FSAE Suspension Tolerancing Project
Research Report: 28 February 2022
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1. INTRODUCTION

Through involvement with this project in the mechanical systems subteam, design of mechanical components has been completed using traditional methods building off the work from previous FSAE teams at WPI. Historically, tolerance development within the FSAE team has been poorly recorded and completed at the most basic level. Despite the students involved trying to produce designs that will work correctly, tolerance has been assigned unnecessarily tight in areas that aren't critical to the part's performance. This can be attributed to lack of education of tolerancing in engineering disciplines without the experience technicians have to understand how tight tolerances can drive up manufacturing cost and lead time. This study aims to provide value in students applying newer tolerancing methods to their work that evaluates the application of a part completely from customer needs to manufacturing capability.

Formula SAE style race cars commonly use an upright style suspension system that attaches the wheel and tires, braking components, and rear drivetrain to a single component. Upper and lower control arms are used to transfer load from the wheel to the vehicle's frame and maintain steering and suspension geometry through the use of ball joints. WPI's formula SAE car has historically used machined uprights that are made from 7075 aluminum. The part complexity is high because of its many attachments and functions. The area that relates the upright to the camber block part provides an adjustable amount of camber to the front and rear suspension. This is beneficial to maximize the contact patch of each tire on the car while cornering which can result in higher cornering speeds. Increased corner speed impacts the autocross and endurance events where the car is attempted to be driven around a given course as quickly as possible.

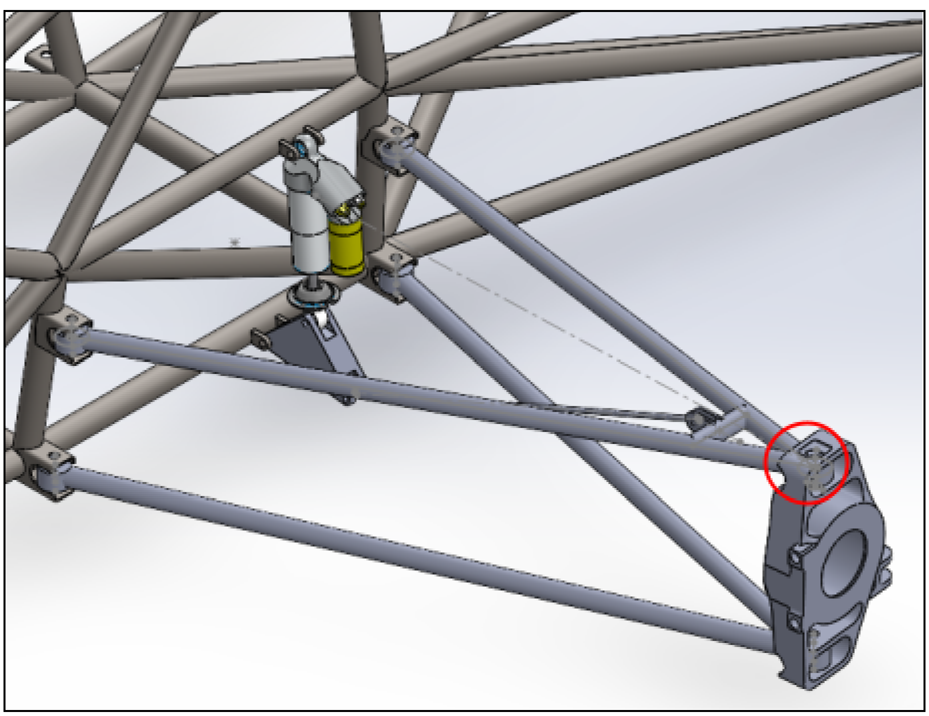

Figure 1: Camber block location in suspension system

2. TOLERANCE RESEARCH, *past and present*

Research has shown that new methods like applying axiomatic design to the tolerancing process is a topic with little professional support or focus. The National Science Foundation (NSF) has funded research to apply computational techniques to map design features of a part to machining features without human interaction. Research has also been funded at the Center for Precision Metrology (CPM) for general metrology development in areas like tool tuning for machining centers and robust engineering methods. There is no evidence of funding for the development of existing or new tolerancing methods in the United States by NSF, whose mission is to promote technological and scientific advancement.

A report written by faculty members of *Universidade Nova de Lisboa* located in Portugal titled *An Axiomatic Design interpretation for the synthesis of dimensional tolerances* shows work completed that is pertinent to the topics discussed in this report. The report provides a background of axiomatic design and its relationship to tolerancing. Specifically, it shows how this method of tolerance synthesis can satisfy "the designer's dilemma" which compares cost and performance to tolerance and shows how cost and performance are proportional (Fradinho, J., Mourão, 2016). Equations used to evaluate the relationship between customer needs and design parameters were found within this report to aid in tolerance development of the camber block component.

WPI has supported two Major Qualifying Projects (MQP) that focus on machining technology, specifically on the tooling and processes related to CNC milling machines. These two reports provide a basic definition of tolerance as related to prints provided to technicians and classify tolerance as either unilateral and bilateral. In the 2011 MQP report titled *CNC Application and Design*, tolerance is defined as "...the amount of variation permitted on dimensions or surfaces of machine parts. Tolerances are determined by finding the maximum and minimum clearances required on operating surfaces" (Collins, P., 2011). No other research or experimental projects that discuss tolerancing methods have been found in the WPI database using keywords "tolerance" or "tolerancing".

3. TOLERANCE METHODS

Traditional tolerancing methods have been commonly practiced in mechanical industries for decades. Traditional engineering thought processes that are conveyed in higher education are consistent with a report found titled *A comprehensive review of tolerancing research.* This article states that, "In design, functionality is of concern. Thus, ideally, tolerances should be as close to zero as possible." (Hong, Y.S., 2002). This mentality is commonly seen in the United States that tightens tolerances and increases cost without evaluating whether these results are necessary to the function of the part or assembly. Standard tolerancing techniques use a process represented in the figure below where functional requirements and considerations to the assembly are examined after manufacturing.

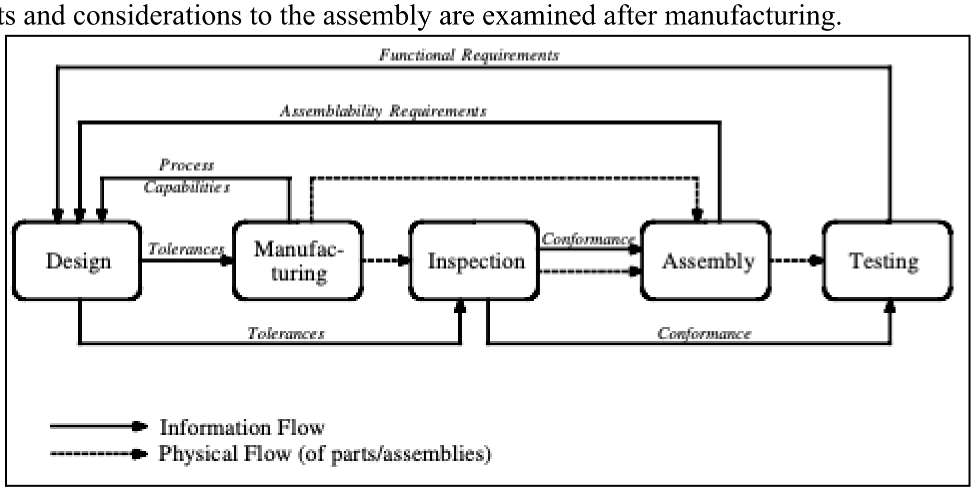

Figure 2: Traditional tolerancing method process flow

The tolerancing methods that are applied to technical drawings can be separated into two schemes; geometric and parametric. Geometric tolerancing schemes assign values to specific elements of a feature like locations and run-outs. This process makes use of datums that each dimension and tolerance is referenced to. This method reduces tolerance stackup by using one reference point or datum. Parametric tolerancing schemes identify sets of parameters with limits that provide a range of values. Unlike geometric tolerancing, parametric schemes can use a different reference point for each dimension. This can be useful for defining important tolerances but is prone to creating excessive tolerance stackup if not used appropriately.

The tolerancing method examined in this report while designing the camber block components integrate axiomatic design principles into the tolerancing process. The basis of axiomatic design are the design axioms and horizontal decomposition into four domains that design concepts are discussed within; the customer, functional, physical, and process domains. There are two axioms that are requirements to effectively use axiomatic design. The Independence axiom requires independence of functional requirements to be maintained. This allows design solutions to be formed to satisfy multiple constraints without the requirements associated with solutions conflicting. The information axiom requires that the information presented in the study be minimized to form clear and concise ideas and solutions that are understandable to the receiving parties (Brown, C.A., 2020).

In a manufacturing application the domains can be further described as customer and stakeholder needs, functional requirements, design parameters, and process variables. These elements of axiomatic design are described in more detail when applied to tolerance development within the camber block requirements section. This study uses axiomatic design principles to change the tolerancing process in search of a more systematic and calculated tolerancing process. Suh's three basic elements of engineering design will guide the integration of axiomatic design theory into this process (Suh, N.P., 1998).

Elements	Components
1. Axioms	Maximize Independence
	Minimize Information
2. Structures	Horizontal Decomposition
	Vertical Decomposition
3. Processes	Zigzagging Decomposition
	Physical Integration

Table 1: Three basic elements of engineering design

4. TRADITIONAL TOLERANCING OF WHEEL BEARING POCKET

Traditional tolerance development can be seen in the FSAE car's wheel bearing pocket design. Dimensions in CAD were assigned to exact dimensions of mating components and then modified to accommodate a force fit (FN) through use of the machinery's handbook as reference. This process is inline with what is used in industry and can provide acceptable results, but doesn't consider stakeholder needs, functional requirements, or design variables formally. Here judgment by the designer was relied upon to decide on an appropriate force fit that will successfully retain the wheel bearing in the car's upright without failure. Bearing manufacturer specifications were referenced to verify the forced bearing fit would not cause failure.

The machinery's handbook definitions for type of force fit was used as judgment of how much smaller to machine the bearing pocket than the outside diameter of the wheel bearing. The definition for force fits classified as FN2 is presented as "Medium drive fits are suitable for ordinary steel parts or for shrink fits on light sections." A fit that meets the specifications of FN2 was decided because the wheel bearing rigidity was determined to be more important than its serviceability because of the short operation time at the car's competition. An interference of .001 to .0029 inches of diameter is required to satisfy the FN2 classification for the 2.955 wheel bearing outside diameter as seen in the figure below.

Table 11. ANSI Standard Force and Shrink Fits *ANSI B4.1-1967 (R2009)*

Nominal Size Range, Inches (Over – To)	Class FN 1 Interference*	Class FN 1 Standard Tolerance Limits: Hole H6	Class FN 1 Standard Tolerance Limits: Shaft	Class FN 2 Interference*	Class FN 2 Standard Tolerance Limits: Hole H7	Class FN 2 Standard Tolerance Limits: Shaft s6	Class FN 3 Interference*	Class FN 3 Standard Tolerance Limits: Hole H7	Class FN 3 Standard Tolerance Limits: Shaft t6	Class FN 4 Interference*	Class FN 4 Standard Tolerance Limits: Hole H7	Class FN 4 Standard Tolerance Limits: Shaft u6	Class FN 5 Interference*	Class FN 5 Standard Tolerance Limits: Hole H8	Class FN 5 Standard Tolerance Limits: Shaft x7
	Values shown below are in thousandths of an inch														
0 – 0.12	0.05 0.5	+0.25 0	+0.5 +0.3	0.2 0.85	+0.4 0	+0.85 +0.6				0.3 0.95	+0.4 0	+0.95 +0.7	0.3 1.3	+0.6 0	+1.3 +0.9
0.12 – 0.24	0.1 0.6	+0.3 0	+0.6 +0.4	0.2 1.0	+0.5 0	+1.0 +0.7				0.4 1.2	+0.5 0	+1.2 +0.9	0.5 1.7	+0.7 0	+1.7 +1.2
0.24 – 0.40	0.1 0.75	+0.4 0	+0.75 +0.5	0.4 1.4	+0.6 0	+1.4 +1.0				0.6 1.6	+0.6 0	+1.6 +1.2	0.5 2.0	+0.9 0	+2.0 +1.4
0.40 – 0.56	0.1 0.8	+0.4 0	+0.8 +0.5	0.5 1.6	+0.7 0	+1.6 +1.2				0.7 1.8	+0.7 0	+1.8 +1.4	0.6 2.3	+1.0 0	+2.3 +1.6
0.56 – 0.71	0.2 0.9	+0.4 0	+0.9 +0.6	0.5 1.6	+0.7 0	+1.6 +1.2				0.7 1.8	+0.7 0	+1.8 +1.4	0.8 2.5	+1.0 0	+2.5 +1.8
0.71 – 0.95	0.2 1.1	+0.5 0	+1.1 +0.7	0.6 1.9	+0.8 0	+1.9 +1.4				0.8 2.1	+0.8 0	+2.1 +1.6	1.0 3.0	+1.2 0	+3.0 +2.2
0.95 – 1.19	0.3 1.2	+0.5 0	+1.2 +0.8	0.6 1.9	+0.8 0	+1.9 +1.4	0.8 2.1	+0.8 0	+2.1 +1.6	1.0 2.3	+0.8 0	+2.3 +1.8	1.3 3.3	+1.2 0	+3.3 +2.5
1.19 – 1.58	0.3 1.3	+0.6 0	+1.3 +0.9	0.8 2.4	+1.0 0	+2.4 +1.8	1.0 2.6	+1.0 0	+2.6 +2.0	1.5 3.1	+1.0 0	+3.1 +2.5	1.4 4.0	+1.6 0	+4.0 +3.0
1.58 – 1.97	0.4 1.4	+0.6 0	+1.4 +1.0	0.8 2.4	+1.0 0	+2.4 +1.8	1.2 2.8	+1.0 0	+2.8 +2.2	1.8 3.4	+1.0 0	+3.4 +2.8	2.4 5.0	+1.6 0	+5.0 +4.0
1.97 – 2.56	0.6 1.8	+0.7 0	+1.8 +1.3	0.8 2.7	+1.2 0	+2.7 +2.0	1.3 3.2	+1.2 0	+3.2 +2.5	2.3 4.2	+1.2 0	+4.2 +3.5	3.2 6.2	+1.8 0	+6.2 +5.0
2.56 – 3.15	0.7 1.9	+0.7 0	+1.9 +1.4	1.0 2.9	+1.2 0	+2.9 +2.2	1.8 3.7	+1.2 0	+3.7 +3.0	2.8 4.7	+1.2 0	+4.7 +4.0	4.2 7.2	+1.8 0	+7.2 +6.0
3.15 – 3.94	0.9 2.4	+0.9 0	+2.4 +1.8	1.4 3.7	+1.4 0	+3.7 +2.8	2.1 4.4	+1.4 0	+4.4 +3.5	3.6 5.9	+1.4 0	+5.9 +5.0	4.8 8.4	+2.2 0	+8.4 +7.0
3.94 – 4.73	1.1 2.6	+0.9 0	+2.6 +2.0	1.6 3.9	+1.4 0	+3.9 +3.0	2.6 4.9	+1.4 0	+4.9 +4.0	4.6 6.9	+1.4 0	+6.9 +6.0	5.8 9.4	+2.2 0	+9.4 +8.0

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Figure 3: Force Fit Selection for Wheel Bearing

The theoretical tolerance capabilities listed in Table 6 and 7 of the machinery's handbook can be used as a guideline for general milling applications. Table 7. Relation of Machining Processes to Tolerance Grades ANSI B4.1-1967 states the general tolerance grade that can be achieved while using a milling machine is 9. This scale reads a lower grade value as more accurate, so drilling produces a tolerance grade of 13 while lapping and honing yields as low as 4. Table 6. ANSI Standard Tolerances was used to find the theoretical tolerance capabilities for milling based on the diameter of the bore being machined. The wheel bearing diameter of 2.9550 inches was used to find machining tolerance capabilities using an endmill because this dimension is assumed to be most critical to the assembly of the race car's wheel system. Theoretical tolerance capabilities of .003 inches were estimated

These estimations do not reflect the capabilities of the Haas VM2 milling machine used for manufacturing the parts discussed in this report. The actual repeatability achieved using tool diameter compensation in the milling machine's control to adjust the final diameter machined was .0005 inches over the four bearing pockets machined measuring 2.9520 to 2.9525 inches throughout the four parts. With the measured outside diameter of the wheel bearing being 2.9550 inches, this produced a force fit between .0025 and .003 inches that satisfies the upper limit of force fit given in the machinery's handbook.

Measurements of these dimensions were completed using a combination of hand measurement tools. The outside diameter of the wheel bearing was measured using a micrometer with two to three inch measuring range that has measuring graduations to tenths of an inch and friction thimble to increase measuring consistency. To measure the bearing pocket a spring loaded snap gauge was used to create an outside dimension that is able to be measured with the same micrometer used to measure the wheel bearing. The error associated with using both of these tools is dependent on the technician operating them, as inexperienced operation can create inaccurate readings that are not taken parallel with the diameter being measured. An experienced technician took the measurements for this study that were referenced to gauge blocks to prove consistency in measurement.

5. CAMBER BLOCK REQUIREMENTS

5.1 Customer needs, Stakeholders

To identify stakeholders that are affected by the tolerance of the camber block in each of the four uprights, the system must be defined. The FSAE race car is a performance vehicle built for a specific annual design competition organized by the Society of Automotive Engineers (SAE). The car is a system made up of hundreds of components that work together to create an operational electric race car that accelerates, brakes, and handles in an intentional manner. The team of twenty-two students that design and build the vehicle are also a system that works together through four sub teams that focus on different subsystems on the car. For this study on tolerance of the car's mechanical components the system will be defined as the vehicle and its success at competition. Students are evaluated based on their engineering work to design and build the car, not its performance at competition.

Stakeholders that are impacted by the performance of the car during competition are those who provide sponsorship to the manufacturing of this race car. The higher WPI's team places in these areas of the competition the more likely existing sponsors will continue their support. Performing well in these areas can also attract new sponsors who may be impressed by the performance and ability to set up the car's suspension for given track conditions. Students on the team building this car are also stakeholders that benefit from the race car performing well during competition. Although grades are independent from the car's performance, reward can come from exceptional performance at competition through employment opportunities from companies in the automotive industry who closely watch these competitions to recruit recent college graduates like Hoosier Racing Tires and Aurora Bearing Company.

5.2 Functional Requirements

Functional Requirements (FRs) of the camber block and upright assembly can be discussed in an effort to make efficient and measured adjustments to the car's suspension system. FRs were developed with emphasis on axiom two to minimize the information being presented while still communicating clear requirements. They were also created in a collectively exhaustive and mutually exclusive (CEME) manner, so not to be repetitive between FRs but cover all necessary requirements for the camber block to operate successfully within the suspension system. A preliminary functional requirement, FR0, can be defined as providing a camber block insert that allows adjustment to the race car's suspension geometry. A constraint present in the analysis of the camber block is that the corresponding upright design is final and has been manufactured. The FRs developed must be satisfied around the existing dimensions and material selection of the uprights. This means the cross sectional shape of the camber block as shown in figure 4 and method that the camber block is secured within the suspension system have already been decided. Variables are assigned that can be used to show how one FR will change when its corresponding design parameter is modified and prove independence to satisfy axiom one. The functional requirements found for the camber block components are as listed below.

FR1. Allow for a minimum one inch of suspension travel (T)
FR2. Tighten securely to suspension assembly with less than .005 inches of deflection to the upright (R)
FR3. Allow for replacement by other camber blocks by hand(C)

Functional tolerances provide boundaries to satisfy each FR within (Srinivasan, R.S., 1996). These will give reference to the effectiveness of design parameters, processes required when manufacturing the camber block, and aid in the assignment of physical tolerances. FSAE regulations state that the car must have a minimum of one inch of suspension travel. This rule produces FR1 and a related functional tolerance of no less than one inch of travel since the upper limit of travel is dependent on the upright geometry, not the camber block component. FR2 gives a lower functional tolerance specification by stating the component must tighten securely without deflecting the upright more than .005 inches. The upper limit for FR2's functional tolerance is given by the camber block's requirement to allow for the suspension components to assemble. If the camber block interferes with other components in the system it cannot be tightened to the upright at all. Functional tolerances for FR3 are assigned by the camber block's ability to be interchanged. The fit to the upright must position the camber block so that the suspension system is provided the desired geometry, but be loose enough to be serviceable without tools needed to separate the camber block from the upright.

5.3 Design Parameters

Design parameters (DPs) directly correlate with functional requirements to create a relationship used when forming possible design solutions. In other words, there is a maximum of one design parameter for each functional requirement. The relationship between FRs and DPs can be described as the design matrix shown below where the FR vector is equal to matrix A multiplied by the DP vector.

$$\{FR\} = [A]\{DP\} \tag{1}$$

The DPs created from FRs are listed below.

DP1. Sits flush with internal upright surfaces (B)
DP2. Stepped feature on bottom (Z)
DP3. Internal pocketed design (A)

A corollary in axiomatic design is that each FR requires exactly one DP to create a design solution that avoids coupling, or the dependence of FRs. Independent change to each FR and its functional tolerance is important for the camber blocks to add value. Value can be added to this component by reducing manufacturing cost by changing the physical tolerances to allow for more variation in part size where it will not disrupt satisfying FRs. The list of FRs and DPs can be applied to equation 1. Variables are used to reference each parameter and requirement, and the design matrix was rewritten to show the change in each variable using the derivative function.

$$\begin{Bmatrix} dT \\ dR \\ dC \end{Bmatrix} = [A] \begin{Bmatrix} dB \\ dZ \\ dA \end{Bmatrix} \tag{2}$$

Equation 2 can be used to populate the matrix A with partial derivatives that relate change of DPs to FRs. The partial derivatives were evaluated by how each change in DP affected each FR. More specifically, how the change in tolerance or fit of each DP would affect the respective FR. The comparisons that produced a relationship were marked with an X to represent a non-zero value and comparisons that showed no relationship between DP tolerance and FR were marked with a zero. In the principles of axiomatic design, a resulting matrix that shows a diagonal pattern of non-zero values is the most effective way to satisfy axiom one, maintaining independence of FRs. The independence of FRs maximizes the ability for the design to adapt to change, which is inherent in any system. Functional tolerances associated with each FR are also independent by the same logic.

$$A = \begin{bmatrix} \frac{\partial C}{\partial A} & \frac{\partial C}{\partial B} & \frac{\partial C}{\partial Z} \\ \frac{\partial T}{\partial A} & \frac{\partial T}{\partial B} & \frac{\partial T}{\partial Z} \\ \frac{\partial R}{\partial A} & \frac{\partial R}{\partial B} & \frac{\partial R}{\partial Z} \end{bmatrix} = \begin{bmatrix} X & 0 & 0 \\ 0 & X & 0 \\ 0 & 0 & X \end{bmatrix} \tag{3}$$

Fully defined DPs and FRs allow design solutions to be made. As mentioned previously, the upright component has fixed geometry that has already been manufactured that is a constraint on physical design solutions for the camber block. The thickness of the upright where the camber block must be installed is .25 inches, and the cross-sectional dimensions of the upright surface is 1.265 inches long and 1.711 inches wide. These dimensions are the absolute greatest size that the camber block could be in order to still locate within the upright using a pocketed design. Another constraint applied to the possible design solutions is the upright being manufactured from 7075 aluminum. This will limit the physical size of the camber block to allow for a factor of safety before deforming the upright when forces are applied.

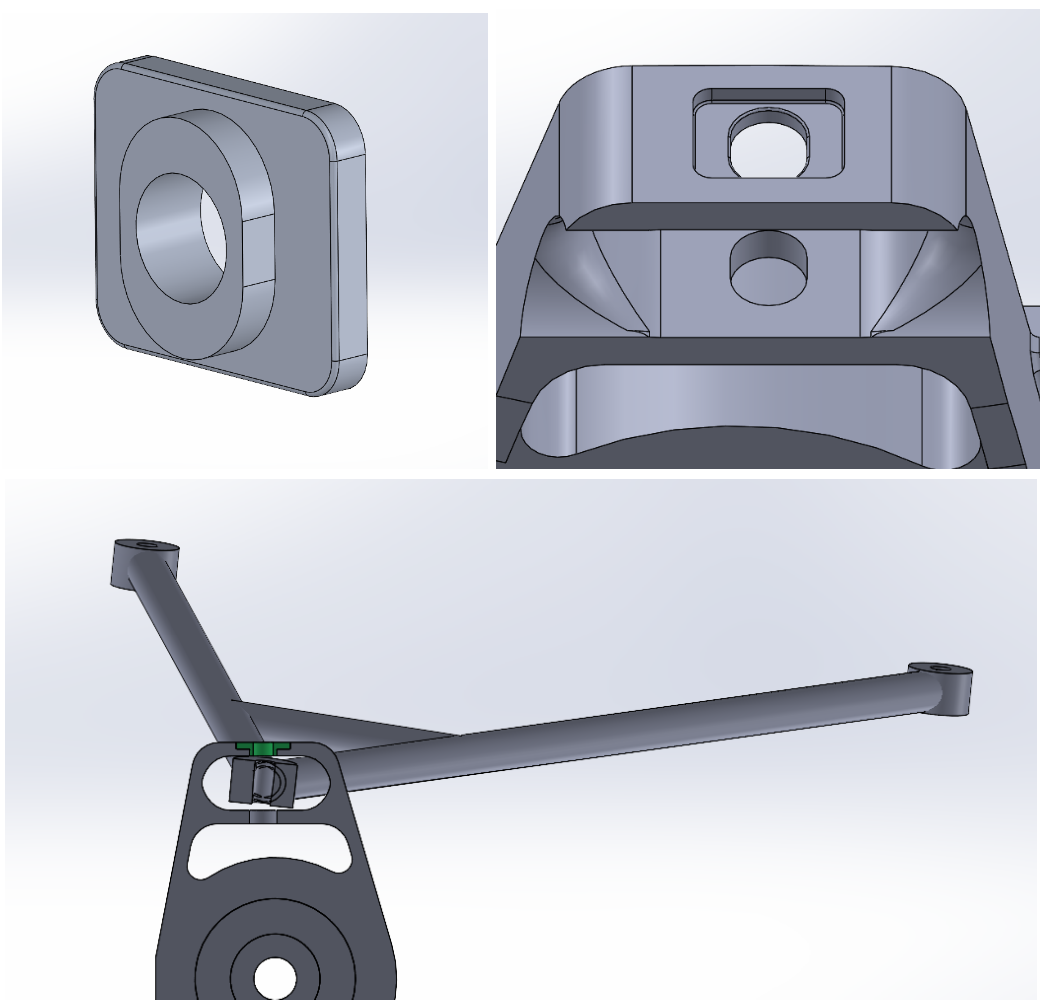

Figure 4: Camber block physical design solution

Force element analysis (FEA) was completed for the upright assembly design after a physical design solution for the camber block was created. This study ensures the design will withstand the forces experienced while under racing conditions to the best estimation possible. Error is inherent in studies like these because the actual forces present are more complex than can be estimated without the track surface and curvature to calculate corner speed. The following assumptions were made when creating the FEA study for the upright assembly:

- Car Weight (approx.) = 800 lbs or 363kg
- 1g: (mass)x(acceleration) = 3630N
- 2g: 7260N will be used as maximum force applied in longitudinal and lateral directions
- 3g: 10890N will be used as maximum force applied in a vertical bump scenario

Forces were applied in the upright strength study at the point where the hub surface of a 16-inch tire meets the ground. The remote load at this point applies forces where they will be experienced on the car with fixtures attached to pins in the control-arm and steering-link locations. The results of this study proved that the design of the upright and camber block is sufficient, providing a factor of safety of at least 1.5 near the pocket where the camber block is inserted connections, and upwards of 10 in the main body of the upright.

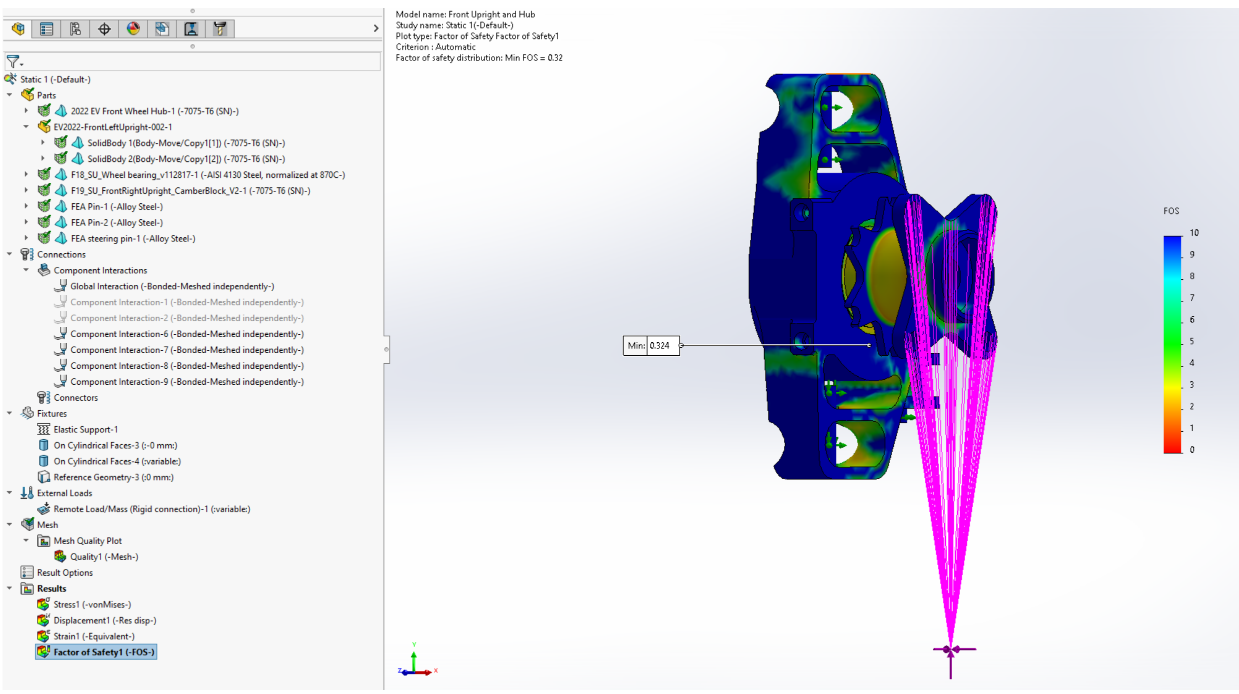

Figure 5: Upright assembly force element analysis

Physical tolerances are created concurrently with development of physical design solutions. The objective for physical tolerances is to allow a physical design solution to satisfy the FRs within their given functional tolerances. Determining which tolerances are important can also be completed by looking at FRs and functional tolerances that must be satisfied. This evaluation also produces the information needed to find process variables like the level of accuracy required by the machine tool. For the camber block, physical tolerances must allow the camber block to provide a minimum of one inch suspension travel to the system, tighten securely to the upright with less than .005 inches of vertical deflection, and allow for replacement of the part without tools needed to separate the camber block from the upright. This information allows the important physical tolerances to be applied to physical dimensions on a technical drawing.

FR1 and FR2 produce a physical tolerance to the length of the camber block below its shoulder. FR2 defines a maximum of .005 inches of vertical deflection to the upright which directly impacts this dimension on the camber block. The length below the part’s shoulder cannot exceed the modeled distance of .125 inches to assemble successfully, but must not be .005 inches shorter than this value to satisfy FR2.

The physical tolerances associated with FR3 and DP3 are referenced using the machinery's handbook. Unlike the wheel bearing pocket tolerancing, rigid limits for functional tolerances have been defined for the camber block and technical literature was used to translate this information from the design domain to the physical domain. Functional tolerances for FR3 are limited by ability to position the camber block to provide correct suspension geometry, and serviceability without tools needed to separate the camber block from the upright. Without number values, the definition for different types of fits was referenced in the machinery’s handbook. The requirements make a locational clearance fit (LC) best for this application, where locating and ease of removal is important. Calculations to find how much angular error would result from a variety of locational error in the camber block was used to decide on the class of LC which would best satisfy FR3. The center-to-center distance between the upright’s control arm mounting points is modeled as 7.189 inches. LC fits range from .0009 inches to .0055 inches of clearance given the size range of .71 to 1.19 inches. The looser tolerance given while still satisfying FR3 and its functional tolerances will provide more value to all stakeholders by maximizing the ease of interchanging camber blocks and reducing manufacturing costs associated with tighter tolerances. The upper limit of tolerance for the fit of the camber block inside the upright pocket is dependent on how accurately the FSAE team at WPI can measure the car’s camber value. Camber is measured using a digital protractor placed against a plate that is held against the outer surface of the wheels. The digital application claims an accuracy of .01 degrees and displays graduations of 0.1 degrees. The most accurate reading possible of 0.1 degrees was compared with the error calculation using .0055 inches of clearance for the LC fit.

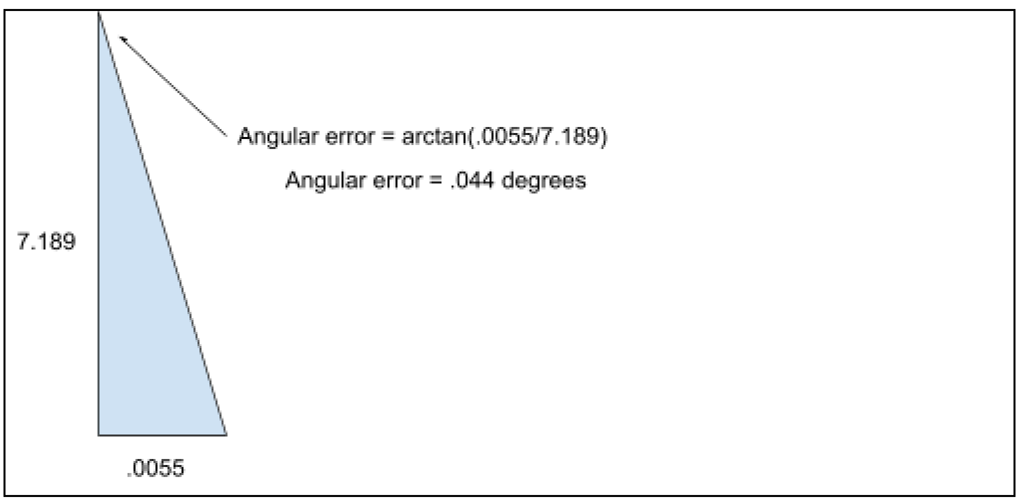

Figure 6: Error calculation from camber block tolerance

Total error possible from a LC4 fit with clearance of .0055 inches is .044 degrees to the upright. This is less than can be measured with the tools available to the FSAE team at WPI so this amount of physical tolerance is appropriate for the camber block. Although the specification for a LC4 clearance locating fit is from 0 to .0055 inches of clearance, zero clearance between the camber block and the upright pocket it is being installed into would result in an unsatisfied FR3 because the block would not be easily removable. A minimum clearance of .002 inches will be necessary to allow for removal, so the values specified for the dimensions in the x-y plane of the camber block are subtracted by .002 in the technical drawing. This will clearly communicate the physical tolerances required to the technician manufacturing the camber blocks by calling out a bilateral tolerance instead of two negative clearance values. The technical drawing shown below only displays the important tolerances discussed in this study, a more complete drawing should be created based on what less important tolerances should be assigned as. For example, machine shops generally have standards for unspecified dimensions like plus or minus five thousandths.

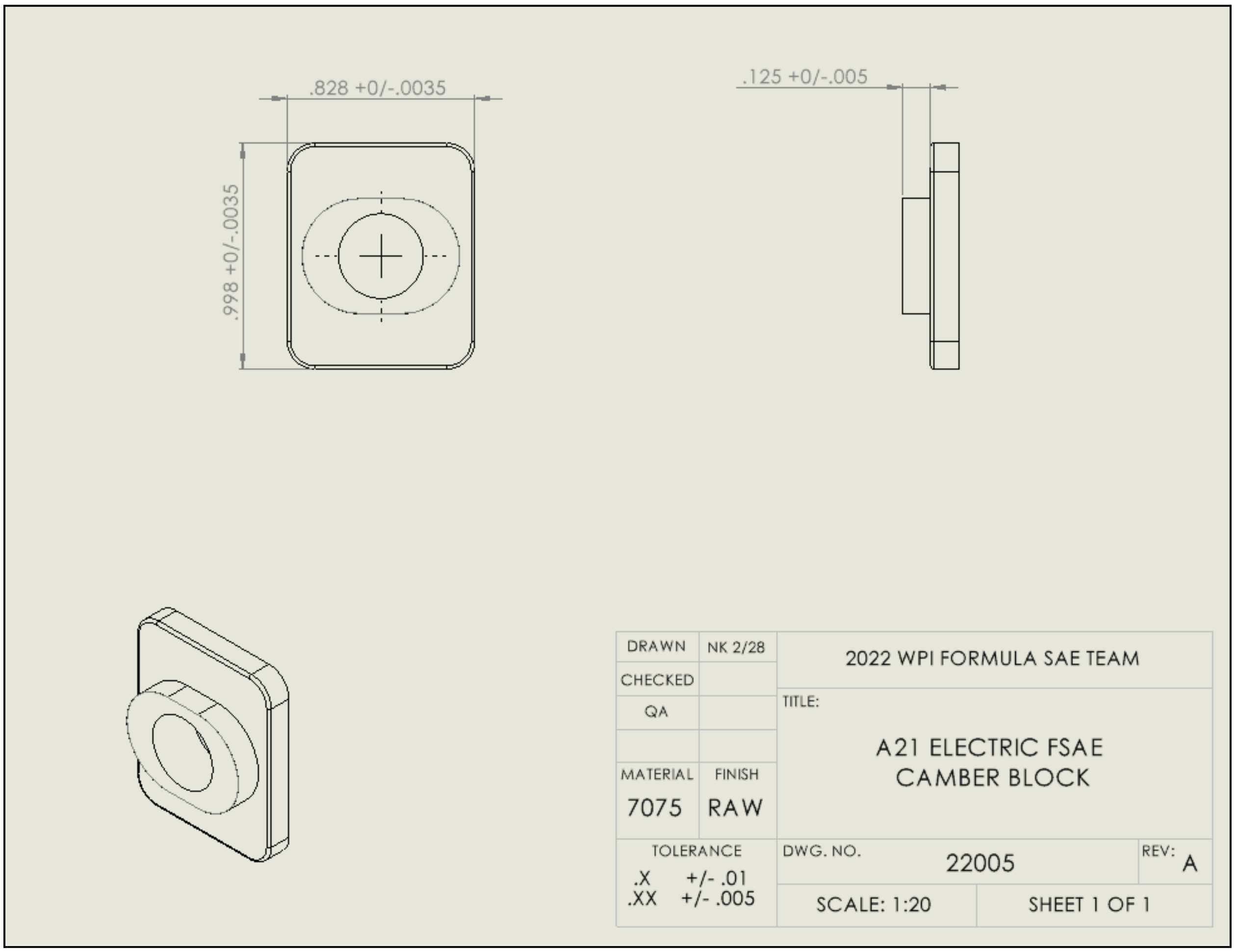

Figure 7: Technical drawing of camber block showing important tolerances

5.4 Process Variables

Nam Suh's publication on Axiomatic design theory for systems defines Process variables (PVs) as the key variables that characterize the processes that generate DPs. Physical design solutions have been created from the three DPs and physical tolerances have been assigned to the design solution that satisfies FRs. The processes involved with sucessfully manufacturing the camber block must be determined. The stepped geometry that fulfills FR2 prevents a laser cutting or water jetting process to be used as they both have cutting media that must cut completely through material. The rectangular geometry of the design solution developed means that milling is a suitable process. From manufacturing the car's upright components, a known accuracy of .0005 inches can be achieved without significant time added to the machining process. With the smallest physical tolerance needed for the camber block being .0035 inches, CNC milling using the Washburn machine shop's Haas VM-2 vertical milling machine is an appropriate process variable.

Inspection of dimensions to verify physical tolerances can be completed using standard dimensional metrology equipment found in the Washburn machine shop. The external distance measurements of .998 and .828 inches can be measured using a micrometer with a range of one inch. The micrometers of this size found in Washburn have a friction thimble to increase consistency of measurement and graduations of .0001 inches. Measurement of the .125-inch distance can be completed using a depth micrometer with graduations of .001 inches. Because of the non-critical nature of the remaining dimensions, standard six-inch calipers should be used.

6. DISCUSSION AND CONCLUSION

Application of axiomatic design principles into tolerance development creates a competitive advantage in the workplace by adding value and reducing non-value adding iteration. Historically the camber block would have been deemed a simple component that should be machined based on CAD dimensions– a technical drawing wouldn't have been created. This study demonstrates how considering requirements of a component in an assembly can eliminate tight physical tolerances where they aren't needed, and where a decrease in the part's performance could be observed. In this system the axiomatic design process increases the ability to meet stakeholder needs. The same advantages can be translated into engineering workplaces, where the reduction in non-value adding iteration and critical analysis of FRs and DPs to design parts can reduce cost and time.

Missing knowledge that would benefit analysis of the camber block component is the importance of surface topography. Understanding the differences in behavior of a camber block that has a coarse surface compared to a smooth surface would affect ease of removing the camber block from the upright pocket. This difference could impact the physical tolerance associated with FR3 and DP3.

Axiomatic principles should be applied to other components in the suspension assembly for more complete tolerance stackup analysis. Completing this method of design during the beginning months of the MQP project can help progress through car design and manufacturing faster. Revisions to suspension design due to overlooked details and requirements is frequent with the FSAE team's current design structure. Integrating these methods could reduce iterations and also provide independence to design solutions so revisions do not result in complete redesign.

7. REFERENCES

Brown, C.A., 2020. Axiomatic Design for Products, Processes, and Systems. *Industry 4.0 for SMEs,* p383-401.

Collins, P., Cummings, C., Dittrich, W., Jones, P., Sealey, A., 2011. CNC Application and Design. *Worcester Polytechnic Institute.*

Fradinho, J., Mourão, A., Gabriel-Santos, A., Gonçalves-Coelho, A., 2016. An Axiomatic Design Interpretation for the Synthesis of Dimensional Tolerances. *Procedia CIRP,* 53, p89-94.

Hong, Y.S., Chang, T.C., 2002. A comprehensive review of tolerancing research. *International Journal of Production Research*, 40(11), p2425-2459.

Molenda, E., Shortlidge, R., 2012. One Machine, One Tool. *Worcester Polytechnic Institute.*

Srinivasan, R.S., Wood, K.L., McAdams, D.A., 1996. Functional Tolerancing: A Design for Manufacturing Methodology. *Research in Engineering Design,* 2, p99-115

Suh, N.P., 1998. Axiomatic Design Theory for Systems. *Research in Engineering Design,* 10, p189–209.

8. APPENDIX

Outline (for content and organization)

1. INTRODUCTION
    - Contrast between traditional and new tolerancing methods
    - History of WPI FSAE team's tolerance approach
    - Value of new tolerance methods
2. PAST TOLERANCE RESEARCH
    - Show importance of this study based on gaps in research findings and MQPs at WPI
    - *An Axiomatic Design interpretation for the synthesis of dimensional tolerances*
    - NSF funding for tolerancing research
3. TOLERANCING METHODS
    - Geometric vs parametric
    - ANSI standards
    - Standard tolerancing vs new methods
    - Axiomatic design correlaries and axioms
4. TRADITIONAL TOLERANCING OF WHEEL BEARING POCKET
    - Wheel bearing tolerancing from progress report 1
    - Bearing manufacturer specifications to ensure failure will not occur
5. CAMBER BLOCK REQUIREMENTS
    - Describe axiomatic design approach for camber block tolerance development
    - 5.1 Customer needs, Stakeholders
    - 5.2 Functional requirements
    - 5.3 Design parameters

Which tolerances are important?
Define design and process equations
Missing information

5.4 Process variables

Manufacturing process variables and inspection to complete tolerance chain
High level abstract concepts to design detains

6. DISCUSSION AND CONCLUSION

Practical benefits to integrating axiomatic design principles into tolerancing process
How process improved in race car application
How this will be implemented within the team for future MQPs

7. REFERENCES

8. APPENDICES