting appropriate tolerancing practices, as costs can skyrocket if parts are unnecessarily tightly toleranced. We explore plasma cutting as an alternative to currently water jetting plate stock, with water jetting for only the parts that are tightly toleranced, as well as utilizing 3D printing to replace our machined nylon bushings.

Plasma Cutting vs. Water Jetting

The 17XT consists of 123 separate designs to be cut from sheet metal, totalling 434 individual parts. Most components are either 4130 alloy steel (mostly 0.1", 0.125", or 0.1875" thick) or 6061 aluminum (mostly 0.125" thick), and have been very precisely water jet cut in previous years. Considering a cheaper, albeit less precise alternative for certain loosely-toleranced parts, such as plasma cutting, can reduce monetary- and time-cost significantly. Therefore, designers should specify the desired tolerance of the tab, plate, or mount they are looking to manufacture, so that all parts can be separated between the two manufacturing processes for optimal cost savings.

By offloading a majority of the 434 cuts to a plasma cutter, the team can save significant water jetting costs, while also maintaining the necessary tolerance on some specific waterjetted components. All frame tabs (located from the bolt holes) and components such as the steering wheel, CVT case covers, center driveshaft covers, firewall, and pedals do not require tight tolerances and can be plasma cut, totaling 294 individual parts. The remaining 140 parts, including upright stock, hub stock, and rotors, should be waterjetted for higher precision. Using standard costs and speeds of plasma cutting ($15/hour @ 60in/min = $0.0042/in) and water jetting ($30/hour @ 15in/min = $0.03/in) we can calculate approximate savings. At these rates, we can expect an estimated 58% cost reduction in cutting plate stock.

Additive Manufacturing

Current parts that could transition to inexpensive plastic 3D printing include bushings, standoffs, and jigging blocks due to their needed reproducibility, moderately loose tolerances, and relatively low loading conditions. For this report, we will present and analyze bushings as a prime candidate to transition to additive manufacturing. Currently, Blue Jay Racing's vehicle utilizes approximately 60 bushings that are milled from 1.25" OD wear resistant nylon round stock. The current price includes $0.79 of material and approximately 10 minutes of machining time per bushing ($0.31 of processes according to the SAE cost report guidelines), totalling $1.10 per bushing or $66 for the entire car.

3D printed bushings would have to meet both durability and strength requirements, in addition to being cheaper than the current nylon alternatives. While nylon itself is printable, it requires higher-end 3D printers; bushings were quoted at $7.50 a piece from a supplier, much more expensive than the current machining method. Therefore, we are left with PLA, ABS, and PETG as the cheapest and most widely available 3D-printable plastic options. For the sake of testing fit and prototyping, we made two PLA bushings for the pedal pivot, as pictured in Appendix 3.1.

The primary load on a bushing is the compression imparted on it by the side of the attached bolt, which is transferred to the surrounding tube. Through a simple hand calculation, we can determine this stress on the bushing under the maximum suspension loading conditions of 1000lbs frontal force to be 2600psi, which can be compared (with a 1.5 FOS) to the yield strengths of the material options. ABS would fail under these conditions, while PLA and PETG are expected to survive the load. The second major requirement of the bushing material is impact resistance and fracture strength. PETG's has a high impact resistance (90ft-lb/in^2) compared to PLA, which is a relatively brittle plastic. We therefore propose PETG as the best material option for the bushings. However, because plastics have widely variable material properties and would be greatly affected by the 3D printing layer settings, such a design must be tested on-car before the 2021-22 design cycle. We plan to use 3D printed bushings during a drive day in Spring 2021 to test them as a viable option. If successful, we can print the bushings at $0.15 a piece, with minimal labor, resulting in a significant decrease in cost and time over the current machined nylon bushings.

4. Operational Standardization

In past years, insufficient communication between subteams and suboptimal purchasing decisions has led to excess purchase of stock material and parts that ultimately never made it onto the final car. By creating new operational practices and standards, Blue Jay Racing is hoping to streamline the process of purchasing the necessary stock and components used to manufacture each year's car. We can therefore find significant cost savings without needing to make substantial design changes on the car.

Material Standardization

While we have previously ordered stock by subteam, numerous raw materials are used frequently on components across the car. Rather than making many smaller purchases, it can oftentimes be far more cost efficient to make one large order for all the stock required for every subteam. Using 0.1" 4130 alloy annealed steel sheets (used to create tabs and gussets for various drivetrain, suspension, and frame components) as an example, we can see the potential cost reduction that is possible with this strategy. By combining all dimensions for 0.1" 4130 plate stock parts during the design process, we can save almost 16% on this single plate stock alone, reducing costs from \$0.17/in^2 to \$0.12/in^2, as shown in Appendix 4.1. This concept can be applied to all material we purchase to achieve similar savings, reducing the cost of the car without needing to make significant design changes.

Fastener Standardization

Cost can similarly be reduced by creating standards for fasteners throughout the car, not only by selecting smaller and cheaper bolts as mentioned previously. Due to low emphasis on bolt selection during the design process, current fasteners are not standardized in any way throughout the car. This results in many unique selections and leads to extra expense. Blue Jay Racing typically orders from McMaster-Carr, where bolts are sold in relatively high-volume packages, far more than any single joining requires. For example, a pack of 50 ¼"-20 x 1.75" screws used to join the steering column to a universal joint sells for $10.20 on McMaster-Carr, resulting in a price of $0.20 per screw, if only a single screw is used in the entire car, the team effectively wastes $10.00. Changing fixtures to more standard fastener sizes would better utilize the bolts in each package and reduce costs. Fastener standardization would also ensure that one package of fasteners can last multiple years, saving cost in the long term as well.

Focusing on the ¼"-20 bolts on the car this year, the cost saving benefits of standardizing lengths is clear. By applying this concept, the team can save $27.86, or 43%, on just a relatively small set of the 17XT bolts, as shown in Appendix 4.2. Applying this standardization process to all fasteners would further increase savings. It is worth noting this method of cost savings slightly conflicts with the Fastener Selection part in the Design to Loading Conditions section, however the two ideas can still effectively work in tandem. In better defining our loading conditions, we can determine a handful of standard diameter and thread count bolts that can be used effectively throughout the car, which can then be further sorted into only select lengths to allow for optimal purchases that maximize cost savings.

Future Continuous Improvement

In order to maintain material and fastener standardization practices into the future, we must make designers aware of such efforts throughout the designs cycle. Therefore, in preparation for next season, we have begun efforts to create an internal standards library for Blue Jay Racing. Current progress includes both material and fastener standards that describe what the common sizes we should be ordering, as well as guidance on the best manufacturing processes based on the desired tolerances, as described previously in this report. We can build operational standardization across the team for continuous improvement into the future Baja seasons.

5. Consider Longevity in Design

Blue Jay Racing has historically designed all new components for each iteration of the car, but not every component has to be remade within the competition rules. Reusing components for two years can save design time, manufacturing costs, and testing efforts. However, running a component at twice as many competitions requires additional analysis to ensure that it will survive the longer required lifetime. Some 17XT drivetrain components are currently analyzed for fatigue life, at 40 drive hours per season, but few other components are considered. We will determine which components are the most promising for reuse and estimate their savings based on materials and manufacturing costs.

Component A: CVT Backplate and Case

The CVT backplate's driving design requirements are both geometric: to locate the CVT and transfer case in the rear envelope of the car, and to sustain the max 270lb backshift load from the CVT with limited deflection. The first design requirement ensures that if we continue to use the same Gaged GX9 CVT for next year (as completing design and testing on the custom CVT will take several years), the dimensions of the backplate will stay the same. This component is therefore a prime candidate to reuse because its fixtures are not expected to change, and would lead to especially impactful savings because of its $4000 price to cast from aluminum.

The second design requirement is to sustain the CVT backshift load, but is analyzed with a deflection-limited study, limiting the bending displacement between input and output shafts to 0.2". When analyzing the fatigue life of the CVT backplate for this report, we concluded fatigue to be a minor factor in the backplate's longevity on the car for multiple years. Because the component is not designed with maximum stress in mind, the resulting stress in the part was so low that fatigue was negligible to the life of the part. At an expected 5000 cyclic 45MPa max loads per season, the component would last well into the future, beyond our projected custom CVT timeline. Therefore, we can confidently reuse the backplate for at least two seasons in a row, saving approximately $4000 in material and manufacturing costs.

Additionally, if the CVT Backplate is reused we can also reuse the CVT case. The only force exerted on the case is the inertial load from its own weight during vehicle impact, and it is designed to match each year's backplate geometry. As long as the SAE rules regarding protective coverings remain the same, we can continue to use the CVT case with the corresponding backplate, saving $138.

Component B: Rotors

Despite the rotors being redesigned every year, the dimensions of the calipers and hubs have not changed, opening the possibility of reusing rotors. In order to fully develop this idea, we analyzed the fatigue life of our rotors. From simulation, it was found that the maximum stress on the rotor was 45ksi, as shown in Appendix 5.1. Referring to the S-N curve of AISI 4130 steel plate from the Metallic Materials Properties Development and Standardization (MMPDS) Handbook (Appendix 5.2), this loading would result in a fatigue life of around 100,000 cycles. In order to verify this number, a fatigue simulation was conducted in Solidworks, indicating the rotor would fail after roughly 80,000 cycles when maximum braking force was applied. Looking at the course and from the drivers' testimonies, we estimate the brakes will be used roughly 1200 cycles in one endurance race. In addition to the other competition events and extensive testing pre-competition, we estimate 6000 loading cycles per season. Therefore, even with a conservative analysis assuming full loading every cycle, rotors can be used for multiple seasons in a row, saving approximately $300 in material and manufacturing costs a year.

Conclusion

We have analyzed every aspect of our vehicle development process to target five key categories for savings. While all ideas are shown to reduce Blue Jay Racing's operational or on-car costs, they will not necessarily all be implemented. The team should more heavily consider cost in design and manufacturing decision making, along with other important metrics for a successful Baja vehicle like durability, serviceability, weight, and manufacturability. This report serves as a guide for Blue Jay Racing's 2022 18XT car, outlining areas for cost reduction throughout the design and build cycle.

Appendix

1. Decrease Dependence on Off-the-Shelf Components

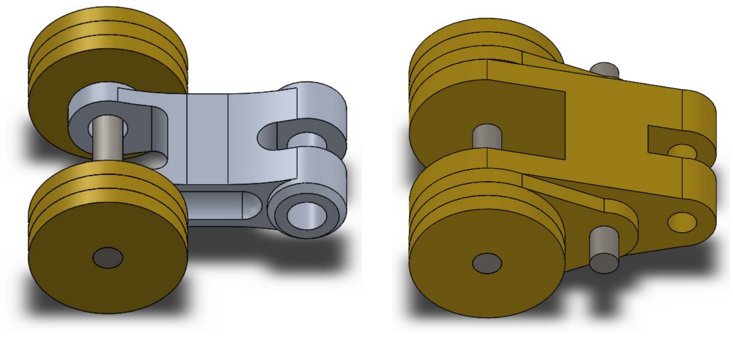
1.1: Front Diff Weighted Decision Matrix

Criteria	Wt.	Hilliard Front Drive System	Open Diff	LSD	Mech. Locking Diff (t-case+front diff shifter)	Hilliard Auto-Lok (clutch + t-case shifter)	Hilliard Auto-Lok (clutch + diff shifter)
Cost	9	0.41	1.00	1.00	1.00	0.39	0.39
Weight	7	1.00	1.79	1.56	1.56	1.56	1.32
Difficulty to Design	3	1.00	0.13	0.07	0.10	0.10	0.08
Ease of Packaging	9	1.00	1.50	1.50	1.50	1.20	1.20
Risk of failure	3	1.00	0.96	0.81	0.91	0.86	0.81
Traction capabilities	9	1.00	0.25	0.70	1.00	1.00	1.00
Cornering Capabilities	7	1.00	1.00	1.25	1.00	1.00	1.00
Manufacturability	3	1.00	0.67	0.50	0.57	0.57	0.57
Accel (straight line)	1	1.00	1.10	0.90	1.00	1.00	1.00
Driver difficulty	3	1.00	0.95	0.95	0.90	0.95	0.95
Weighted Scores		**48.69**	**53.45**	**56.38**	**57.88**	**49.69**	**47.76**

1.2: CVT Weighted Decision Matrix

Criteria	Weight	Gaged GX9	CVTech	Custom CVT
Max Torque Ratio	7	1.00	0.90	1.00
General Knowledge/Experience	3	1.00	0.70	0.50
Modifiability	7	1.00	0.80	1.40
Weight	9	1.00	0.60	1.00
Effect on other components	9	1.00	0.60	0.60
Cost	9	0.40	0.71	1.00
Risk of Failure	3	1.00	0.90	0.70
Difficulty to Design	3	1.00	0.90	0.50
Weighted Scores		**44.60**	**36.59**	**45.30**

1.3: Gaged GX9 Flyweight with Aluminum Body (Left), Custom Flyweight with Brass Body (Right)

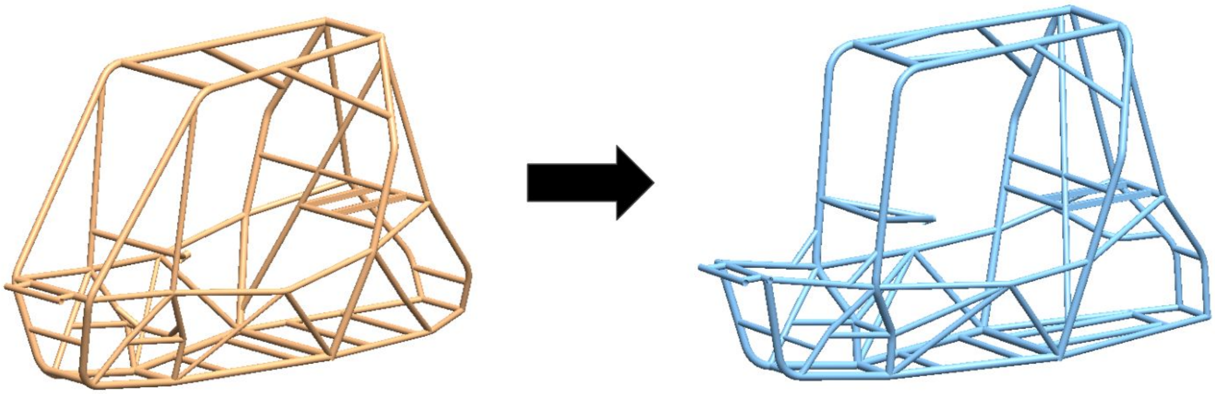


2. Design to Loading Conditions

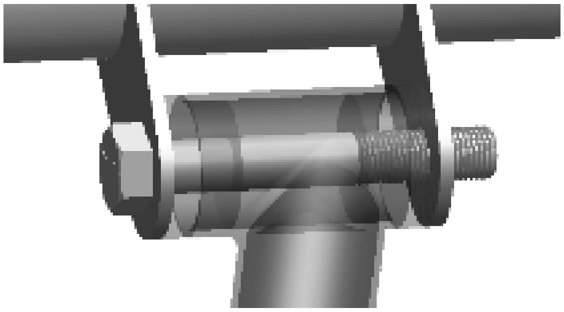
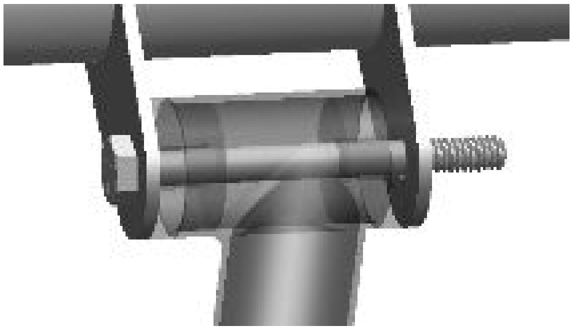
2.1: Table Comparing Current Tie Rod and Clevis Design to Proposed Change

Component	Current	Design Change
Rod End (McMaster)	3/8”-24 Super-Swivel (55deg) $10.68 each Safety factor = 49	¼”-28 Ball Joint (27deg) $3.51 each Safety factor = 12
Carbon Fiber (ACP Composites)	0.555” ID, 0.619” OD $8.40/ft = $10.50/tie rod Safety factor = 30	0.375” ID, 0.439” OD $7.60/ft = $9.50/tie rod Safety factor = 5.5
Insert Stock (Online Metals)	0.75” 4130 Round Stock $13.13/ft = $2.18/tie rod	0.4375” 4130 Round Stock $3.66/ft = $0.61/tie rod
Clevis Stock (Online Metals)	1.625” OD Aluminum Round $32.73/ft = $3.50/tie rod Safety factor = 8.0	1.125” OD Aluminum Round $15.70/ft = $1.30/tie rod Safety factor = 3.2
Clevis / Rod End Fasteners (McMaster)	⅜”-16x2” Grade 5 Bolt, $0.32 each ⅜” Grade 5 Nut, $0.09 each	¼”-20x1.5” Grade 5 Bolt, $0.12 each ¼” Low Strength Nut, $0.04 each
Total Price	**$27.27**	**$15.08**

2.2: Switch from 16XT Front (left) to 17XT Rear (right) Chassis Bracing

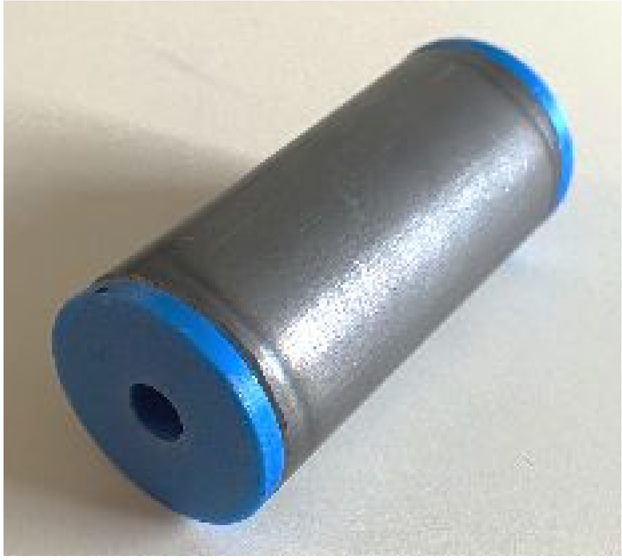


2.3: Table Comparing Current Suspension Fastener with Proposed Change

Current Design:	**Proposed Design:**
	
⅜”-24 x 2-½” Grade 5 Hex (81ksi) $10.79 for 25 = $0.43 each 0.3228” minor diameter 15.6ksi max = 5.2 FOS	¼”-20 x 2-¾” Stainless Hex (65ksi) $5.99 for 25 = $0.24 each 0.25” actual diameter (at shank) 20ksi max = 3.25 FOS Worst case (0.1887” minor diameter)= 2.75 FOS

3. Manufacturing Process Selection for Appropriate Tolerancing

3.1: Image of Example PLA Bushings in Pedal Pivot



4. Operational Standardization

4.1: Table of 0.1” 4130 Plate Stock Consolidation
Pricing from OnlineMetals.com

Individual Purchases (Current Method)		**Cumulative Purchase (Proposed Method)**	
Plate Dimensions	Price	Plate Dimensions	Price
12” x 24” (Drivetrain)	$52.93	36” x 36” (All Subteam Combined)	$160.76
24” x 24” (Suspension, Steering, Brakes)	$85.06		
12” x 24” (Frame)	$52.93		
Total Area: 1152 in^2	$190.92	Total Area: 1296 in^2	$160.76
Cost per in^2	**$0.17/$\text{in}^2$**	**Cost per in^2**	**$0.12/$\text{in}^2$**

4.2: Table of Current and Optimized ¼”-20 Bolt Selection

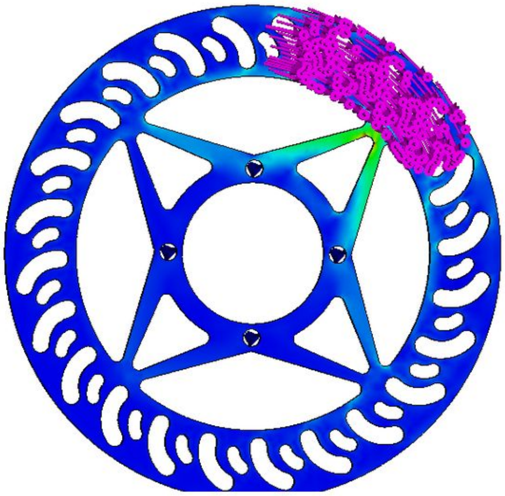
Size	**Length**	**Quantity Needed**	**Current Price/ Pkg Quantity**	**Combined Bolt Selection**	**Optimized Price/ Pkg Quantity**
¼”-20	0.375”	5	$10.81/50	5x 0.375”	$10.81/50
¼”-20	0.75”	43	$7.86/50	43x 0.75”	$7.86/50
¼”-20	0.875”	19	$8.82/50	23x 1”	$8.55/50
¼”-20	1”	4	$8.55/50		
¼”-20	1.75”	1	$10.20/50	8x 2.5”	$9.60/25
¼”-20	2.25”	4	$8.84/25		
¼”-20	2.5”	3	$9.60/25		
Totals Price:			**$64.68**		**$36.82**

Note: the design of the components where changes are proposed were checked for any packaging issues

5. Consider Longevity in Design

5.1: Solidwork Max Stress Study on Rotors

Primary Load	*Front:* 4000 lb-in Torque 2200 lb Normal Force *Rear:* 1750 lb-in Torque 950 lb Normal Force
Constraints	4x bearing support at pins
Allowable Stress (ksi)	Yield: 75 ksi Ultimate: 95 ksi
Max Stress from Study (ksi)	44.72 ksi
Design Factor Margin	Yield: -29% Ultimate: -25%



5.2: MMPDS 4130 Sheet Steel S-N Curve