Swerve Robotic Platform

Structural and Mechanical Analysis

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Report Outline

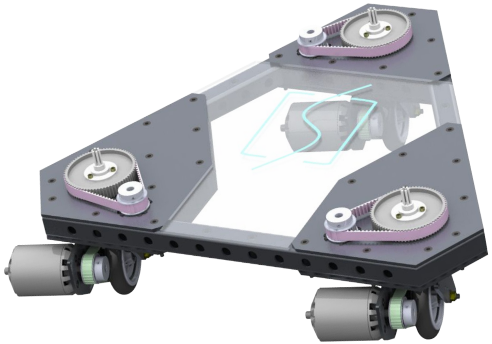
1. Vehicle Introduction

Vehicle Performance, Component Detail

1. Vehicle Introduction
Performance Criteria

The vehicle is intended to accelerate and maneuver as quickly as possible. For design and analysis purposes, the acceleration rate was chosen to be 32.2 ft/s^2 (1g). Additionally, the vehicle is intended to carry a single passenger who stands on top of the vehicle in specifically marked locations. To accommodate different people, a large patron weight of 300lbs [1] was assumed for analysis purposes as a worst case. By leaning in a desired direction, the vehicle will accelerate in that direction, similar to a segway. Using pressure sensors, the vehicle accelerates at a rate that prevents the vehicle and leaning patron from tipping. Below is a rendered image of the proposed vehicle design.

The following is an structural and mechanical analysis package for the vehicle system. Using ABAQUS/CAE, a finite element model was created and analyzed per the specifications listed above. Additionally, supporting structural and mechanical calculations were completed to validate the proposed design.



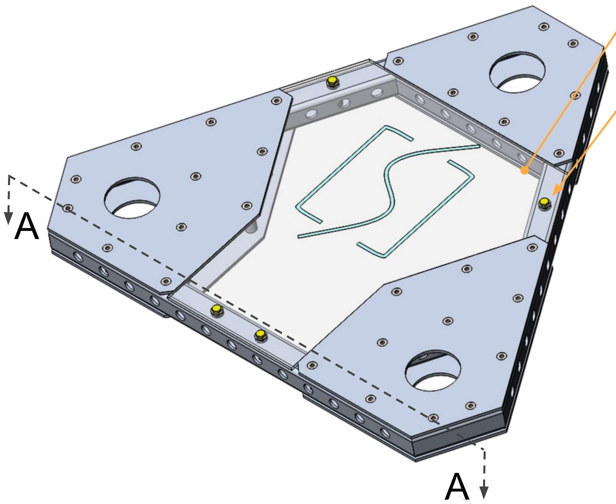
1. Vehicle Introduction

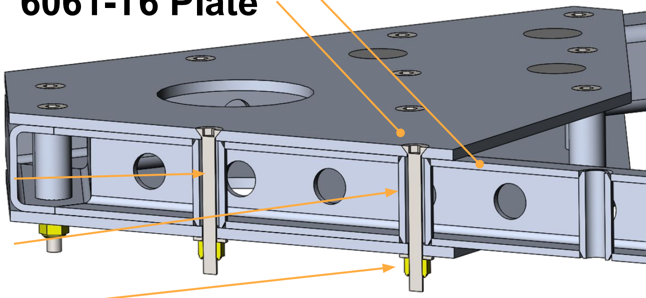
A Note About the Analysis

Per the university requirements, the timeline for this project was restricted to nine months, so the vehicle design and analysis were completed in parallel. As a result, some of the mechanical and structural components have changed since the formation of this report. However, the modifications that were made are expected to have little to no effect on the structural integrity of the system. Some changes that were made include the addition of small holes for mounting, modifications to hole size and location, etc. Over the course of the next few months, the team will return to this analysis to update accordingly, though the report will be used to validate the design for now.

1. Vehicle Introduction
Chassis Mechanical / Structural Components

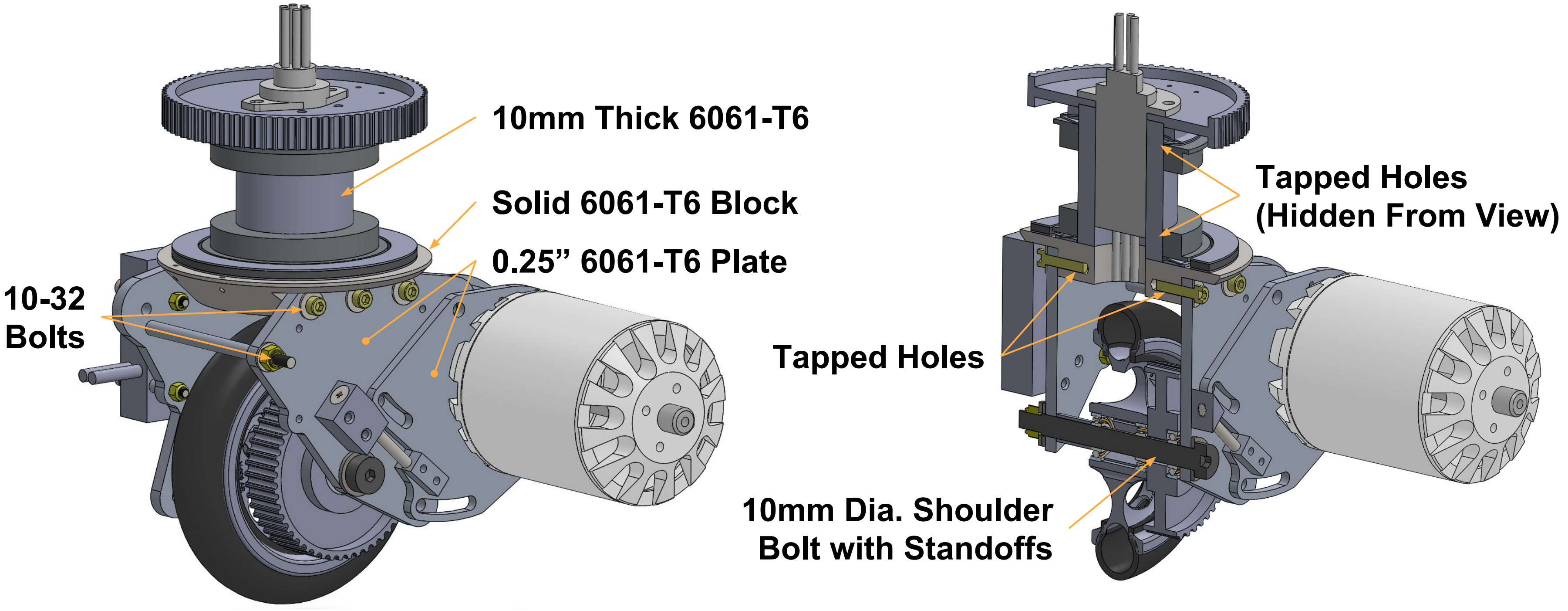
Below are the structural components of the chassis used for analysis. Due to the oversized holes in the acrylic, the acrylic is intended to be removed from the load path, and therefore it will not be used in the structural analysis.





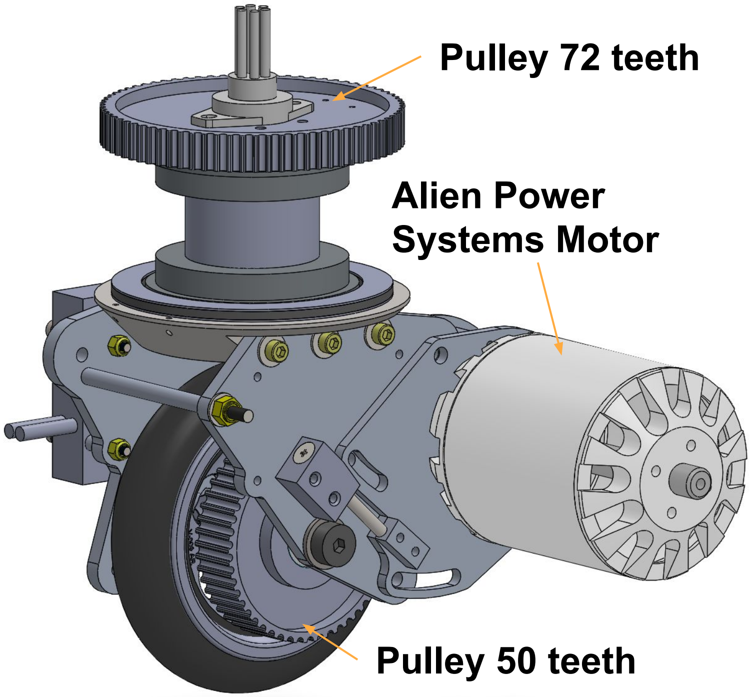
Section A-A
View Cut for Clarity

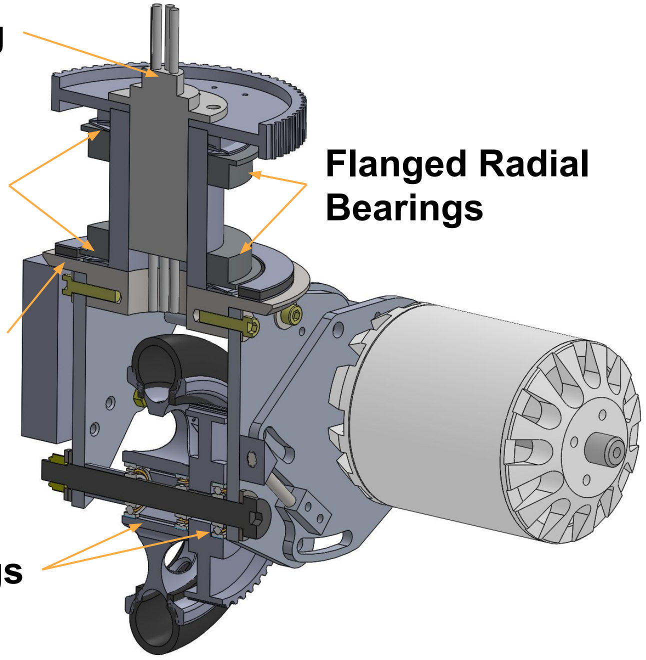
1. Vehicle Introduction
Wheel Assembly Structural Components



1. Vehicle Introduction

Wheel Assembly Mechanical Components





2. Analysis Overview

Assumptions, Success Criteria, Material Properties

2. Analysis Overview

Analysis Assumptions and Considerations

Low-Cycle Life Expectancy - ***Fatigue is Not Considered***

Conservative Safety Factors - ***Compliant with Standards***

Consistent, Moderate Climate - ***No Corrosion Considered***

This system is intended to be used for recreation, for short periods of time, and in dry as well as clean environments. Therefore, fatigue considerations and material corrosion are beyond the scope of these analyses. For analysis success, the mechanical and structural components are expected to pass conservative safety factors for strength load cases. A description of the loading criteria can be found on Page 13 of this report.

2. Analysis Overview
Material Properties and Allowables

Below are the material properties for the general materials used in the proceeding analysis. Additionally, the required safety factors for aluminum are listed as well. If a different material or safety factor is used for analysis, it will be noted specifically within that section of the report. The welded aluminum allowables are highlighted for clarification in addition to the aluminum safety factors used for the analyses. For simplicity, Building Type structures are static load dominated, while Bridge Type structures are dynamic load dominated.

Structural Materials

Material Name	Density [lb / in^3]	E-Modulus [psi]	Poisson -	Yield σ [psi]	Ult. σ [psi]	Reference
Aluminum 6061-T6	0.098	9.9E+06	0.33	35000	42000	2
Structural Steel A36	0.284	2.9E+07	0.32	36000	55000	2
Welded 6061-T6	0.098	9.9E+06	0.33	15000	24000	3

TABLE 6.1 Safety Margins in the Aluminum *Specification [3]*

Type of Structure	Yield Strength	Ultimate Strength
Building Type	1.65	1.95
Bridge Type	1.85	2.20

2. Analysis Overview
Component Material Information

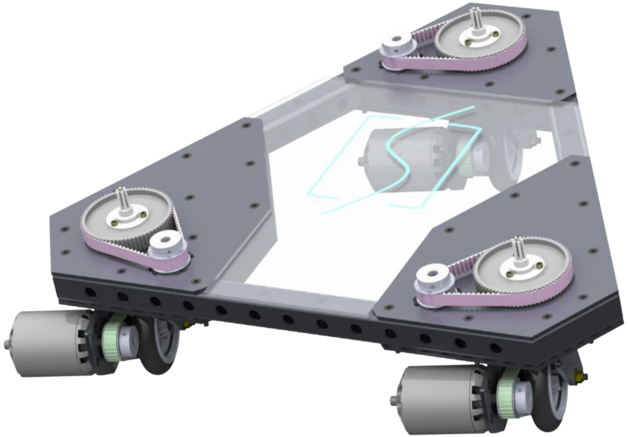
Chassis Components

Part	Material
Structural Beams	6061-T6
Gusset Plates	6061-T6
Crush Tubes	6061-T6

Wheel Assembly Components

Part	Material
Rotating Yaw Shaft	6061-T6
Connecting Block	6061-T6
Side Plates	6061-T6

To reduce the weight of the system, aluminum 6061-T6 was used for many of the structural and mechanical components. Unless otherwise specified, it was assumed that bulk material was manufactured from aluminum 6061-T6 and all bolts were made from A36 steel.



2. Analysis Overview
Load Cases and Analysis Methodology

Structural Analysis Methodology

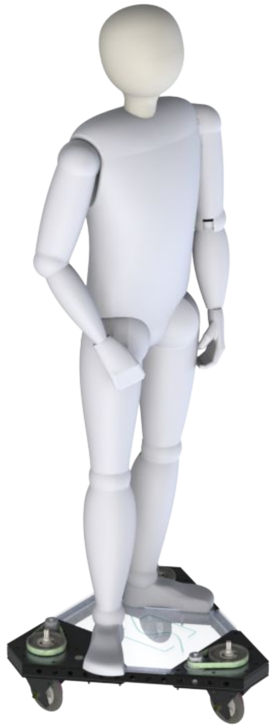
The structural components were analyzed for full-load, full performance operation. During operation, the patron will lean in a desired direction at a specific angle. This places the patron Center of Gravity (CG) away from the vehicle, and a calculated acceleration is required to avoid tipping. A lumped point mass of 300lbs was placed in the finite element model at the specified location to represent the patron CG. The contact locations of the wheels were constrained to only allow rotation (translations fixed) and global accelerations were applied to the model to represent the accelerations of the vehicle. Important factors and values are listed below:

- A Dynamic Factor was not added to loads since it is included in the required safety factor
- A 1.2 Impact Factor was applied to all accelerations per Reference 1 (ASTM F2291-17).
- The Patron CG is located 40.7in on top of the gusset plates per Reference 4.

Mechanical Analysis Methodology

The mechanical components were analyzed for full-load, full-performance operation as well as system abuse and impact while patrons are getting on and off the system. The component calculations were completed assuming all of the system and patron weight are applied to only one wheel assembly. This type of loading is unlikely and will therefore be considered conservative. All of the loads are derived assuming the system will accelerate and perform at the proposed 1g rate. Important factors are listed below:

- A 2.0 Impact Factor was used in many cases for system abuse



2. Analysis Overview

Patron Center of Gravity Information

Table for Estimated Percentiles

Percentile	Factor	Equation
99.9	3.000	99.9 = Mean + (3 x SD)
99.5	2.576	99.5 = Mean + (2.576 x SD)
99	2.326	99.0 = Mean + (2.326 x SD)
97.5	1.950	97.5 = Mean + (1.95 x SD)
97	1.880	97.0 = Mean + (1.88 x SD)
95	1.650	95.0 = Mean + (1.65 x SD)
90	1.280	90.0 = Mean + (1.28 x SD)
85	1.040	85.0 = Mean + (1.04 x SD)
80	0.840	80.0 = Mean + (0.84 x SD)
75	0.670	75.0 = Mean + (0.67 x SD)
50	0.000	50.0 = Mean + (0 x SD)
25	-0.670	25.0 = Mean + (-0.67 x SD)
20	-0.840	20.0 = Mean + (-0.84 x SD)
15	-1.040	15.0 = Mean + (-1.04 x SD)
10	-1.280	10.0 = Mean + (-1.28 x SD)
5	-1.650	5.0 = Mean + (-1.65 x SD)
3	-1.880	3.0 = Mean + (-1.88 x SD)
2.5	-1.950	2.5 = Mean + (-1.95 x SD)
1	-2.326	1.0 = Mean + (-2.326 x SD)
0.5	-2.576	0.5 = Mean + (-2.576 x SD)
0.1	-3.000	0.1 = Mean + (-3 x SD)

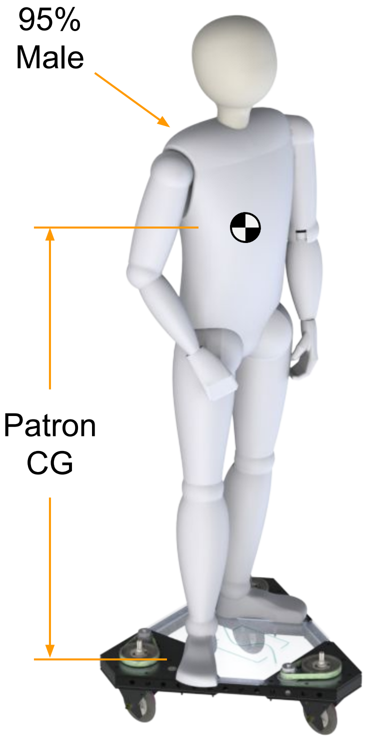
SD = Standard Deviation

Table Taken from *The Measure of Man & Woman*, John Wiley & Sons (C) 2002

Vertical CG Location (From Feet)

	Percentile	Measurement
Mean Data:	50	37.9 in
2nd Data:	99	41.8 in
Standard Dev:	*SD*	*1.68 in*
Interpolated:	**95**	**40.7 in**

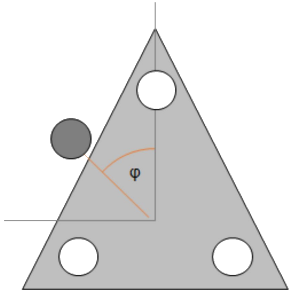
A 95 percentile male (73.7in tall) was the design patron height per Reference 1. This large patron height coupled with the large patron weight (300lbs) is conservative as the system would not accommodate riders larger than this.

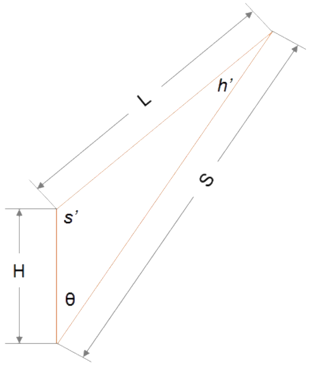


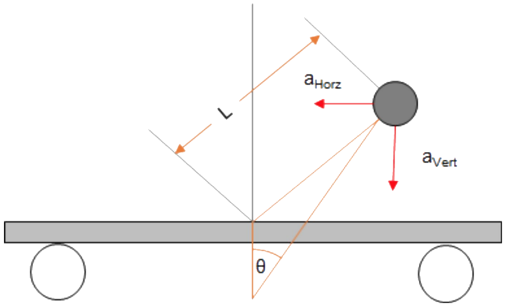
2. Analysis Overview

Patron CG Positioning Calculation for Finite Element Model

All straight-line and perpendicular load cases are derived using the table to the right. These load cases are acceleration driven and the Patron CG location can be derived.







Determine CG Location due to Applied Accelerations

Name	Var	Value	Unit	Comment / Equation
User Input				
Gravitational Acceleration	g	1	g	Given
Vertical Acceleration	a_{Vert}	1.2	g	Vertical Loading on System
Horizontal Acceleration	a_{Horz}	1.2	g	Horizontal Loading on System
CG Height of Patron	L	40.7	in	Height From Chassis Platen
Platen Height off Floor	H	7.86	in	Height From Floor to Platen
Direction Off Straight	φ'	30	deg	Direction From Straight Travel
Geometry Calculations - Law of Sines				
Direction Vector Angle	φ	0.5	rad	$= (\pi/180) * \varphi'$
Acceleration Vector Angle	θ	0.785	rad	$= \mathrm{ATAN}(a_{Horz} / a_{Vert})$
Angle: Patron / Line of Act	*h'*	0.137	rad	$= \mathrm{ASIN}[(H/L) * \mathrm{SIN}(\theta)]$
Angle: Internal Patron Lean	*s'*	2.2	rad	$= \pi - \theta - h'$
CG to Floor - Dist Vector	S	45.9	in	$= L * [\mathrm{SIN}(s') / \mathrm{SIN}(\theta)]$
Resulting Acceleration Components and Patron CG Location				
Accel Comp-LAT	a_{lat}	**-0.600**	**g**	$= a_{Horz} * \mathrm{SIN}(\varphi)$
Accel Comp-FWD	a_{fwd}	**-1.039**	**g**	$= a_{Horz} * \mathrm{COS}(\varphi)$
Accel Comp-VERT	a_{vert}	**-1.200**	**g**	$= a_{Vert}$
CG Lateral Location	CG_{lat}	**16.22**	**in**	$= S * \mathrm{SIN}(\theta) * \mathrm{SIN}(\varphi)$
CG Forward Location	CG_{fwd}	**28.09**	**in**	$= S * \mathrm{SIN}(\theta) * \mathrm{COS}(\varphi)$
CG Vertical Location	CG_{vert}	**24.58**	**in**	$= S * \mathrm{COS}(\theta) - h$
Calc. Patron CG Height	L_{Calc}	40.7	in	$= (CG_{fwd}^2 + CG_{lat}^2 + CG_{vert}^2)^{(1/2)}$

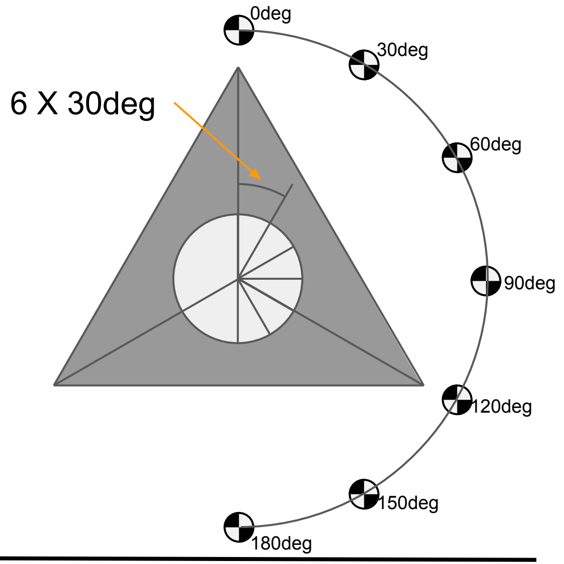
Calculated Patron CG Height is Consistent with Input Data

2. Analysis Overview
Load Cases for the Finite Element Model

Dead	Accel-X:	0.00 g	CG-X:	0.0 in
	Accel-Y:	0.00 g	CG-Y:	0.0 in
	Accel-Z:	-1.20 g	CG-Z:	40.7 in
0deg	Accel-X:	-1.20 g	CG-X:	32.4 in
	Accel-Y:	0.00 g	CG-Y:	0.0 in
	Accel-Z:	-1.20 g	CG-Z:	24.6 in
30deg	Accel-X:	-1.04 g	CG-X:	28.1 in
	Accel-Y:	-0.60 g	CG-Y:	16.2 in
	Accel-Z:	-1.20 g	CG-Z:	24.6 in
60deg	Accel-X:	-0.60 g	CG-X:	16.2 in
	Accel-Y:	-1.04 g	CG-Y:	28.1 in
	Accel-Z:	-1.20 g	CG-Z:	24.6 in
90deg	Accel-X:	0.00 g	CG-X:	0.0 in
	Accel-Y:	-1.20 g	CG-Y:	32.4 in
	Accel-Z:	-1.20 g	CG-Z:	24.6 in
120deg	Accel-X:	0.60 g	CG-X:	-16.2 in
	Accel-Y:	-1.04 g	CG-Y:	28.1 in
	Accel-Z:	-1.20 g	CG-Z:	24.6 in
150deg	Accel-X:	1.04 g	CG-X:	-28.1 in
	Accel-Y:	-0.60 g	CG-Y:	16.2 in
	Accel-Z:	-1.20 g	CG-Z:	24.6 in
180deg	Accel-X:	1.20 g	CG-X:	-32.4 in
	Accel-Y:	0.00 g	CG-Y:	0.0 in
	Accel-Z:	-1.20 g	CG-Z:	24.6 in
Perp.	Accel-X:	0.00 g	CG-X:	0.0 in
	Accel-Y:	-1.20 g	CG-Y:	32.4 in
	Accel-Z:	-1.20 g	CG-Z:	24.6 in

To simulate 1g acceleration in any direction, the patron CG and acceleration vectors were manipulated for load cases at 30deg increments from 0deg to 180deg. Since the structure is symmetric about the X-Z plane, only the first 180deg need to be analyzed. Nine load cases were analyzed using ABAQUS/CAE including 7 straight line acceleration load cases (0deg - 180deg) as well as one perpendicular load case where the wheels are oriented 90deg from the direction of travel. This case is to simulate high speed cornering at 1g.

The table to the left shows the cartesian vectors for the acceleration as well as the coordinates for the patron CG location per each load case. On the right is a visual representation of the patron CG location for each load case.



2. Analysis Overview
Welded Aluminum Specification and Discussion

"The damage is summarized in Aluminum Specification Table 3.3-2, Minimum Mechanical Properties for Welded Aluminum Alloys (included here as Appendix C and discussed in Section 4.5) … The values in Table 3.3-2 for ultimate tensile strengths (F_{tuw}) must be multiplied by 0.9 before they are used for structural design. This is to account for the fact that welds may get only visual inspection and might not reliably attain the strengths in Table 3.3-2 due to undetected defects. This 0.9 factor is not applied to minimum properties other than ultimate tensile strength; here, as elsewhere in the Specification, the margin of safety against tensile fracture is the greatest concern." [3]

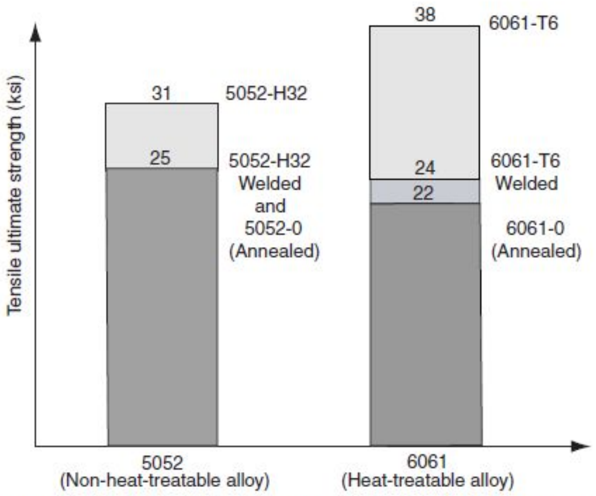


Figure 9.1 Effect of welding on tensile ultimate strength of alloys 5052 and 6061.

Although the text above recommends that a knockdown factor of 0.9 is to be used on the allowable stresses for welded aluminum, the proposed system is not intended for use at high cycles. Since inspection is not a concern, the 0.9 knockdown factor will be omitted, though the ultimate strength criteria for bridge type structures (as defined on Slide 10) will be used for the welded analysis.

Ultimate Strength of Welded 6061-T6 (Defined in Graph) = **24.0ksi**
Required Ultimate Strength Factor of Safety (Bridge Type) = **2.20**
Corresponding Allowable Stress in Weld = 24.0ksi / 2.20 = **10.9ksi**

3. Vehicle Structural Analysis

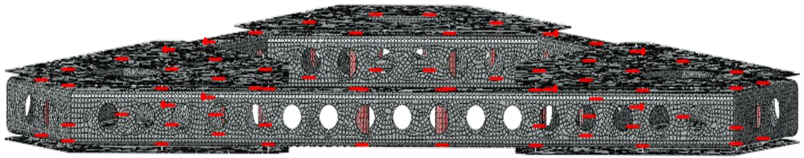
Finite Element Model and Supporting Calculations

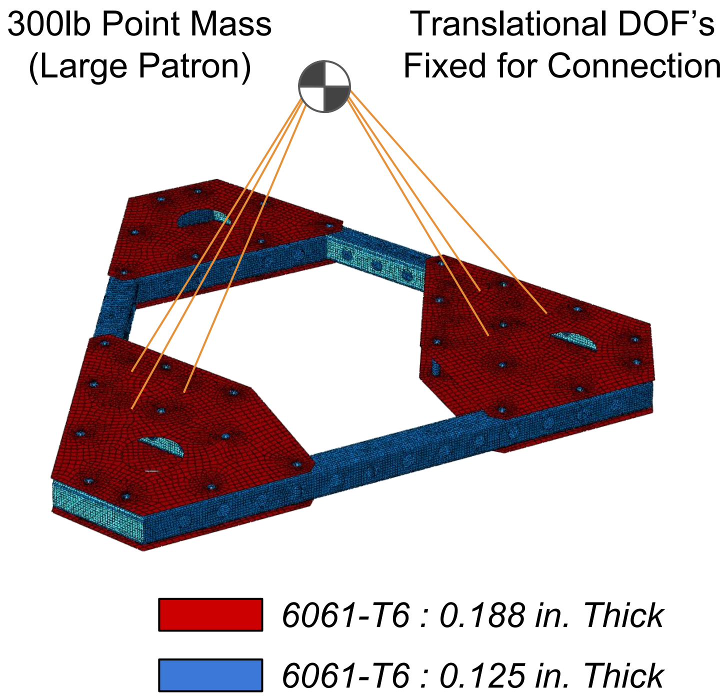
3. Vehicle Structural Analysis - Finite Element Model

Finite Element Model of the Chassis

FEM Creation and Element Formation

- Gusset plates modeled with 2D, linear shell elements that are 0.25 in. big
- Beams and tubes modeled with 2D, linear shell elements that are 0.125 in. big
- bolts are modeled with 1D beam elements





The elements representing the crush tubes were stitched to the elements representing the beams. This is to model the welded connection by allowing direct transfer of load.

3. Vehicle Structural Analysis - Finite Element Model

Finite Element Model of the Wheel Assembly

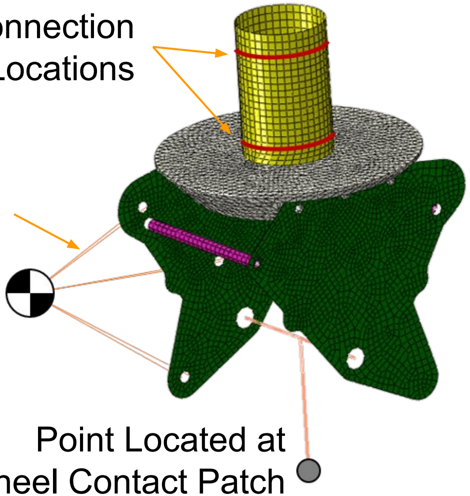
FEM Creation and Element Formation

- Side plates and shaft modeled with 2D, linear shell elements that are 0.125 in. big
- Connecting Plate modeled with 3D, linear tetrahedral elements that are 0.125 in. big
- bolts are modeled with 1D beam elements

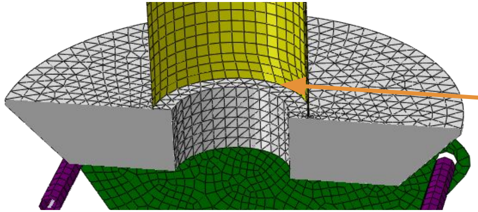
Bearing Connection Node Locations

Rigid Constraint to attach point mass

4.5lb Point Mass (Drive Motor)



Point Located at Wheel Contact Patch



Shell to Solid Mesh Connection Constraint

6061-T6 : 0.029 in. Thick

6061-T6 : 0.250 in. Thick

6061-T6 : 10.0 mm. Thick

Instead of bolted connections, the nodes at the shaft and plate interface are merged to limit model size. Stresses in shaft connection are expected to be low.

3. Vehicle Structural Analysis - Finite Element Model

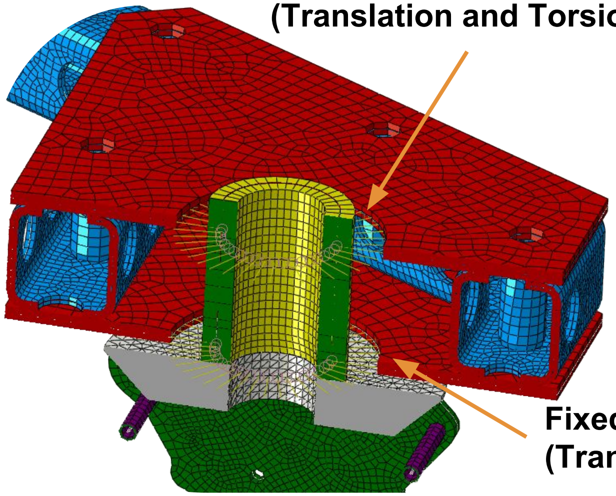
Finite Element Model of the Vehicle Assembly

The finite element assembly is shown on the right as well as the model loads and boundary conditions. Below is a detailed view of the part-to-part constraint that is consistent for all wheel assemblies.

Total FEM Weight = 355.6 lbs

- Chassis Model 18.7 lbs
- Swerve Model (3) 12.3 lbs
- Large Patron 300 lbs

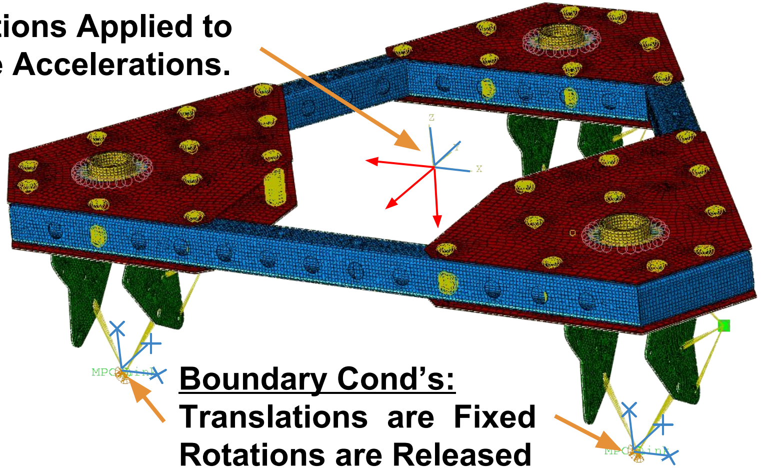
Fixed DOF Constraint (Translation and Torsion)



Fixed DOF Constraint (Translation Only)

Assembly Bearing Connections
Shell Thickness Rendered for Clarity

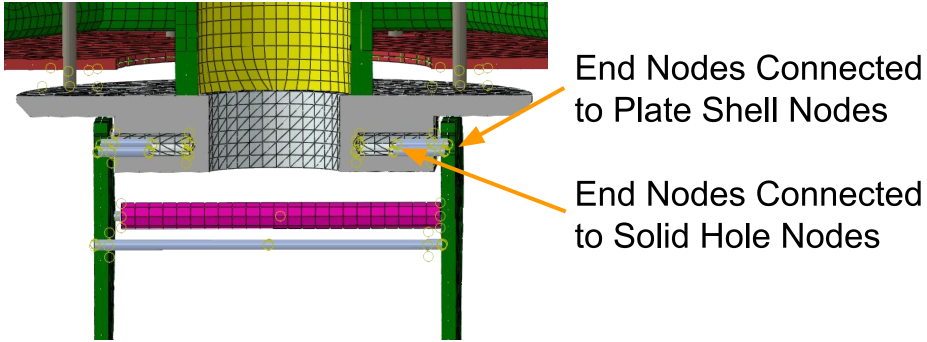
<u>LOADS:</u>
Global Accelerations Applied to Simulate Vehicle Accelerations.



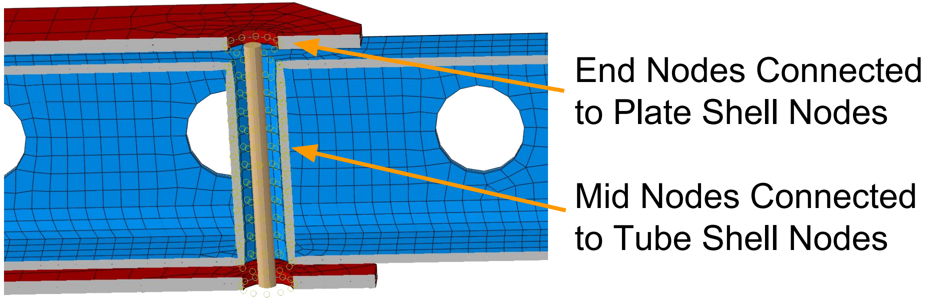
<u>Boundary Cond's:</u>
Translations are Fixed Rotations are Released

3. Vehicle Structural Analysis - Finite Element Model

Modeling Bolted Connections



Bolted Connections in Wheel Assembly



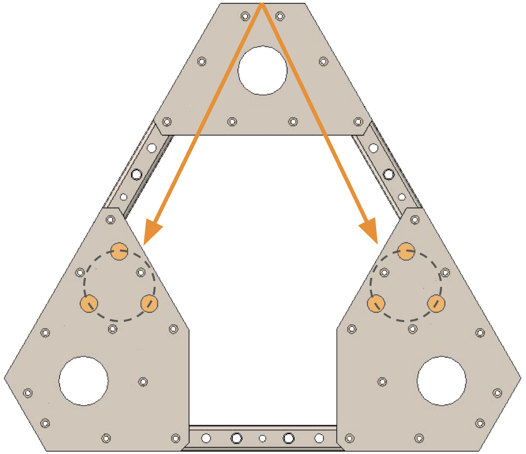
Bolted Connections in Chassis

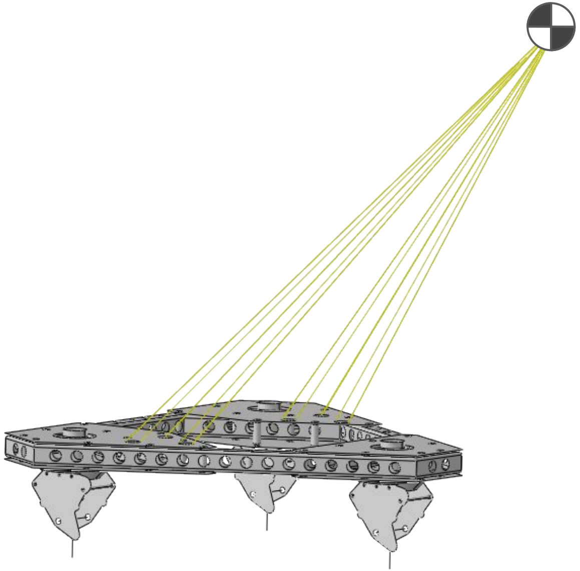
For bolted connections, 1D beam elements were used with a simulation diameter twice the diameter of the proposed bolt. This is to ensure the model is adequately stiff and large deflections are avoided. The methodology used to the left is consistent for all bolted connections throughout this analysis. To account for preloaded bolts, rigid (fixed) elements were used to connect the beam nodes to the surface and solid nodes. This allows the transfer of both forces and moments.

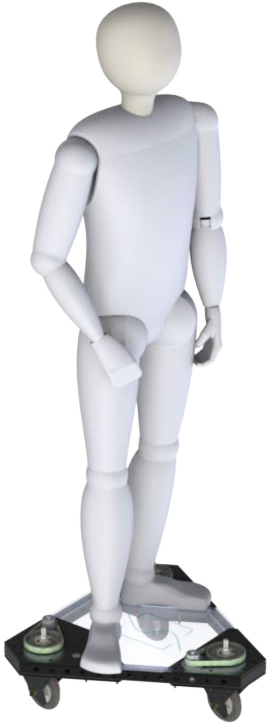
3. Vehicle Structural Analysis - Finite Element Model
Modeling Patron Connections

To constrain the patron to the chassis, it was assumed that the feet would apply loads to the model in a distributed circle described on the below. Three smaller circles were created on the model to represent these force locations. The CG was then constrained using a Multi Point, Link constraint, the translation of the point mass was held constant while the CG was free to rotate, simulating the pitch/roll of the patron ankle.

Patron CG Mass Connected to Elements in Highlighted Locations







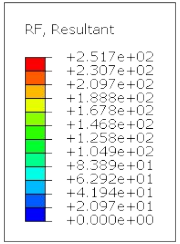
3. Vehicle Structural Analysis - Finite Element Model

Model Check: Simulation Reaction Forces

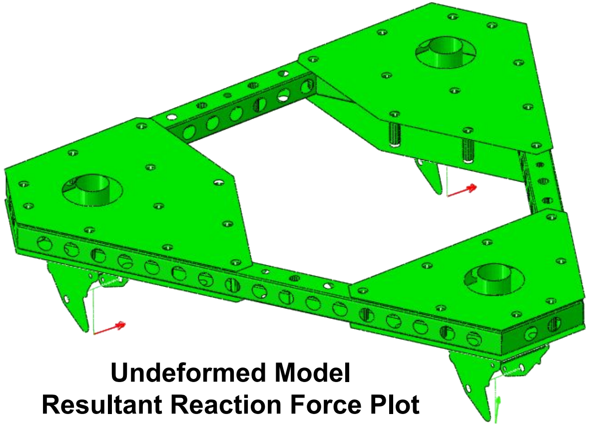
Reaction Forces

- Reactions Equal (*Model Mass * Accelerations)*
- Verify Loads, Masses, and Boundary Conditions

Load Case: 0deg



Units above are lbs



Undeformed Model
Resultant Reaction Force Plot

Mass Information		
Chassis Material	18.73 lbs	Output from Simulation
Patron (95th%)	300.0 lbs	Output from Simulation
Swerve System	36.84 lbs	Output from Simulation
Total Mass	355.6 lbs	Mass Summation

MODEL REACTION FORCES AS COMPARED TO THE EXPECTED REACTION FORCES

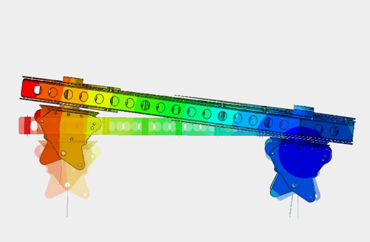
	Applied Accelerations		Expected Forces		Simulation Forces		Modeling Error	
Dead Load	Accel-X	0.000 g	Force-X	0.0 lbs	Force-X	0.0 lbs	Percent Error:	0.0%
	Accel-Y	0.000 g	Force-Y	0.0 lbs	Force-Y	0.0 lbs	Percent Error:	0.0%
	Accel-Z	-1.200 g	Force-Z	-426.7 lbs	Force-Z	-426.7 lbs	Percent Error:	0.0%
0deg	Accel-X	-1.200 g	Force-X	-426.7 lbs	Force-X	0.0 lbs	Percent Error:	100.0%
	Accel-Y	0.000 g	Force-Y	0.0 lbs	Force-Y	-426.7 lbs	Percent Error:	0.0%
	Accel-Z	-1.200 g	Force-Z	-426.7 lbs	Force-Z	-426.7 lbs	Percent Error:	0.0%
30deg	Accel-X	-0.600 g	Force-X	-213.3 lbs	Force-X	-213.4 lbs	Percent Error:	0.0%
	Accel-Y	-1.039 g	Force-Y	-369.5 lbs	Force-Y	-369.5 lbs	Percent Error:	0.0%
	Accel-Z	-1.200 g	Force-Z	-426.7 lbs	Force-Z	-426.7 lbs	Percent Error:	0.0%
60deg	Accel-X	-1.039 g	Force-X	-369.5 lbs	Force-X	-369.5 lbs	Percent Error:	0.0%
	Accel-Y	-0.600 g	Force-Y	-213.3 lbs	Force-Y	-213.4 lbs	Percent Error:	0.0%
	Accel-Z	-1.200 g	Force-Z	-426.7 lbs	Force-Z	-426.7 lbs	Percent Error:	0.0%
90deg	Accel-X	-1.200 g	Force-X	-426.7 lbs	Force-X	-426.7 lbs	Percent Error:	0.0%
	Accel-Y	0.000 g	Force-Y	0.0 lbs	Force-Y	0.0 lbs	Percent Error:	0.0%
	Accel-Z	-1.200 g	Force-Z	-426.7 lbs	Force-Z	-426.7 lbs	Percent Error:	0.0%
120deg	Accel-X	-1.039 g	Force-X	-369.5 lbs	Force-X	-369.5 lbs	Percent Error:	0.0%
	Accel-Y	0.600 g	Force-Y	213.3 lbs	Force-Y	213.4 lbs	Percent Error:	0.0%
	Accel-Z	-1.200 g	Force-Z	-426.7 lbs	Force-Z	-426.7 lbs	Percent Error:	0.0%
150deg	Accel-X	-0.600 g	Force-X	-213.3 lbs	Force-X	-213.4 lbs	Percent Error:	0.0%
	Accel-Y	1.039 g	Force-Y	369.5 lbs	Force-Y	369.5 lbs	Percent Error:	0.0%
	Accel-Z	-1.200 g	Force-Z	-426.7 lbs	Force-Z	-426.7 lbs	Percent Error:	0.0%
180deg	Accel-X	0.000 g	Force-X	0.0 lbs	Force-X	0.0 lbs	Percent Error:	0.0%
	Accel-Y	1.200 g	Force-Y	426.7 lbs	Force-Y	426.7 lbs	Percent Error:	0.0%
	Accel-Z	-1.200 g	Force-Z	-426.7 lbs	Force-Z	-426.7 lbs	Percent Error:	0.0%

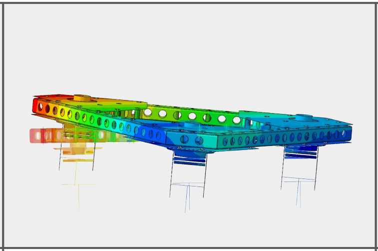
3. Vehicle Structural Analysis - Finite Element Model

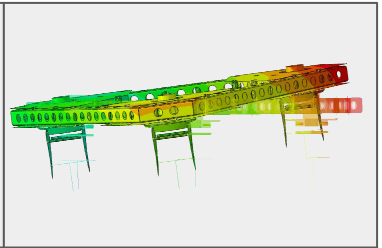
Model Check: Free-Free Modes Analysis

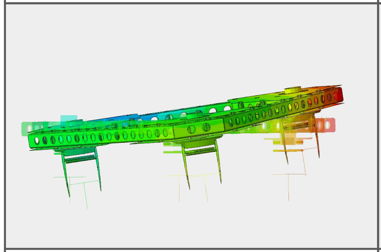
Free-Free Modes

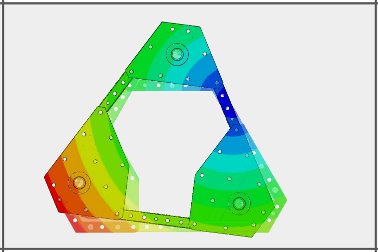
- Rigid body modes at least five orders below first flexural body mode
- Verify model is accurately constrained and all parts are connected

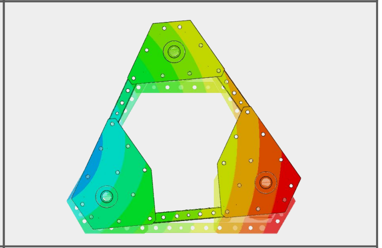

Mode 1: 0.00 Hz


Mode 2: 0.00 Hz


Mode 3: 6.42E-6 Hz


Mode 4: 1.49E-5 Hz


Mode 5: 2.63E-5 Hz


Mode 6: 4.46E-5 Hz

Below is a list of the first ten modes output by the Free-Free Modes Simulation. Note that the first six modes are the rigid body modes, while the modes following are flexural body modes. This is consistent with the rule listed above.

Frame

Index	Description
0	Increment 0: Base State
1	Mode 1: Value = -3.33695E-08 Freq = 0.0000 (cycles/time)
2	Mode 2: Value = -1.62283E-08 Freq = 0.0000 (cycles/time)
3	Mode 3: Value = 1.62733E-09 Freq = 6.42034E-06 (cycles/time)
4	Mode 4: Value = 8.76245E-09 Freq = 1.48982E-05 (cycles/time)
5	Mode 5: Value = 2.73584E-08 Freq = 2.63248E-05 (cycles/time)
6	Mode 6: Value = 7.86217E-08 Freq = 4.46264E-05 (cycles/time)
7	Mode 7: Value = 657.16 Freq = 4.0800 (cycles/time)
8	Mode 8: Value = 837.53 Freq = 4.6060 (cycles/time)
9	Mode 9: Value = 1193.8 Freq = 5.4991 (cycles/time)
10	Mode 10: Value = 1858.1 Freq = 6.8604 (cycles/time)

3. Vehicle Structural Analysis

Safety Factor Summary by Load Case

Load Case	Assem. Criteria	Allow σ [ksi]	Expect σ [ksi]	Expect SF	Required SF
0deg	Chassis Assembly	35.0	14.28	2.45	1.85
	Chassis Welded	24.0	7.14	3.36	2.20
	Wheel Assemblies	35.0	6.32	5.54	1.85
30deg	Chassis Assembly	35.0	14.75	2.37	1.85
	Chassis Welded	24.0	7.81	3.07	2.20
	Wheel Assemblies	35.0	8.77	3.99	1.85
60deg	Chassis Assembly	35.0	8.67	4.04	1.85
	Chassis Welded	24.0	8.63	2.78	2.20
	Wheel Assemblies	35.0	5.66	6.18	1.85
90deg	Chassis Assembly	35.0	6.80	5.15	1.85
	Chassis Welded	24.0	7.78	3.08	2.20
	Wheel Assemblies	35.0	8.31	4.21	1.85
120deg	Chassis Assembly	35.0	10.68	3.28	1.85
	Chassis Welded	24.0	5.43	4.42	2.20
	Wheel Assemblies	35.0	6.70	5.22	1.85
150deg	Chassis Assembly	35.0	12.49	2.80	1.85
	Chassis Welded	24.0	4.26	5.64	2.20
	Wheel Assemblies	35.0	6.35	5.51	1.85
180deg	Chassis Assembly	35.0	10.82	3.24	1.85
	Chassis Welded	24.0	3.61	6.66	2.20
	Wheel Assemblies	35.0	4.82	7.26	1.85
Perpendicular	Chassis Assembly	35.0	7.13	4.91	1.85
	Chassis Welded	24.0	8.53	2.81	2.20
	Wheel Assemblies	35.0	8.61	4.07	1.85

The expected stresses and resulting safety factors for the structural components are listed to the left. All analyzed components meet the required strength. The load cases with the smallest margin for each part is highlighted in green and corresponding stress contours are displayed on the following slides. For convenience, the minimum required safety factors for aluminum are listed below.

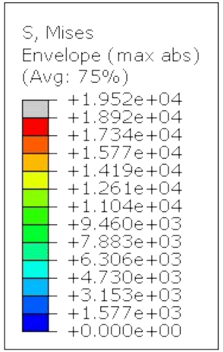
TABLE 6.1 Safety Margins in the Aluminum *Specification [3]*

Type of Structure	Yield Strength	Ultimate Strength
Building Type	1.65	1.95
Bridge Type	1.85	2.20

3. Vehicle Structural Analysis - Finite Element Model

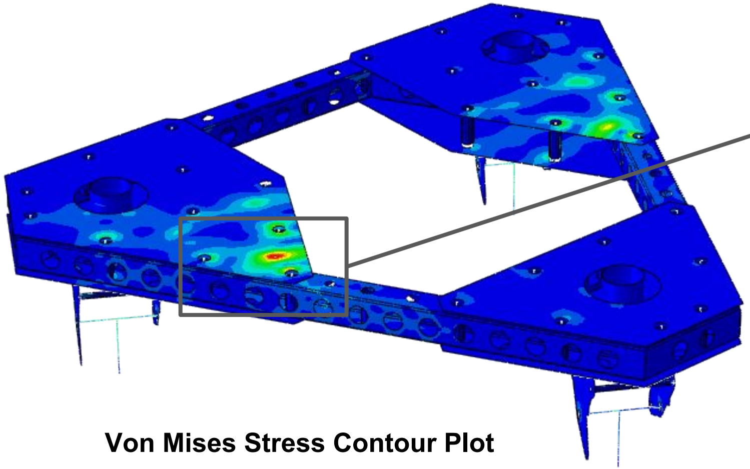
Expected Von Mises Stresses are Acceptable in Chassis Gusset Plates

Load Case: 30deg

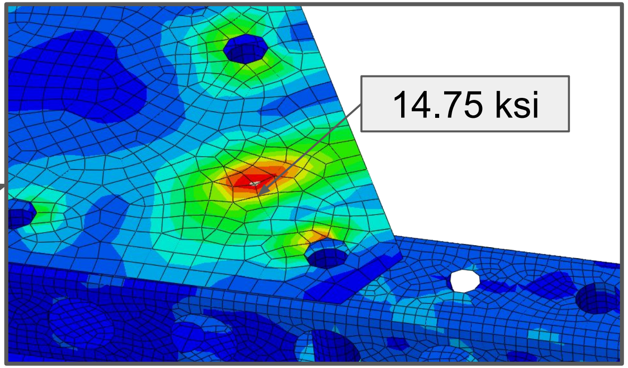


Units above are in psi

35 ksi / 1.85 = 18.9 ksi



Von Mises Stress Contour Plot



Components Removed for Clarity

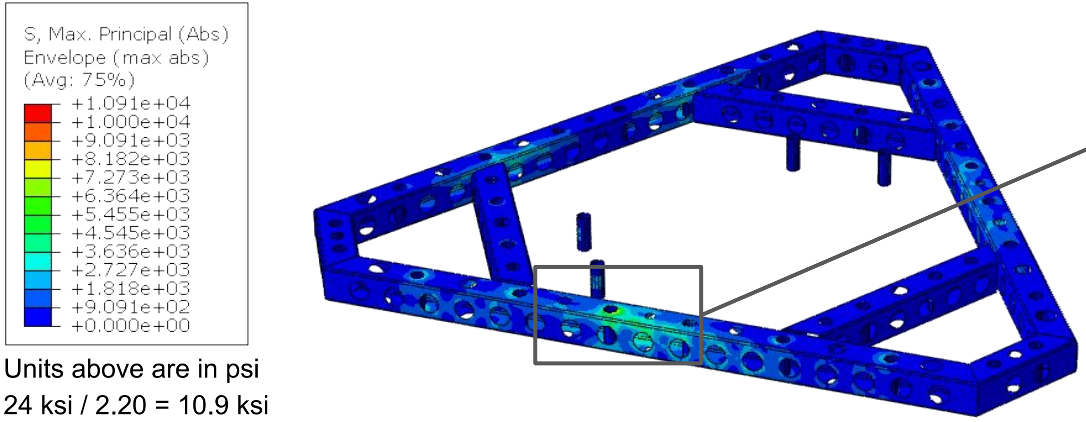
Yield Strength of 6061-T6 = 35 ksi
Expected Stress in Part = 14.75 ksi
Resulting FoS = **2.37 > 1.85**

Stresses evaluated in the chassis gusset plates are compared to the dynamic loading (bridge type) yield safety factor of 1.85. Stresses near bolted and patron connections are evaluated two elements away from the connection to ignore singularities and artifacts of the simulation. This provides a nominal stress in the parent material at the connection location.

3. Vehicle Structural Analysis - Finite Element Model

Expected Principal Stresses are Acceptable in Welded 6061-T6 Material

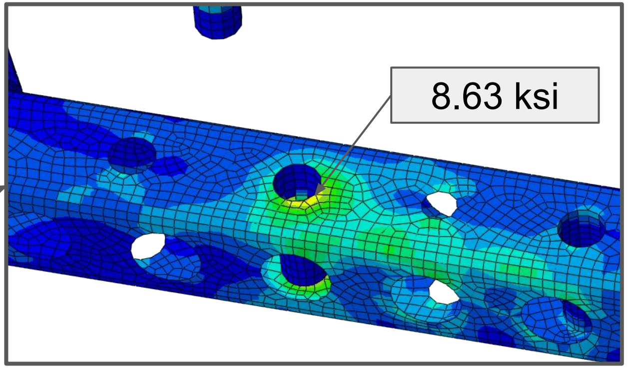
Load Case: 60deg



Units above are in psi

24 ksi / 2.20 = 10.9 ksi

Abs. Principal Stress Contour Plot
Only Welded Components are Displayed



Ult. Strength Welded 6061-T6 = 24 ksi
Expected Stress in Part = 8.63 ksi
Resulting FoS = **2.78 > 2.20**

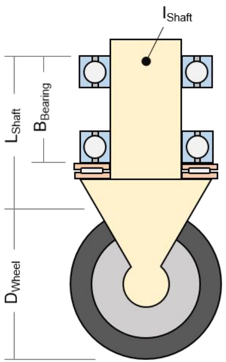
Stresses evaluated in the chassis beam members are compared to the dynamic loading (bridge type) ult safety factor of 2.20. Stresses at welded connections are evaluated at the worst nodal location, typically at the node connecting the crush tube and the chassis beam. Evaluating stresses at this location is to account for welding defects despite the conservative stress values due to the singularity of connecting shell elements at 90deg angles.

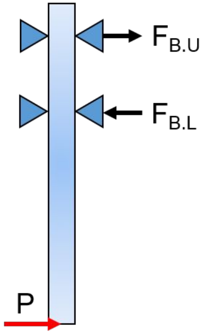
3. Vehicle Structural Analysis - Supporting Calculations

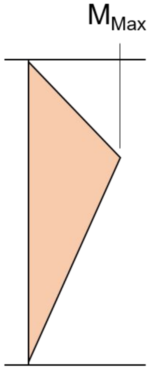
Bending Stresses in Rotating Yaw Shaft

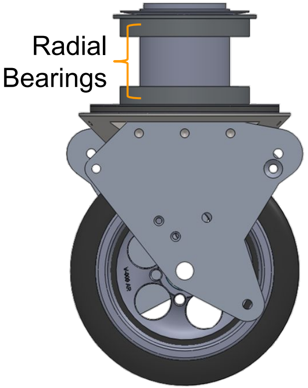
Bending Stresses Induced in Rotating Yaw Shaft

Name	Var	Val	Unit	Comment / Equation
System Geometry				
Wheel Diameter	D_{Wheel}	5	in	Assumed
Shaft Length Above Wheel	L_{Shaft}	3.29	in	Assumed
Distance Between Bearings	$B_{Bearing}$	2.03	in	Height of Beams
Shaft Outer Diameter	d_{outer}	1.97	in	50mm Shaft to Inches
Shaft Inner Diameter	d_{inner}	1.18	in	Required for Slip Ring
Load Information (Assumed on One Wheel)				
Acceleration of Vehicle	a	1.0	g	Specified from Stakeholder
Weight of Passenger	w_P	300	lbs	95th Percentile Male
Weight of System	w_S	62.5	lbs	Assumed per Weight Budget
Total Weight of System	W	363	lbs	$= w_P + w_S$
Total Mass of System	m	0.94	slug*in	$= W / 386.4$
Applied Load at Bottom of Wheel	P	363	lbs	$= m * (a * 386.4)$
Modeled as an Overhang Beam				
Shaft Area Moment of Inertia	I_{Shaft}	0.64	in^4	$= (\pi/64) * (d_{outer}^4 - d_{inner}^4)$
Effective Beam Length	L_{Eff}	8.29	in4	$= D_{Wheel} + L_{Shaft}$
Reaction Force on Lower Bearing	$F_{B.L}$	1478	lbs	$= (P * L_{Eff}) / B_{Bearing}$
Reaction Force on Upper Bearing	$F_{B.U}$	-1116	lbs	$= P - F_{B.L}$
Maximum Bending Moment	M_{Max}	-2267	in-lbs	$= F_{B.U} * B_{Bearing}$
Bending Stress on Shaft	σ_{Bend}	3476	psi	$= M_{Max} * (d_{outer} / 2) / I_{Shaft}$
Aluminum 6061-T6 Yield Strength	σ_{Yield}	35000	psi	Referenced in MMPDS
Resulting Factor of Safety	FoS	**10.1 > 1.85**		$= \sigma_{Yield} / \sigma_{Bend}$









The bending stresses in the vehicle rotating yaw shaft were determined by modeling the shaft as an effective beam. Although the bolt preload and the bolt holes are not considered, the significant strength margin proves the design is sufficient.

3. Vehicle Structural Analysis - Finite Element Model

Small Hole Analysis Methodology

The wheel assembly includes small holes for mounting electronics and sensors. These holes affect the mesh size and can increase the solve time. The model is idealized by removing these small holes and a nominal stress through the section is determined by the finite element solver. Using the stress concentration equations on the right, the adjusted stress can be calculated. For simplicity, the same concentration factor equations apply to holes in near proximity to others.

The maximum stresses were calculated in the wheel assembly plates over all load cases. It was determined that the *Perpendicular* load case was the most severe, and it can be seen below.

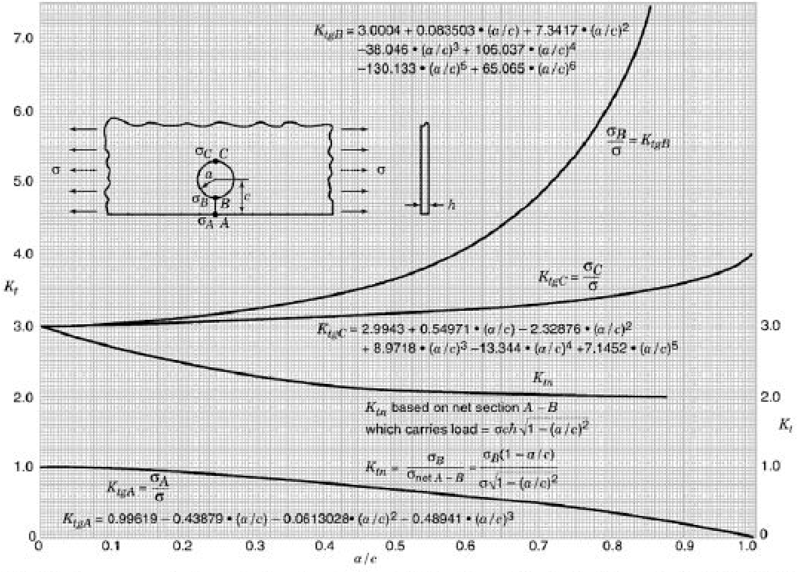
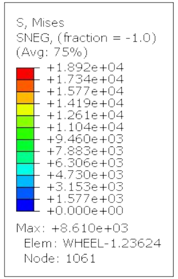
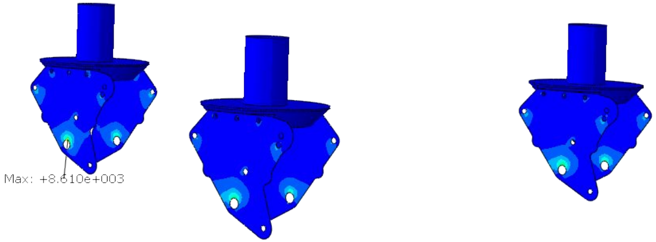


Chart 4.2 Stress concentration factors for the tension of a thin semi-infinite element with a circular hole near the edge (Udoguti 1947; Mindlin 1948; Isida 1955a).

Figure above taken from Reference 5.

Load Case: Perpendicular





Von Mises Stress Contour Plot

Units above are in psi

35 ksi / 1.85 = 18.9 ksi

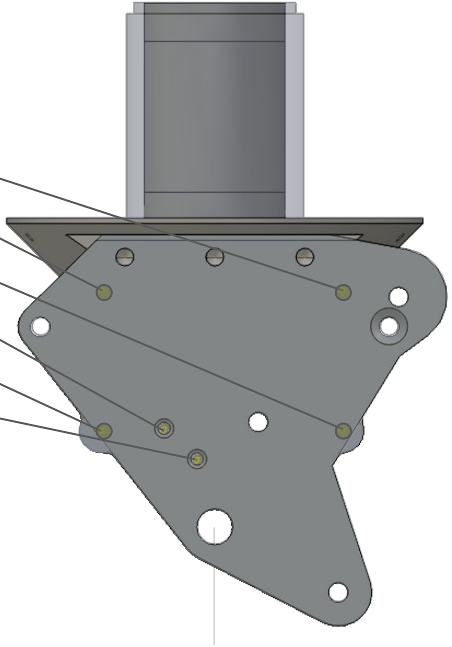
The stress contour plot for the front wheel assembly is detailed on following slides.

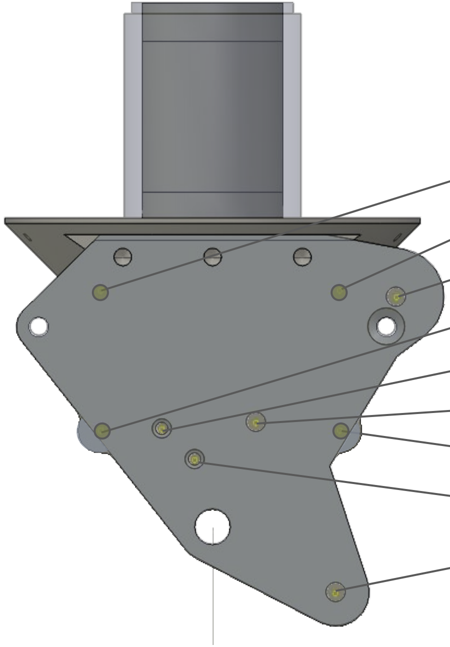
3. Vehicle Structural Analysis - Finite Element Model

Small Hole Locations in Wheel Assembly Side Plates

The holes shown below were idealized out of the finite element model. The hole diameter and distance away from the nearest edge or adjacent hole was recorded and used to determine the appropriate stress concentration factor. The results are tabulated on the following pages and the adjusted stress value is compared to the allowable.

Hole	Dia. [in]
L1	0.130
L2	0.130
L3	0.130
L4	0.136
L5	0.130
L6	0.136





Hole	Dia. [in]
R1	0.130
R2	0.130
R3	0.213
R4	0.130
R5	0.136
R6	0.213
R7	0.130
R8	0.136
R9	0.213

3. Vehicle Structural Analysis - Finite Element Model
Small Hole Stresses in Left Side Plate of Wheel Assembly

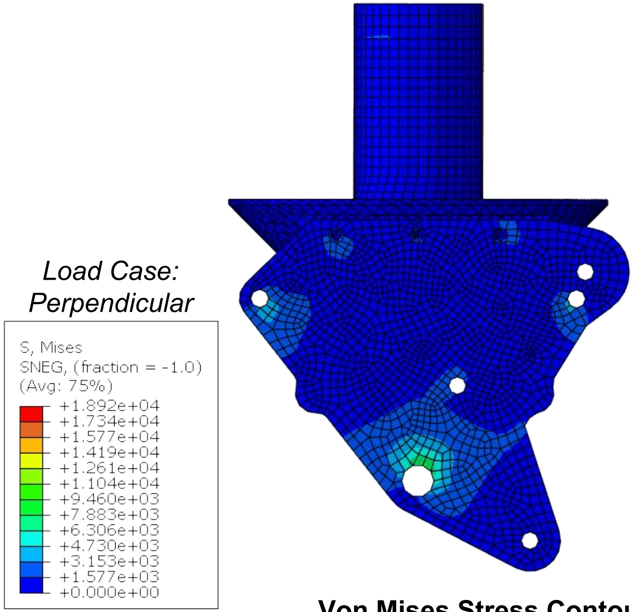
Hole	Dia. [in]	Dist [in]	Rad/Dist	K_{tgA}	K_{tgB}	K_{tgC}	Nom. σ	Adjust σ
L1	0.130	0.459	0.14	0.92	3.09	3.05	0.74	2.28
L2	0.130	0.353	0.18	0.89	3.12	3.06	1.30	4.06
L3	0.130	0.250	0.26	0.83	3.20	3.08	0.50	1.59
L4	0.136	0.432	0.16	0.91	3.10	3.05	0.82	2.55
L5	0.130	0.250	0.26	0.83	3.20	3.08	0.48	1.54
L6	**0.136**	**0.432**	**0.16**	**0.91**	**3.10**	**3.05**	**2.35**	**7.29**

The most severe load case for the wheel assemblies is the *Perpendicular* load case. A detailed view of the nominal stress in the left side plate of the front wheel assembly is shown to the right. The table above uses values from this contour plot.

Max Expected Stress = 7.29 ksi
6061-T6 Yield Stress = 35.0 ksi
FoS 35.0 / 7.29 = 4.80 > 1.85

Front Wheel Assembly
Left Side Shown

Load Case: Perpendicular



Units above are in psi
35 ksi / 1.85 = 18.9 ksi

Von Mises Stress Contour Plot

3. Vehicle Structural Analysis - Finite Element Model

Small Hole Stresses in Right Side Plate of Wheel Assembly

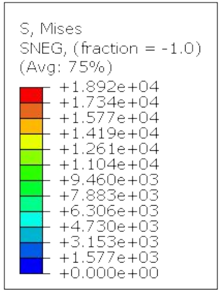
Hole	Dia. [in]	Dist [in]	Rad/Dist	K_{tgA}	K_{tgB}	K_{tgC}	Nom. σ	Adjust σ
R1	0.130	0.459	0.14	0.92	3.09	3.05	1.72	5.31
R2	0.130	0.353	0.18	0.89	3.12	3.06	0.94	2.92
R3	0.213	0.155	0.69	0.25	4.73	3.30	0.07	0.35
R4	0.130	0.250	0.26	0.83	3.20	3.08	0.62	1.99
R5	0.136	0.432	0.16	0.91	3.10	3.05	0.72	2.22
R6	0.213	0.730	0.15	0.92	3.09	3.05	0.67	2.08
R7	0.130	0.250	0.26	0.83	3.20	3.08	0.45	1.44
R8	0.136	0.432	0.16	0.91	3.10	3.05	1.53	4.75
R9	0.213	0.375	0.28	0.81	3.23	3.09	0.15	0.47

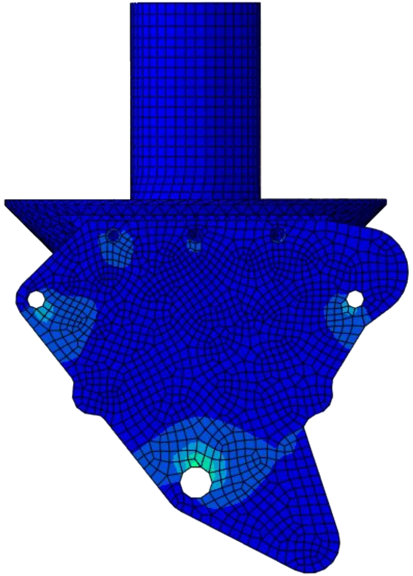
The most severe load case for the wheel assemblies is the *Perpendicular* load case. A detailed view of the nominal stress in the right side plate of the front wheel assembly is shown to the right. The table above uses values from this contour plot.

Max Expected Stress = 5.31 ksi
6061-T6 Yield Stress = 35.0 ksi
FoS 35.0 / 5.31 = 6.59 > 1.85

Front Wheel Assembly
Right Side Shown

Load Case: Perpendicular





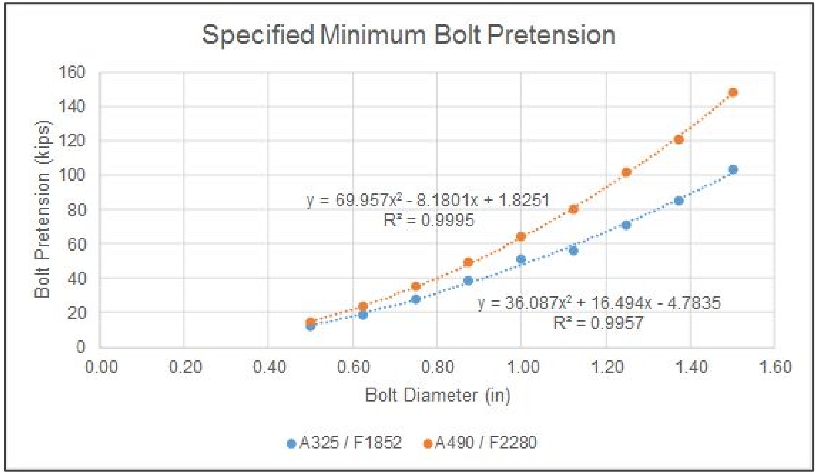
Units above are in psi
35 ksi / 1.85 = 18.9 ksi

Von Mises Stress Contour Plot

3. Vehicle Structural Analysis - Finite Element Model
Required Pretension for Bolted Structural Connections

Nominal Bolt Diameter	Specified Minimum Bolt Pretension, Tm (kips)	
	ASTM A325 and F1852	ASTM A490 and F2280
1/2	12	15
5/8	19	24
3/4	28	35
7/8	39	49
1	51	64
1 1/8	56	80
1 1/4	71	102
1 3/8	85	121
1 1/2	103	148

Table 7.1 Minimum Bolt Pretension for Pre-Installation Verification [6]



Interpolating to a Different Diamter Bolt

Diameter = 0.25 in	1.60 kips	4.15 kips
	A325 / F1852	A490 / F2280

To accurately analyze the bolted connections, preload values for the structural connections were required. Using Table 7.1 presented in the *Specification for Structural Joints Using High-Strength Bolts* from the Research Council on Structural Connections (RCSC), a quadratic fit was calculated using the documented values, and different bolt pretensions were determined. It is shown on the next page that the A325 / F1852 value is required for slip-critical joints, though the system is expected to operate safety in the event of bolt slipping.

3. Vehicle Structural Analysis - Finite Element Model

Bolted Joint Analysis: RCSC Calculations

RCSC Bolt Calculations for 1/4 - 20 Bolts

Name	Var	Val	Unit	Comment / Equation	Eqn #
Constants and Factors for Bolted Connection					
Required Tensile Strength	T_u	0.35	kips	Output From FEM Simulation	
Required Shear Strength	V_u	0.37	kips	Output From FEM Simulation	
Nominal Diameter of Bolt	d_b	0.25	in	Defined by CAD Geometry	
Clamped Material Thickness	t	0.19	in	Defined by CAD Geometry	
Hole Clearance Distance	L_c	0.06	in	Defined by CAD Geometry	
Resistance Factor	Φ	0.75		RCSC Specified, Except for Slip Critical	
Shear and Tension Check					
Nominal Strength per Unit Area	$F_{n\text{-}Ten}$	90	ksi	Values Referenced in Table 5.1	
Nominal Strength per Unit Area	$F_{n\text{-}Shear}$	54	ksi	Values Referenced in Table 5.1	
Bolt Cross-sectional Area	A_b	0.05	in^2	$= (\pi / 4) * d_b^2$	
Nominal Tensile Strength of Bolt	$R_{n\text{-}Ten}$	5.89	kip	$= F_{n\text{-}Ten} * A_b / \Phi$	(5.1)
Nominal Shear Strength of Bolt	$R_{n\text{-}Shear}$	3.53	kip	$= F_{n\text{-}Shear} * A_b / \Phi$	(5.1)
Resulting Tension Safety Factor	$X_{Tension}$	**16.7 > 1.67**		$= R_{n\text{-}Ten} / T_u$	
Resulting Shear Safety Factor	X_{Shear}	**9.6 > 1.67**		$= R_{n\text{-}Shear} / V_u$	

The required tensile and resultant shear strengths were extracted from the finite element model beam elements. For conservatism, it was assumed that the maximum shear and tensile forces acted on the same bolt. The equations and analysis procedure were referenced using Reference 6, and the resulting tension and shear safety factors are referenced using Reference 7.

RCSC Bolt Calculations for 1/4 - 20 Bolts (Continued)

Name	Var	Val	Unit	Comment / Equation	Eqn #
Combined Shear and Tension Check					
Design Strength in Tension	$(\Phi R_n)_t$	4.42	kip	$= R_{n\text{-}Ten} / Tu$	
Design Strength in Shear	$(\Phi R_n)_v$	2.65	kip	$= R_{n\text{-}Shear} / Vu$	
Limit-State of Bolt Configuration	L_{Comb}	0.03		$= [T_u / (\Phi R_n)_t]^2 + [V_u / (\Phi R_n)_v]^2$	(5.2)
Resulting Combination Margin	X_{Comb}	**38.9 > 1.67**		$= 1 / L_{Comb}$	
Bearing Strength Calculations					
Tensile Strength for 6061-T6	F_u	35.0	ksi	Yield Material in Bearing	
Capacity of Material (Lowest Factor)	R_{Cap}	3.28	kip	$= 2 * d_b * t * F_u$	(5.5)
Required Bolt Load (Highest Factor)	R_n	0.62	kip	$= 1.5 * L_c * t * F_u$	(5.4)
Resulting Combination Margin	$X_{Bearing}$	**5.3 > 1.85**		$= R_{Cap} / R_n$	
Slip Critical Connection					
Resistance Factor for Slip Critical	Φ	0.85		Specified RCSC Section 5.4.1	
Mean Slip Coefficient	μ	0.33		Assume Lowest Slip Coefficient	
Pretention Multiplier	D_u	1.0		Assume Bolt Pretentioned to Minimum	
Number of Bolts in Joint	N_b	1		Assume Load on One Bolt	
Specified Minimum Pretention	T_m	1.60	kip	Interpolated From Table 7.1	
Nominal Slip Resistance of Plane	R_n	0.41	kip	$= \mu * D_u * T_m * N_b [1 - T_u / (D_u T_m N_b)]$	(5.6)
Resulting Slip Critical Margin	X_{Slip}	**1.1 > 1.0**		$= R_n / V_u$	

Equations and Analysis Procedure Correspond to RCSC 2009 [6]

Load Case: ***150deg Configuration***

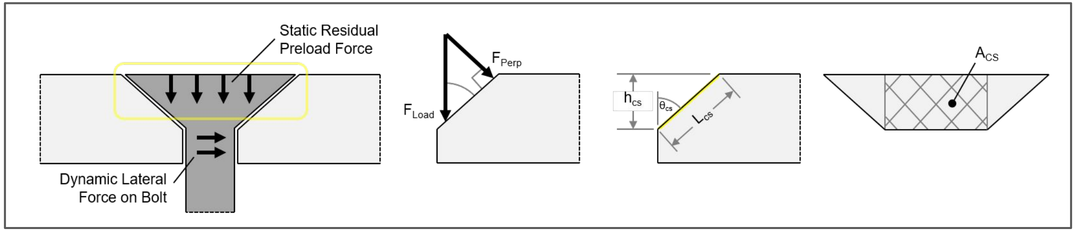
3. Vehicle Structural Analysis - Supporting Calculations

Countersunk Bolted Connections on Chassis Gusset Plates

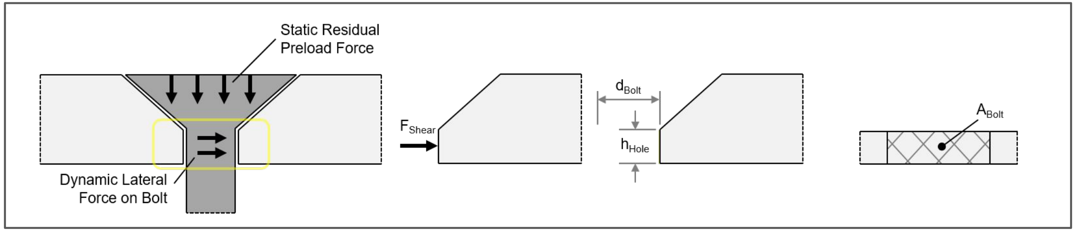
Countersink Preload and Dynamic Bolt Loading

Name	Var	Val	Unit	Comment / Equation
Material Specifications and System Geometry				
Bearing Strength 6061-T6	$\sigma_{Bearing}$	50000	psi	Referenced in MMPDS
Angle of Countersink	θ_{CS}	100	deg	Given
Gusset Plate Thickness	t_{Gusset}	0.188	in	Specified in CAD
Height of Countersink	h_{CS}	0.095	in	Specified by Countersink
Inner Diameter of Countersink	d_{Bolt}	0.25	in	1/4-20 Bolt Diameter
Preload Derivation and Dynamic Loading				
Preload Applied to Joint	F_{Load}	1600	lbs	Assumed Preload Applied
Angle of Taper (1/2 Side)	$\theta_{Working}$	0.873	rad	$= (\pi/180) * (\theta_{CS}/2)$
Perpendicular Force	F_{Perp}	1226	lbs	$= F_{Load} * \mathrm{SIN}(\theta_{Working})$
Max Shear Force on Bolt	F_{Shear}	369	lbs	Output From FEM
Projected Area Derivation				
Height of Through Hole	h_{Hole}	0.092	in	$= t_{Gusset} - h_{CS}$
Countersink Taper Length	L_{CS}	0.148	in	$= h_{CS} / \mathrm{COS}(\theta_{Working})$
Projected Countersink Area	A_{CS}	0.116	in^2	$= \pi * L_{CS} * d_{CS}$
Projected Bolt Shank Area	A_{Bolt}	0.023	in^2	$= h_{Hole} * d_{CS}$
Expected Stresses - Preload and Dynamic				
Preload Bearing Stress	$\sigma_{PreLoad}$	10533	psi	$= F_{Perp} / A_{CS}$
Dynamic Bearing Stress	$\sigma_{Dynamic}$	16002	psi	$= F_{Shear} / A_{Bolt}$
Expected Total Bearing Stress	σ_{Expect}	26535	psi	$= \sigma_{PreLoad} + \sigma_{Dynamic}$
Bearing Strength Safety Factor:		**1.88 > 1.85**	**OK**	

Preload Residual Stresses



Dynamic Bearing Stresses



The total stress in the countersink connection is the superposition of residual stresses due to preload and the dynamic stresses due to loading. It is conservative to add the stresses together. The shear and preload values are referenced on previous pages.

4. Vehicle Mechanical Analysis

Supporting Calculations

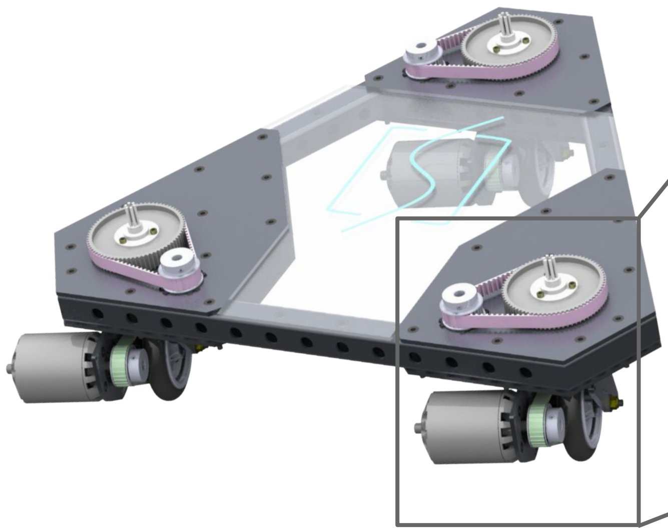
4. Vehicle Mechanical Analysis
Safety Factor Summary by Component

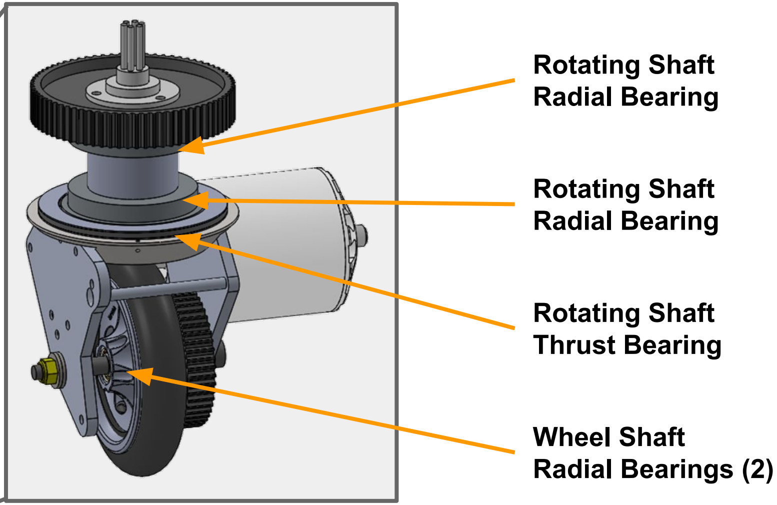
The expected stresses and resulting safety factors for the mechanical components are listed below. For the mechanical components, either stresses or forces were analyzed and were then compared to documented allowables. The resulting safety factor is calculated below and compared to the required safety factor. If the component is a consumer off the shelf (COTS) part, the required safety factor is 1.0. The cutsheets for the COTS parts can be found in the appendix.

Component	Specification	Allowable	Expected	Expect SF		Required SF
Radial Bearing Yaw Shaft	Force Margin	2.63 kip	1.5 kip	**1.78**	>	**1.00**
Thrust Bearing Yaw Shaft	Force Margin	11.6 kip	0.6 kip	**19.3**	>	**1.00**
Radial Bearing Wheel Shaft	Force Margin	405 lbs	300 lbs	**1.35**	>	**1.00**
Timing Belt	Force Margin	750 lbs	587 lbs	**1.28**	>	**1.00**
Wheel Shaft Shoulder Bolt	Axial Stress	160 ksi	102 ksi	**1.57**	>	**1.00**
	Shear Stress	160 ksi	6.0 ksi	**26.8**	>	**1.00**
	Bearing Stress	54 ksi	7.4 ksi	**7.33**	>	**1.85**
Motor Bolts	Shear Stress	500 MPa	17.9 MPa	**27.9**	>	**1.00**
	Bearing Stress	372 MPa	47.9 MPa	**7.78**	>	**1.85**

4. Vehicle Mechanical Analysis

Vehicle Bearings - Design





View Rotated for Clarity

Each wheel assembly includes two radial bearings on the rotating yaw shaft as well as a thrust bearing. Additionally, each assembly includes two radial bearings pressed into the wheel hub and another radial bearing pressed into the timing belt pulley (enveloped in the following calculations).

4. Vehicle Mechanical Analysis

Vehicle Bearings - Force Margins

Force Margin for Bearings

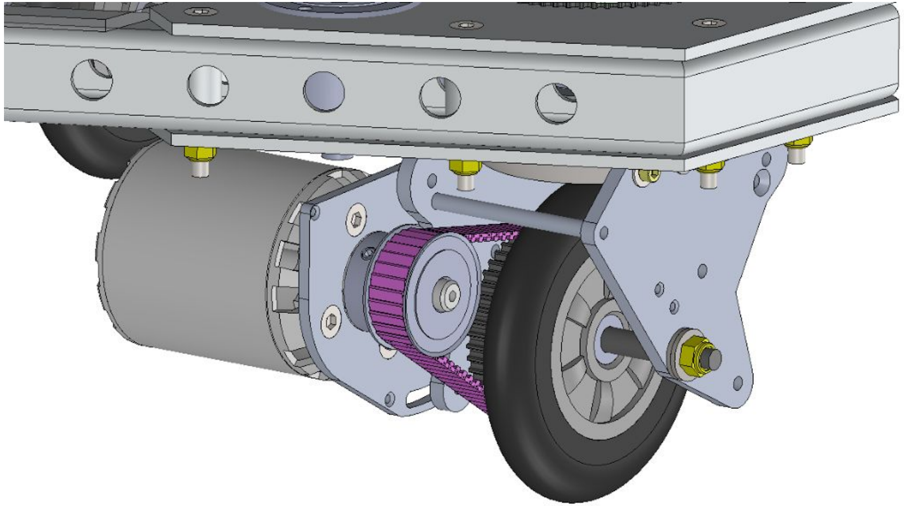
Name	Var	Val	Unit	Comment / Equation
Rotating Yaw Shaft - Radial Bearing				
Max Expected Load on Bearing	P_{Expect}	1.48	kip	Reaction Force on Lower Bearing
Allowable Load on Bearing (KN)	P_{Allow}	11.7	KN	VXB F6910ZZ | Static Load
Allowable Load on Bearing (lbs)	P_{Allow}	2.63	kip	Conversion to Imperial Units
Resulting Force Margin	X_{Thrust}	**1.78**		$= P_{Allow} / P_{Expect}$
Rotating Yaw Shaft - Thrust Bearings				
Maximum Patron Load	W_{Patron}	300	lbs	Max Patron Allowable
Abuse Loading Factor	f_{Abuse}	2.0		Conservative Impact Factor
Max Expected Load on Bearing	P_{Expect}	0.60	kip	$= W_{Patron} * f_{Abuse} / 1000$
Allowable Load on Bearing (KN)	P_{Allow}	51.6	KN	Koyo NRB NTA-5266 | Dynamic Load
Allowable Load on Bearing (lbs)	P_{Allow}	11.6	kip	Conversion to Imperial Units
Resulting Force Margin	X_{Thrust}	**19.3**		$= P_{Allow} / P_{Expect}$
Wheel Shaft - Radial Bearing				
Number of Bearings	$N_{Bearing}$	2		Bearings Pressed into Wheel Hub
Max Expected Load on Bearing	P_{Expect}	600	lbs	$= W_{Patron} * f_{Abuse}$
Allowable Load on Bearing (KN)	P_{Allow}	1800	N	AST 71900C | Static Load
Allowable Load on Bearing (lbs)	P_{Allow}	404.7	lbs	Conversion to Imperial Units
Resulting Force Margin	X_{Thrust}	**1.35**		$= P_{Allow} / (P_{Expect} / N_{Eearing})$

Using bearing cutsheets available online, the expected forces through the bearings were compared to the rated allowables. All bearing force margins were calculated considering a 300lb patron moving at the maximum acceleration, and in the most severe direction, in order to react the forces on one wheel assembly.

For the bearing reaction force calculation, please refer to the *Bending Stresses in Rotating Yaw Shaft* calculations. In all calculations show to the left, the expected forces, P-Expect, are compared against the allowable force, P-Allow.

4. Vehicle Mechanical Analysis

Timing Belt Pulley - Design



Single Wheel Assembly
Shown for Clarity

An L-Series timing belt is proposed for the propulsion system (shown in purple). The belt will be tensioned by rotating the motor mount plate away from the wheel. The wheel pulley is attached to the wheel through six bolts to transfer the torque. By using the maximum expected load on the wheel as well as the maximum acceleration, the load through the timing belt could be calculated.

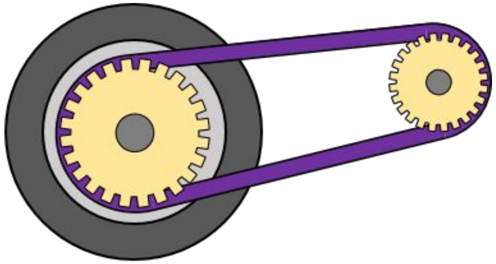
4. Vehicle Mechanical Analysis

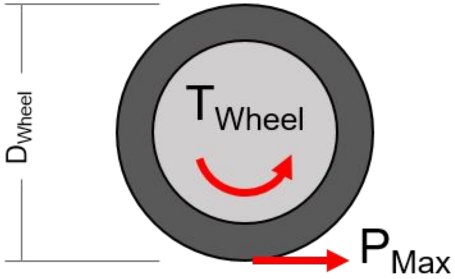
Timing Belt Pulley - Force Margin

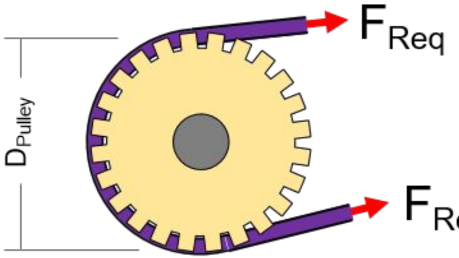
Force Margin for Timing Belt Pulley

Name	Var	Val	Unit	Comment / Equation
System Geometry and Belt Specifications				
Maximum Force on Wheel	P_{Max}	362.5	lbs	Weight of System and Patron
Diameter of Wheel	D_{Wheel}	5.0	in	5in Pneumatic Wheel
Diameter of Pulley (mm)	D_{Pulley}	78.4	mm	SDP-SI Pulley Listed Below
Diameter of Pulley (inch)		3.1	in	Convert to Inch Measurement
Belt Breaking Strength (per Width)	F_{Break}	125	lbs/(1/8")	SDP-SI L Timing Belts
Width of Timing Belt	W_{Belt}	0.75	in	SDP-SI L Timing Belts
Resulting Calculations for Timing Belt				
Total Breaking Strength on Belt	F_{Belt}	750.0	lbs	$= F_{Break} * (W_{Belt} / 0.125)$
Effective Torque on Pulley	T_{Wheel}	906.3	in-lbs	$= P_{Max} * (D_{Wheel} / 2)$
Force Required by Belt	F_{Req}	587.2	lbs	$= T_{Wheel} / (D_{Pulley} / 2)$
Resulting Force Margin	X_{Force}	**1.28**		$= F_{Belt} / F_{Req}$

Using the total weight of the system (300lb patron and 62.5lb vehicle), a conservative force margin in the timing belt was calculated. Since it is assumed that the total weight is on one pulley assembly, the narrow force margin listed to the left is acceptable.

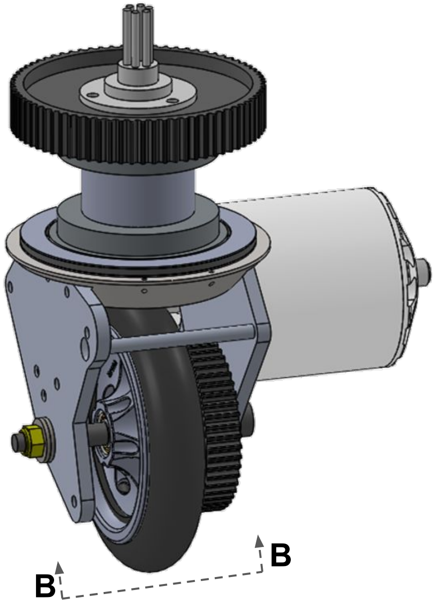


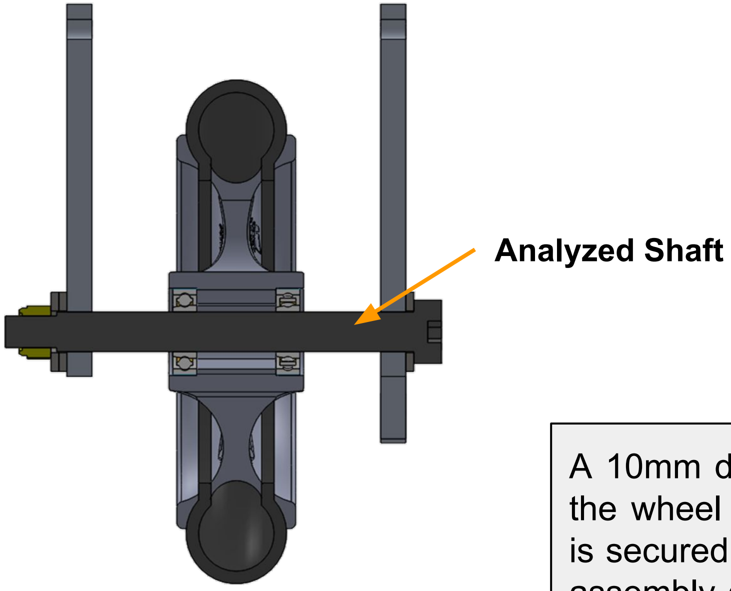




4. Vehicle Mechanical Analysis

Wheel Shaft - Design



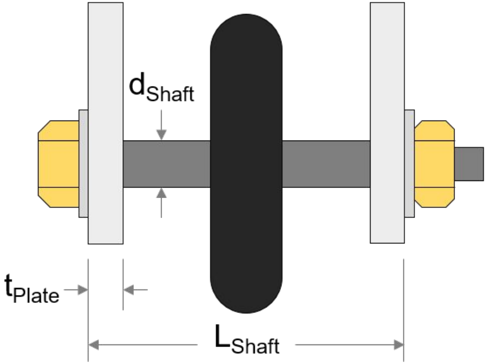


Section B-B
Extra Components
Removed for Clarity

A 10mm diameter shoulder bolt supports the wheel and pulley assembly. The bolt is secured to the side plates of the wheel assembly and load is transferred through the bearings.

4. Vehicle Mechanical Analysis

Wheel Shaft - Calculations

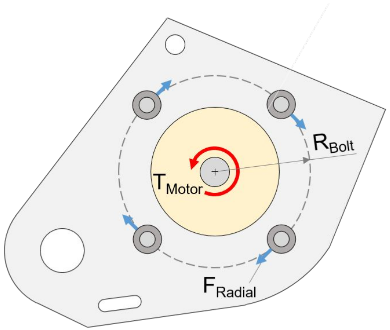


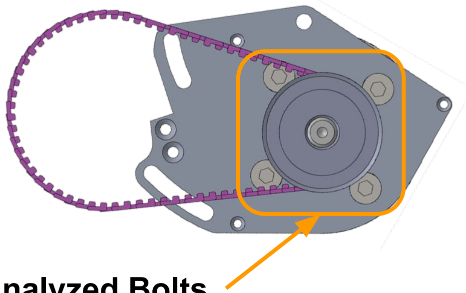
Using the total weight of the system (300lb patron and 62.5lb vehicle) and an impact / abuse factor, conservative strength safety factors for the wheel shaft were calculated. Considering the bending and shear of the shaft as well as the bearing loads in the plate, the calculated margins are acceptable and the design is sufficient for the expected loads.

Wheel Shaft Strength Calculations

Name	Var	Val	Unit	Comment / Equation
System Geometry and System Loading				
Shaft Diameter (mm)	d_{Shaft}	10	mm	10mm Shoulder Bolt Diameter
Shaft Diameter (in)	d_{Shaft}	0.39	in	Conversion to Imperial Units
Unsupported Length	L_{Shaft}	3.4	in	Unsupported Length of Bolt
Thickness of Plate Support	t_{Plate}	0.25	in	Side Plate Thickness
Total Weight of System	W	363	lbs	Weight of System and Patron
Abuse Loading Factor	f_{Abuse}	2.0		Conservative Impact Factor
Aluminum and Bolt Allowables				
Aluminum 6061-T6 Yield Strength	$\sigma_{Alum\text{-}Y}$	35.0	ksi	Referenced in MMPDS
Aluminum 6061-T6 Bearing Strength	$\sigma_{Alum\text{-}B}$	54.0	ksi	Referenced in MMPDS
Class 12.9 Min Yield Strength (MPa)	$\sigma_{Bolt\text{-}Y}$	1100	MPa	Class 12.9 Allowable
Class 12.9 Min Yield Strength (ksi)	$\sigma_{Bolt\text{-}Y}$	160	ksi	Conversion to Imperial Units
Bending Stress in Bolt				
Shaft Moment of Inertia	I_{Shaft}	0.001	in^4	$= (\pi / 64) * d_{Shaft}^4$
Max Expected Load on Bearing	P_{Expect}	725	lbs	$= W * f_{Abuse}$
Max Bending Moment in Shaft	M_{Max}	610	in-lbs	$= P_{Expect} * L_{Shaft} / 4$ | Simply Support
Bending Stress in Shaft	σ_{Bend}	102	ksi	$= M_{Max} * (d_{Shaft} / 2) / (I_{Shaft} * 1000)$
Resulting Factor of Safety	**FoS**	**1.57**		$= \sigma_{Yield} / \sigma_{Bend}$
Shear and Bearing Stresses				
10mm Bolt Shear Area	A_{Shear}	0.122	in^2	$= (\pi / 4) * d_{Shaft}^2$
Shear Stress in Bolt	σ_{Shear}	5.96	ksi	$= P_{Expect} / (A_{Shear} * 1000)$
Resulting Shear Safety Factor	X_{Shear}	**26.8**		$= \sigma_{Shear} / \sigma_{Bolt\text{-}Y}$
Plate Bearing Area	$A_{Bearing}$	0.098	in^2	$= d_{Shaft} * t_{Plate}$
Bearing Stress in Plate	$\sigma_{Bearing}$	7.37	ksi	$= P_{Expect} / (A_{Bearing} * 1000)$
Max Bending Moment in Shaft	$X_{Bearing}$	**7.33**		$= \sigma_{Bearing} / \sigma_{Alum\text{-}B}$

4. Vehicle Mechanical Analysis
Motor Bolts Strength Calculations





Analyzed Bolts

The torque required from the motor will be reacted by the bolts mounted to the motor plate. Assuming the torque is reacted equally to all bolts in the bolt pattern, the resultant load per bolt can be calculated. The shear stress in the bolt and the bearing stress in the plate were analyzed and compared to allowables.

Motor Bolts Strength Calculations

Name	Var	Val	Unit	Comment / Equation
System Geometry and Allowable Strengths				
Motor Bolt Diamter	d_{Bolt}	6	mm	Bolts Used to Mount Motor
Bolt Pattern Radius	R_{Bolt}	28	mm	Center to Center Distance
Engaged Length of Bolt	L_{Bolt}	1.8	mm	Thickness After Countersink
Diameter of Motor Pulley	D_{Pulley}	43.4	mm	SDP-SI Timing Belt Pulley
DIN 965 Bolt Tensile Strength	$\sigma_{Bolt\text{-}T}$	500	MPa	Referenced Bolted Allowable
6061-T6 Bearing Strength (ksi)	$\sigma_{Alum\text{-}B}$	54	ksi	Referenced in MMPDS
6061-T6 Bearing Strength (MPa)		372	MPa	Conversion to Metric Units
Effective Forces on Motor Bolts				
Force Through Belt (lbs)	F_{Req}	587	lbs	Weight of System and Patron
Force Through Belt (N)		2612	N	Conversion to Metric Units
Expected Torque on Motor	T_{Motor}	56,695	N-mm	$= F_{Req} * (D_{Pulley} / 2)$
Radial Loads on Bolts	F_{Radial}	2025	N	$= T_{Motor} / R_{Bolt}$
Resulting Safety Factors for Bolts and Aluminum				
Shear Area on Single Bolt	A_{shear}	28.3	mm^2	$= (\pi / 4) * d_{Bolt}^2$
Shear Stress in Bolt	σ_{Shear}	17.9	MPa	$= (F_{Radial} / 4) / A_{Shear}$
Resulting Shear Safety Factor	X_{Shear}	**27.9**		$= \sigma_{Bolt\text{-}T} / \sigma_{Shear}$
Bearing Area on Single Bolt	$A_{Bearing}$	10.6	mm^2	$= d_{Bolt} * L_{Bolt}$
Bearing Stress in Plate	$\sigma_{Bearing}$	47.9	MPa	$= (F_{Radial} / 4) / A_{Bearing}$
Resulting Bearing Safety Factor	$X_{Bearing}$	**7.78**		$= \sigma_{Alum\text{-}B} / \sigma_{Bearing}$

5. References

5. References
Publications Used for Analysis

[1] ASTM International F2291-17 "*Standard Practice for Design of Amusement Rides and Devices*" 2017.

[2] D.O.T, *"Metallic Materials Properties Development and Standardization"*. January, 2003.

[3] J. Randolph Kissell. "*Aluminum Structures: A Guide to Their Specifications and Design*" 2002.

[4] John Wiley and Sons. "*The Measures of Man and Woman Revised Edition"*. Human Factors in Design. 2002.

[5] Walter D. Pilkey, "*Peterson's Stress Concentration Factors, Third Edition*" 2008.

[6] Research Council on Structural Connections "*Specification for Structural Joints Using High-Strength Bolts*" 2014.

[7] American Institute of Steel Construction 360-16 "*Specification for Structural Steel Buildings*" 2016.

6. Appendix

Specific References, COTS Cutsheets

6. Appendix: 6061-T6 Material Properties

Metallic Materials Properties Development and Standardization (2003)

Table 3.6.2.0(b$_2$). Design Mechanical and Physical Properties of 6061 Aluminum Alloy Plate

Specification	AMS 4026 and AMS-QQ-A-250/11				AMS-QQ-A-250/11		AMS 4025, AMS 4027 and AMS-QQ-A-250/11					
Form	Plate											
Temper	T451				T42[a]		T651 and T62[b]					
Thickness, in.	0.250-2.000		2.001-3.000		0.250-1.000	1.001-3.000	0.250-2.000		2.001-3.000		3.001-4.000	4.001-6.000[c]
Basis	A	B	A	B	S	S	A	B	A	B	S	S
Mechanical Properties:												
F_{tu}, ksi:												
L	...	...	...	...	...	...	42	43	...	...	...	...
LT	30	32	30	32	30	30	42	43	42	43	42	40
F_{ty}, ksi:												
L	...	...	...	...	...	...	36	38	...	...	...	...
LT	16	18	16	18	14	14	35	37	35	37	35	35
F_{cy}, ksi:												
L	...	...	...	...	...	...	35	37	...	...	...	...
LT	16	18	...	...	...	...	36	38	...	...	...	...
F_{su}, ksi	20	21	...	...	...	...	27	28	...	...	...	...
F_{bru}, ksi:												
(e/D = 1.5)	48	52	...	...	...	...	67	69	...	...	...	...
(e/D = 2.0)	63	67	...	...	...	...	88	90	...	...	...	...
F_{bry}, ksi:												
(e/D = 1.5)	22	25	...	...	...	...	50	53	...	...	...	...
(e/D = 2.0)	26	29	...	...	...	...	58	61	...	...	...	...
e, percent:												
L	[d]	...	16	...	18	16	[d]	...	6	...	6	6
E, 10^3 ksi	9.9											
E_c, 10^3 ksi	10.1											
G, 10^3 ksi	3.8											
μ	0.33											
Physical Properties:												
ω, lb/in.^{3}	0.098											
C, K, and α	See Figure 3.6.2.0											

a Design allowables were based upon data obtained from testing samples of material, supplied in the O temper, which were heat treated to demonstrate response to heat treatment by suppliers. Properties obtained by the user may be lower than those listed if the material has been formed or otherwise cold or hot worked, particularly in the annealed temper, prior to solution heat treatment.
b Design allowables were based upon data obtained from testing T651 plate and from testing samples of plate, supplied in the O temper, which were heat treated to demonstrate response to heat treatment by suppliers. Properties obtained may be lower than those listed if the material has been formed or otherwise cold worked, particularly in the annealed temper, prior to solution heat treatment.
c Properties for this thickness apply only to T651 temper.
d See Table 3.6.2.0(b$_3$).

6061-T6 Plate

Tensile Ultimate Strength

Tensile Yield Strength

Shear Ultimate Strength

Bearing Yield Strength

Mechanical Properties

6. Appendix: 1025 Steel Material Properties

Metallic Materials Properties Development and Standardization (2003)

Table 2.2.1.0(b). Design Mechanical and Physical Properties of AISI 1025 Carbon Steel

Specification	AMS 5046 and AMS-S-7952	AMS 5075, AMS 5077 and AMS-T-5066[a]	ASTM A 108
Form	Sheet, strip, and plate	Tubing	Bar
Condition	Annealed	Normalized	All
Thickness, in.	...	...	...
Basis	S	S	S[b]
Mechanical Properties:			
F_{tu}, ksi:			
L	55	55	55
LT	55	55	55
ST	...	...	55
F_{ty}, ksi:			
L	36	36	36
LT	36	36	36
ST	...	...	36
F_{cy}, ksi:			
L	36	36	36
LT	36	36	36
ST	...	...	36
F_{su}, ksi	35	35	35
F_{bru}, ksi:			
(e/D = 1.5)	...	...	...
(e/D = 2.0)	90	90	90
F_{bry}, ksi:			
(e/D = 1.5)	...	...	...
(e/D = 2.0)	...	...	...
e, percent:			
L	...	c	c
LT	c	...	...
E, 10^3 ksi		29.0	
E_c, 10^3 ksi		29.0	
G, 10^3 ksi		11.0	
μ		0.32	
Physical Properties:			
ω, lb/in.^{3}		0.284	
C, Btu/(lb)(°F)		0.116 (122 to 212°F)	
K, Btu/[(hr)(ft^2)(°F)/ft]		30.0 (at 32°F)	
α, 10^{-6} in./in./°F		See Figure 2.2.1.0	

a Noncurrent specification.
b Design values are applicable only to parts for which the indicated F_{tu} has been substantiated by adequate quality control testing.
c See applicable specification for variation in minimum elongation with ultimate strength.

Plain Carbon Steel

Tensile Ultimate Strength

Tensile Yield Strength

Shear Ultimate Strength

Mechanical Properties

6. Appendix: 6061-T6 Welded Allowables

Aluminum Structures: A Guide to Their Specifications and Design

Minimum Mechanical Properties of Aluminum Alloys (Welded) (U.S. Units)

Alloy	Temper	Product	Thickness Range from (in.)	Thickness Range to (in.)	Tension F_{tu} (ksi)	Tension F_{ty} (ksi)	Compression F_{cy} (ksi)	Shear F_{su} (ksi)
1100	H12, H14	All			11	3.5	3.5	8
3003	H12, H14, H16, H18	All			14	5	5	10
Alclad 3003	H12, H14, H16, H18	All			13	4.5	4.5	10
3004	H32, H34, H36, H38	All			22	8.5	8.5	14
Alclad 3004	H32, H34, H36, H38	All			21	8	8	13
3005	H25	Sheet			17	6.5	6.5	12
5005	H12, H14, H32, H34	All			15	5	5	9
5050	H32, H34	All			18	6	6	12
5052	H32, H34, O	All			25	9.5	9.5	16
5083	H111, O	Extrusions			39	16	15	23
5083	H116, H321, O	Sheet and Plate	0.188	1.500	40	18	18	24
5083	H116, H321, O	Plate	1.501	3.000	39	17	17	24
5086	H111, O	Extrusions			35	14	13	21
5086	H112, H32, H34, H116, O	Sheet and Plate			35	14	14	21
5154	H38	Sheet			30	11	11	19
5454	H111, O	Extrusions			31	12	11	19
5454	H112	Extrusions			31	12	12	19
5454	H32, H34, O	Sheet and Plate			31	12	12	19
5456	H116, H321, O	Sheet and Plate	0.188	1.500	42	19	18	25
5456	H116, H321, O	Plate	1.501	3.000	41	18	17	25
6005	T5	Extrusions		0.250	24	13	13	15
6061	T6, T651, T6510, T6511(2)	All			24	15	15	15
6061	T6, T651, T6510, T6511(3)	All	0.375		24	11	11	15
6063	T5, T52, T6	All			17	8	8	11
6351	T5, T6(2)	Extrusions			24	15	15	15
6351	T5, T6(3)	Extrusions	0.375		24	11	11	15
6463	T6	Extrusions	0.125	0.500	17	8	8	11
7005	T53	Extrusions		0.750	40	24	24	22

Notes

(1) Yield strengths ared based on a 2 in. gauge length.
(2) Values when welded with 5183, 5356, or 5556 filler, regardless of thickness, and to thicknesses ≤ 0.375 in. when welded with 4043, 5554, or 5654 filler.
(3) Values when welded with 4043, 5554, or 5654 filler.

6. Appendix: Cutsheets

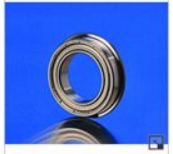
Bearings for Yaw Shaft and Wheels / Pulley Mechanisms

All Categories > Extra Thin Metric Series Bearings > Flanged Shielded Extra Thin Metric Ball Bearings > Item # F6910ZZ

Item # F6910ZZ, 1.9685 Inch (in) Bore Diameter (d) Flanged Shielded Extra Thin Metric Ball Bearing

Request Information

Printable Page | Email This Page



All bearings are available in 52100 Chrome Steel or 440 Stainless Steel.
Bearings also available with single shield or seal : suffix Z, RS, RU.

Specifications | Ball Complement

Specifications

Bearing Type	Extra Thin Metric Bearing
Bore Diameter (d)	50 mm 1.9685 in
Outer Diameter (D)	72 mm 2.8346 in
Flange Diameter (D_f)	75.0 mm 2.9528 in
Min. Radius (r_s)	0.60 mm 0.0236 in
Width (B)	12.0 mm 0.4724 in
Flange Width (B_f)	2.5 mm 0.0984 in
Load Rating (Cr)	14540 N
Load Rating (Cor)	11710 N

AST Bearings and Related Products & Services

US TOLL FREE 888-906-2320

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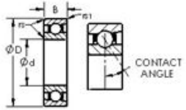
Home » Bearings Catalog » Ball Bearings » Angular Contact Ball Bearings » 71900C

71900C Angular Contact Ball Bearing

Model: **71900C**



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View Spec Sheet

1. 15 degree contact angle, relieved outer ring
2. Also available with metal shields (ZZ) or rubber seals (2RS)
3. The desired preload must be specified.

Product Details

Specifications		
Bearing Type	15 deg contact angle	
Bore Dia (d)	10.000	mm
Outer Dia (D)	22.000	mm
Width (B)	6.000	mm
Radius (min) (rs)	0.30	mm
Dynamic Load Rating (Cr)	2,900	N
Static Load Rating (Cor)	1,800	N
Max Speed (Grease)	70,000	rpm
Max Speed (Oil)	110,000	rpm

Documentation
General
Nomenclature
Material
Cages and Retainers
Tolerances and Precision
Lubrication
Fitting and Mounting
Load and Life Calculation Information
eDrawings file (.ePRT, eASM)

6. Appendix: Cutsheets

Bearings for Yaw Shaft Axial Loading

Promotions Locations About Mi Services Support

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Home > Bearings > Roller Bearings > Roller Thrust Bearings > Needle Roller Thrust Bearings > NTA-5266

Koyo

Koyo NRB NTA-5266

Needle Roller Thrust Bearing - 3-1/4 in Bore, 4-1/8 in OD, 1/8 in Width

Mi Item #: 00094529

0 Reviews - Be the first to review this item.

$36.99 each

IN STOCK

Quantity QTY

Add to Cart

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Please Note: Photo may not represent actual item, please refer to title and product specifications for all details.

Product Content Feedback

Specifications

Bore diameter:	3-1/4 in	**Dynamic load capacity:**	51.6 kN
Outside diameter:	4-1/8 in	**Cage material:**	Steel
Bearing width:	1/8 in	**Maximum rpm:**	4000 RPM
Thrust bearing type:	Roller & Cage Assembly	**Compatible washer:**	TRA-5266
Bearing material:	Steel	**Series:**	NTA
Static load capacity:	294.9 kN		

6. Appendix: Cutsheets

Timing Belt Pulley

L TIMING BELTS • 3/8" OR 9.525 mm PITCH SDP/SI

PHONE: 516.328.3300 • FAX: 516.326.8827 • WWW.SDP-SI.COM

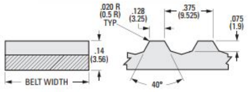
BELT WIDTHS
INCH - 1/2, 3/4 & 1 in.
METRIC - 12.5, 19 & 25.4 mm

MATERIAL:
Nylon Covered, Fiberglass Reinforced, Neoprene

SPECIFICATIONS:
Breaking Strength:
125 lbf per 1/8 in. (175 N per 1 mm) Belt Width; not representative of the load-carrying capacity of the belt.
Temperature Range:
-30°F to +185°F (-34°C to +85°C)

MODIFICATIONS:
Special Widths - cut to size from sleeves available from stock.

Pulleys are available with inch or metric standards.



NOTE: Dimensions in ( ) are mm.

INCH COMPONENT CATALOG NUMBER

A 6R 4- □□□ □□□

No. of Grooves Code

Belt Width Inch	Width Code
1/2	050
3/4	075
1	100

METRIC COMPONENT CATALOG NUMBER

A 6R 4M □□□ □□□

No. of Grooves Code

Belt Width mm	Width Code
12.5	125
19	190
25.4	254

Groove Code	Pitch Length Inch	Pitch Length mm
026	9.750	247.65
029	10.875	276.23
033	12.375	314.33
035	13.125	333.38
036	13.500	342.9
038	14.250	361.95
040	15.000	381
041	15.375	390.53
042	15.750	400.05
044	16.500	419.1
045	16.875	428.63
046	17.250	438.15
047	17.625	447.68
050	18.750	476.25
052	19.500	495.3
053	19.875	504.83
054	20.250	514.35
055	20.625	523.88
056	21.000	533.4
058	21.750	552.45
060	22.500	571.5
062	23.250	590.55
063	23.625	600.08
064	24.000	609.6
065	24.375	619.13
066	24.750	628.65
067	25.125	638.18
068	25.500	647.7
069	25.875	657.23
070	26.250	666.75
072	27.000	685.8
074	27.750	704.85
076	28.500	723.9
080	30.000	762
081	30.375	771.53
082	30.750	781.05
084	31.500	800.1
085	31.875	809.63
086	32.250	819.15
089	33.375	847.73
090	33.750	857.25
092	34.500	876.3
094	35.250	895.35
096	36.000	914.4
098	36.750	933.45
100	37.500	952.5
104	39.000	990.6
105	39.375	1000.13
108	40.500	1028.7
112	42.000	1066.8
114	42.750	1085.85
116	43.500	1104.9
117	43.875	1114.43
119	44.625	1133.48
120	45.000	1143
123	46.125	1171.58

Continued on the next page

L TIMING BELTS • 3/8" OR 9.525 mm PITCH SDP/SI

PHONE: 516.328.3300 • FAX: 516.326.8827 • WWW.SDP-SI.COM

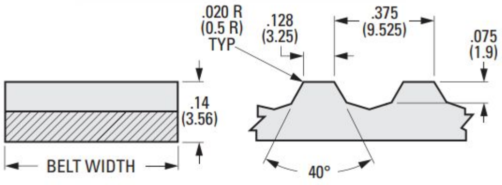
BELT WIDTHS
INCH - 1/2, 3/4 & 1 in.
METRIC - 12.5, 19 & 25.4 mm

MATERIAL:
Nylon Covered, Fiberglass Reinforced, Neoprene

SPECIFICATIONS:
Breaking Strength:
125 lbf per 1/8 in. (175 N per 1 mm) Belt Width; not representative of the load-carrying capacity of the belt.
Temperature Range:
-30°F to +185°F (-34°C to +85°C)

MODIFICATIONS:
Special Widths - cut to size from sleeves available from stock.

Pulleys are available with inch or metric standards.



NOTE: Dimensions in ( ) are mm.

6. Appendix: Cutsheets

Pulley - Attached to Motor

GT®2 / GT®3 TIMING BELT PULLEYS • 5 mm PITCH SDP/SI

PHONE: 516.328.3300 • FAX: 516.326.8827 • WWW.SDP-SI.COM

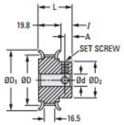
FOR 15 mm BELTS
FOR USE WITH GT®2 and GT®3 BELTS
DOUBLE FLANGE
TRUE METRIC® PROFILE

› MATERIAL:
Aluminum Alloy

› FINISH:
Clear Anodized

› SPECIFICATIONS:
D Tolerance: 12 to 16 grooves is +0.05/0
17 to 32 grooves is +0.08/0
34 grooves is +0.10/0

Pulleys with 12 and 13 grooves have 1 set screw; others have 2 set screws at 90°



I R T 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16

METRIC COMPONENT

Catalog Number	No. of Grooves	P.D.	D Dia.	D_1 Dia. ± 0.4	d Bore +0.025 0	L Length ± 0.4	D_2 Hub Dia. ± 0.4	l Hub Proj.	A	Set Screw
A 6A55M012DF1506	12	19.1	17.96	22.2	6	26.2	11.1	6.4	3.2	M3
A 6A55M013DF1506	13	20.7	19.56	23.8	6	26.2	12.7	6.4	3.2	M3
A 6A55M014DF1506	14	22.28	21.13	25.4	6	26.2	12.7	6.4	3.2	M3
A 6A55M015DF1506	15	23.88	22.73	27	6	26.2	14.2	6.4	3.2	M3
A 6A55M016DF1506	16	25.48	24.33	27.8	6	26.2	14.2	6.4	3.2	M3
A 6A55M017DF1506	17	27.05	25.91	30.2	6	26.2	15.9	6.4	3.2	M3
A 6A55M018DF1506	18	28.65	27.51	31.8	6	26.2	17.5	6.4	3.2	M3
A 6A55M019DF1506	19	30.25	29.11	33.3	6	26.2	19.1	6.4	3.2	M3
A 6A55M020DF1506	20	31.83	30.68	34.9	6	26.2	20.6	6.4	3.2	M3
A 6A55M022DF1506	22	35.03	33.88	38.1	6	26.2	23.8	6.4	4.8	M5
A 6A55M024DF1510	24	38.2	37.06	41.3	10	29.4	25.4	9.5	4.8	M5
A 6A55M025DF1510	25	39.78	38.63	42.9	10	29.4	25.4	9.5	4.8	M5
A 6A55M026DF1510	26	41.38	40.23	44.5	10	32.5	27	9.5	6.4	M6
A 6A55M028DF1512	28	44.55	43.41	47.6	12	32.5	30.2	12.7	6.4	M6
A 6A55M030DF1512	30	47.75	46.61	50.8	12	32.5	30.2	12.7	6.4	M6
A 6A55M032DF1512	32	50.93	49.78	54	12	32.5	31.8	12.7	6.4	M6
A 6A55M034DF1512	34	54.1	52.96	57.2	12	32.5	35	12.7	6.4	M6

REV: 02.20.15 JC

2-173

METRIC COMPONENT

Catalog Number	No. of Grooves	P.D.	D Dia.	D_1 Dia. ± 0.4	d Bore +0.025 0	L Length ± 0.4	D_2 Hub Dia. ± 0.4	l Hub Proj.	A	Set Screw
A 6A55M012DF1506	12	19.1	17.96	22.2	6	26.2	11.1	6.4	3.2	M3
A 6A55M013DF1506	13	20.7	19.56	23.8	6	26.2	12.7	6.4	3.2	M3
A 6A55M014DF1506	14	22.28	21.13	25.4	6	26.2	12.7	6.4	3.2	M3
A 6A55M015DF1506	15	23.88	22.73	27	6	26.2	14.2	6.4	3.2	M3
A 6A55M016DF1506	16	25.48	24.33	27.8	6	26.2	14.2	6.4	3.2	M3
A 6A55M017DF1506	17	27.05	25.91	30.2	6	26.2	15.9	6.4	3.2	M3
A 6A55M018DF1506	18	28.65	27.51	31.8	6	26.2	17.5	6.4	3.2	M3
A 6A55M019DF1506	19	30.25	29.11	33.3	6	26.2	19.1	6.4	3.2	M3
A 6A55M020DF1506	20	31.83	30.68	34.9	6	26.2	20.6	6.4	3.2	M3
A 6A55M022DF1506	22	35.03	33.88	38.1	6	26.2	23.8	6.4	4.8	M5
A 6A55M024DF1510	24	38.2	37.06	41.3	10	29.4	25.4	9.5	4.8	M5
A 6A55M025DF1510	25	39.78	38.63	42.9	10	29.4	25.4	9.5	4.8	M5
A 6A55M026DF1510	26	41.38	40.23	44.5	10	32.5	27	9.5	6.4	M6
A 6A55M028DF1512	28	44.55	43.41	47.6	12	32.5	30.2	12.7	6.4	M6
A 6A55M030DF1512	30	47.75	46.61	50.8	12	32.5	30.2	12.7	6.4	M6
A 6A55M032DF1512	32	50.93	49.78	54	12	32.5	31.8	12.7	6.4	M6
A 6A55M034DF1512	34	54.1	52.96	57.2	12	32.5	35	12.7	6.4	M6

Contact Us

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