NAU
NORTHERN
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UNIVERSITY

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Engineering 224

Project Description

Department of Mechanical Engineering

- NAU Baja SAE Capstone
- NAU Formula SAE Capstone
- Professor David Willy

Why?

- Yearly SAE collegiate competitions
- Ongoing need for mobile tools and equipment at competition
- Incremental increase from current wagon storage

Figures 1, 2, 3: Project Background

Black Box Model

Figure 4: Black Box Model [1]

Functional Decomposition

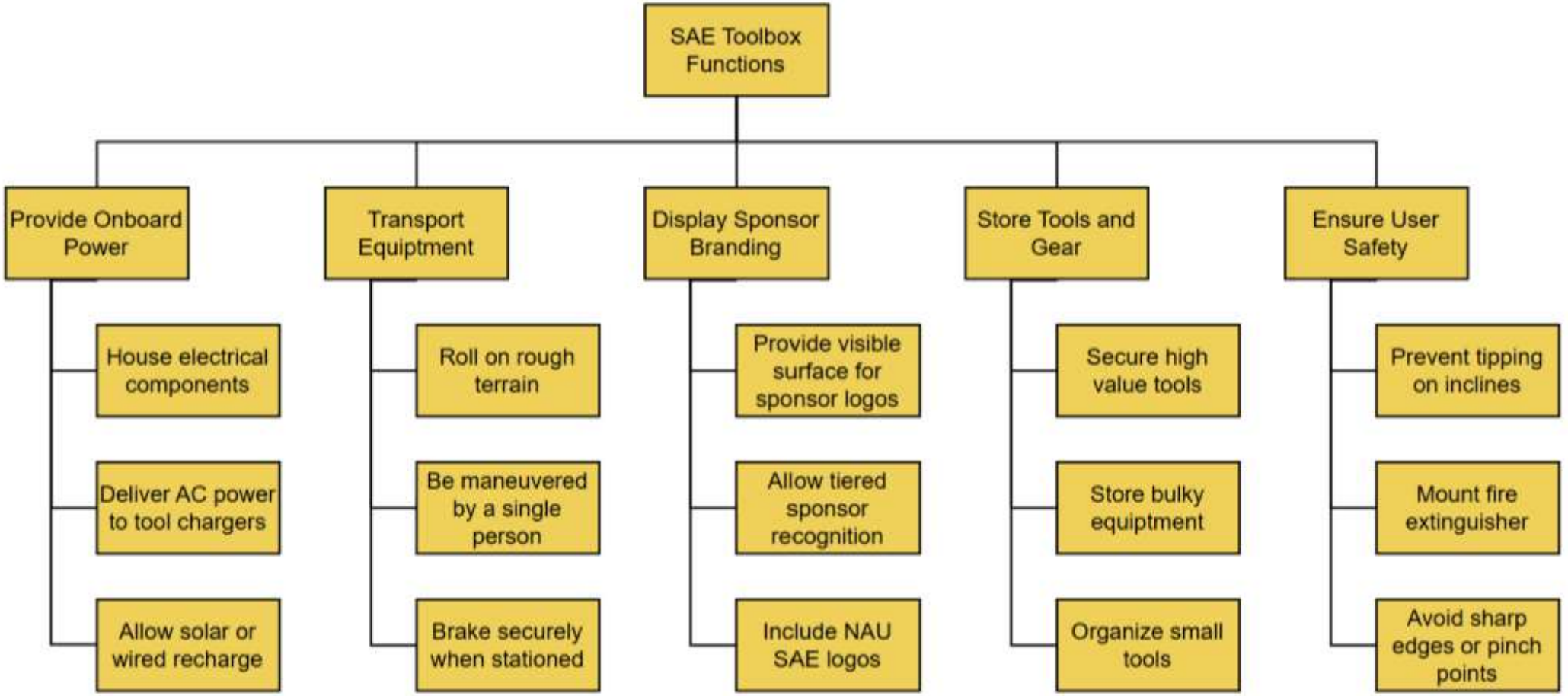


Figure 5: Toolbox Functional Decomposition Chart [2], [3]

Braking Force Calculations

Brake Force Equations: [4]

- $W = F * d$ (1)
- $E_k = \frac{1}{2}mv^2$ (2)
- $F_b = \frac{\frac{1}{2}mv^2}{d}$ (3)

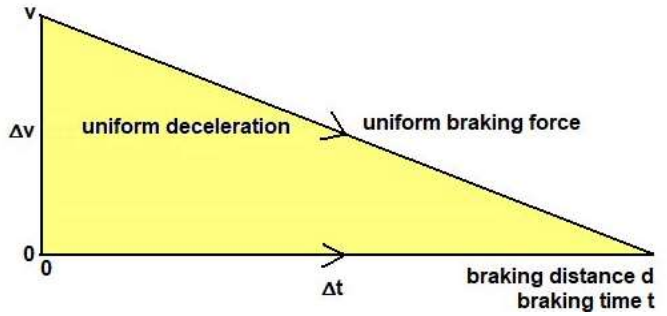


Figure 6: Braking Diagram

For braking force calculations, we will assume the load for the cart to be approximately 227 kg with a velocity of 1 m/s and a stopping distance of 3 m.

$$F_b = \frac{\frac{1}{2}(227kg)\left(2\frac{m}{s}\right)^2}{3m} = 151.33\ N\ \approx 34lbf\ (4)$$

Brake Design Calculations

Brake Rotor Torque $T = F * r$:

$$\alpha = \frac{(2\frac{m}{s})^2}{2(3m)} = 0.667\ m/s^2 \quad (5)$$

$$T_{rotor} = F_{brake} * r_{rotor} = 227\ kg * 0.667\frac{m}{s^2} * 0.1m = 15.14\ Nm \quad (6)$$

Brake Clamping Force F_n:

$$15.14\ Nm = 2 * 0.2276 * F_n * 0.1\ m \rightarrow F_n = 332.6\ N \approx 75\ lbf \quad (7)$$

Frame Sub Assembly Calculations

Variables: [5]

- **Material:** A36 Steel
- **Yield Strength (σ_y):** 36,000 psi
- **Modulus of Elasticity (E):** 29 × 10^6 psi
- **Cross-Section:** 1" × 1" square tubing, 0.125" wall thickness
- **Span (L):** 60 in
- **Load (F):** 500 lb. (representing toolbox + equipment weight)

1. Maximum Bending Moment: [6]

$$M = \frac{F*L}{4} = \frac{500*36}{4} = 7500\ in/lbf \quad (8)$$

2. Section Modulus (S): [7]

$$S = \frac{b^4-(b-2t)^4}{6b} = \frac{1^4-(0.75)^4}{6(1)} = 0.114\ in^3 \quad (9)$$

3. Bending Stress:

$$\sigma = \frac{M}{S} = \frac{7500}{0.114} = 65{,}789.47\ psi \quad (10)$$

4. Factor of Safety: [8]

$$FoS = \frac{\sigma_y}{\sigma} = \frac{36000}{65{,}790} = 0.55 \quad (11)$$

5. Maximum Deflection: With I=0.057 in^4, deflection is:

$$\delta = \frac{F*L^3}{48*E*I} = \frac{500*60^3}{48*29x10^6*0.06} = 0.449\ in \quad (12)$$

Stability and Tipping Calculations

Critical Tipping Angle: [9]

- Track Width (T): 30 in
- Height (H): 32 in

$$SSF = \frac{T}{2H} = \frac{30}{32} = 0.9375 \quad (13)$$

$$\theta_t = tan^{-1}(SSF) = tan^{-1}(0.9375) = 43.15° \quad (14)$$

- **To verify, we modeled the CG as acting 15 inches horizontally from the pivot and 16 inches (CG) vertically:**

$$\tan(\theta_t) = \frac{15}{16}, \theta_t = 43.15° \quad (15)$$

Previously:

Calculated based on 600 lbs, center of gravity at 29 in, the critical tipping angle was 27.35 degrees. By changing the carts geometry, we gained 15.8 degrees of tipping angle.

Caster Sub Assembly Calculations

Variables: [10]

- **Total Load (*W*):** 600 *N* (134.88 *lbf*)
- **Number of Casters (*n*):** 4
- **Wheel Diameter (*D*)**: 8 or 10in
- **Rolling Resistance Coefficient (C_r):** 0.015
- **Bearing Type:** Ball bearing (low friction)
- **Material:** Rubber

1. Load per Caster:

$$F = \frac{W}{n} = \frac{134.88}{4} = 33.72\ lbf \quad (16)$$

2. Rolling Resistance Force per Caster:

$$F_r = F_c C_r = 0.015 * 33.72 = 0.5058\ lbf \quad (17)$$

3. Total Rolling Resistance:

$$F_{total} = 4 * F_r = 4 * 0.5058 = 2.0232\ lbf \quad (18)$$

4. Torque Required at Caster Bearing (Startup):

$\tau = F_r \cdot \frac{D}{2} = 0.5058 \cdot 4 = 2.0232\ lb * in$ or $0.5058 \cdot 5 = 2.529\ lbf * in$ (19)

(Used to determine the required startup torque capacity of the bearing to ensure smooth and responsive steering.)

We validated the rolling resistance calculation by comparing the estimated C_r with standard values from engineering handbooks and manufacturer specifications for rubber tires designed for off-road and rugged terrain.

Steering Sub Assembly Calculations

Variables: [11]

- Arm Length: 38 in
- Hand Force: 20 lbf
- Kingpin Offset: 2.5 in
- Trail: 1.2 in
- Steering Angle: $\pm 25^{\circ}$
- Friction (μ): 0.02
- Front Load: 300 N
- Wheel Radius: 5 in
- Efficiency: 0.9

1. Trail Torque:

$$\tau_{trail} = Front\ Load \times Trail = 67.4 \times 1.2 = 80.88\ lbf * \text{in} \quad (20)$$

2. Friction Torque:

$$\tau_{fric} = \mu \times Front\ Load \times Kingpin\ Offset = 0.02 \times 67.4 \times 2.5 = 3.37\ lbf * \text{in} \quad (21)$$

3. Total Steering Torque:

$$\tau_{total} = \tau_{trail} + \tau_{fric} = 80.88 + 3.37 = 84.25\ lbf * \text{in} \quad (22)$$

4. Required Hand Force:

$$F_{required} = \frac{\tau_{total}}{Arm\ Length \times Efficiency} = \frac{84.25}{38*0.9} = 2.46\ lbf \quad (23)$$

We confirmed that the required hand force is within an acceptable range by comparing the calculated result (2.46 lbf) with the ergonomic limit (≤ 25 lbf) [12].

Battery Sub Assembly Calculations

This sub system uses a 12V battery (sealed lead-acid or lithium-ion) to supply power to: [13]

- Three 120V AC outlets
- Two USB ports

Its primary function is to provide short-term, independent power for electric tools and mobile devices. It ensures stable and reliable operation of auxiliary systems in situations where external power is unavailable.

1. Ideal Energy Requirement:

$$E_{ideal} = P * t \qquad (24)$$

2. Actual Energy with Efficiency Losses:

$$E_{actual} = \frac{E_{ideal}}{\eta} \qquad (25)$$

3. Battery Capacity (Ah) Estimation with DoD and Margin :

$$Q = \frac{E_{actual}}{v} * \frac{1}{DoD} * \text{Margin Factor} \qquad (26)$$

Battery Sub Assembly Calculations

Variables Provided:

1. Battery Voltage: V = 12V
2. AC Load: 3×60 = 180W
3. USB Load: 2×10 = 20W
4. Total Power: P = 200W
5. Duration: t = 1h
6. Efficiency: η = 0.75
7. DoD (Depth of Discharge): 60% = 0.6
8. Margin: 25% = 1.25

Step-by-Step Calculation:

1. Ideal Energy

$$E_{ideal} = 200W \times 1h = 200Wh \quad (27)$$

2. Actual Energy:

$$E_{actual} = \frac{200}{0.75} \approx 267Wh \quad (28)$$

3. Battery Capacity (Ah) Estimation with DoD and Margin :

$$Q = \frac{267}{12} \times \frac{1}{0.6} \times 1.25 \approx 46.4Ah \quad (29)$$

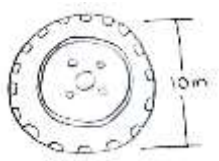
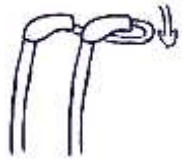
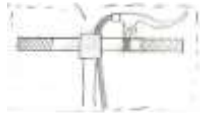
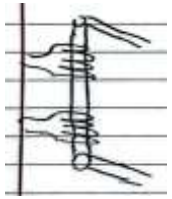
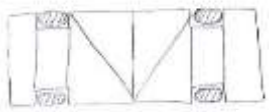
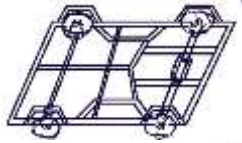
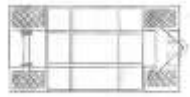
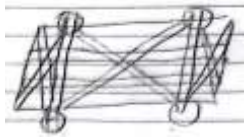
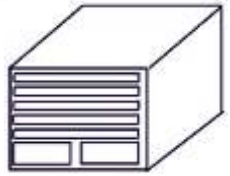
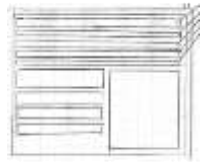
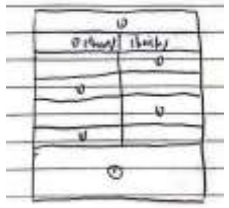
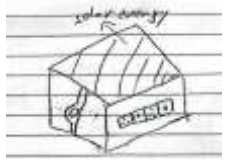
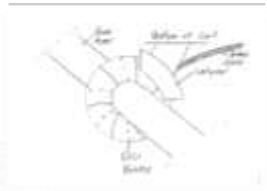
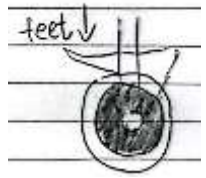
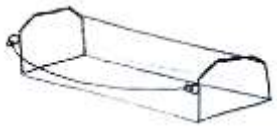
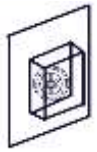
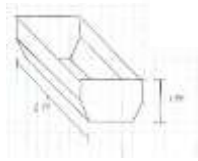
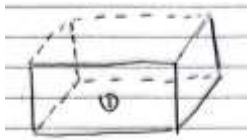
Calculation Summary Table

Table 1: Calculations Supporting Customer Needs

Subsystem	Initial Values	Values to Date	Improvement?	Customer Need Met
Brakes	3200 *lbf*	34 *lbf*	Yes	Safety and Achievability
Frame	Critical tipping angle: 27.35°	Critical tipping angle: 43.15°	Yes	Stability
Casters	9 *N*	2.0232 *lbf*	No	Different Terrain
Steering	-	2.46 *lbf*	Yes	Maneuverability
Battery	-	46.4 *Ah*	Yes	Power supply

Concept Generation

Table 2: Morphological Matrix

Subsystem	1	2	3	4
Casters	A1 	A2 	A3 	A4 
Steering System	B1 	B2 	B3 	B4 
Base Frame	C1 	C2 	C3 	C4 
Toolbox	D1 	D2 	D3 	D4 
Power System	E1 	E2 	E3 	E4 
Brake System	F1 	F2 	F3 	F4 
Tire Storage	G1 	G2 	G3 	G4 

Concept Evaluation

Table 3: Quantifications of Engineering Requirements

Requirement	Quantified Engineering Requirement
Lightweight Design	Total mass < 500lbs
High Durability	Survives > 5 years of competition travel
Compact Size	Max dimensions: 60” L x 30” W x 45” H
Fast Response Time	Response braking time < 1 second
Safe to use	Meets ISO 12100 Safety Standards

Pugh Chart Designs

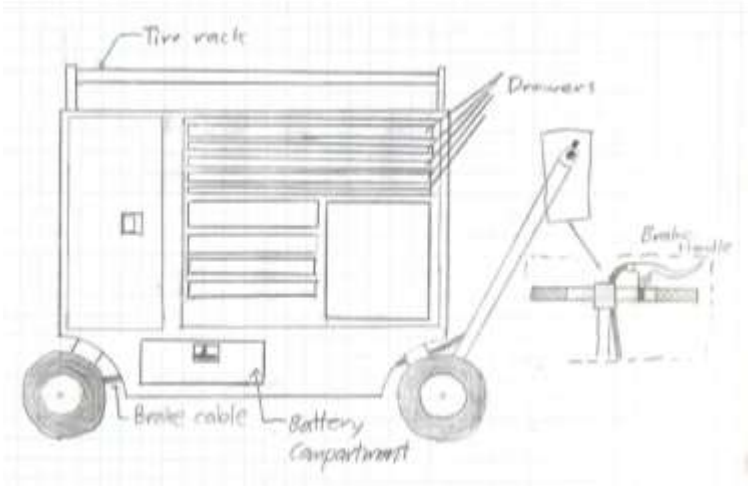


Figure 7: Design 1

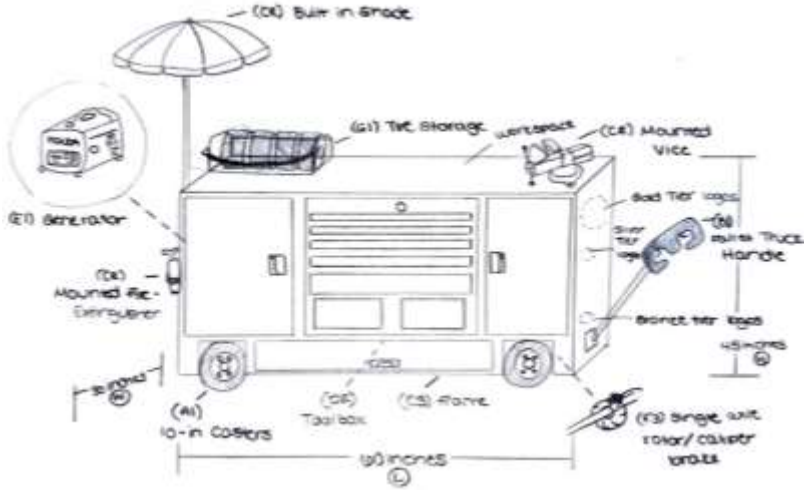


Figure 8: Design 2

Figure 9: Design 3

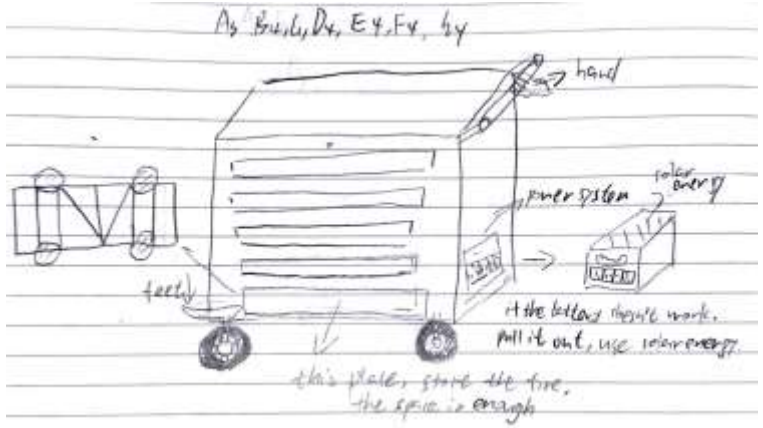


Figure 10: Design 4

Pugh Chart

Table 4: Pugh Chart

Criteria	Design 1	Design 2	Design 3	Design 4	Competitor
Affordability	+	+	+	+	DATUM
Aesthetic	S	-	+	-	DATUM
Durability	S	S	S	S	DATUM
Lightweight	S	S	+	+	DATUM
Add-on Components	+	+	+	S	DATUM
Quality Materials	S	-	S	S	DATUM
Total	2	0	4	1	DATUM

Decision Matrix

Table 5: Decision Matrix

		Design 1	Design 3
Criteria	Weight	Average Weighted Score	Average Weighted Score
Affordability	20%	4	4
Aesthetic	10%	2	3
Durability	25%	3	4
Lightweight	15%	4	3
Add-on Components	20%	2	5
Quality Materials	10%	3	3
Total	100%	61%	77%

Current CAD

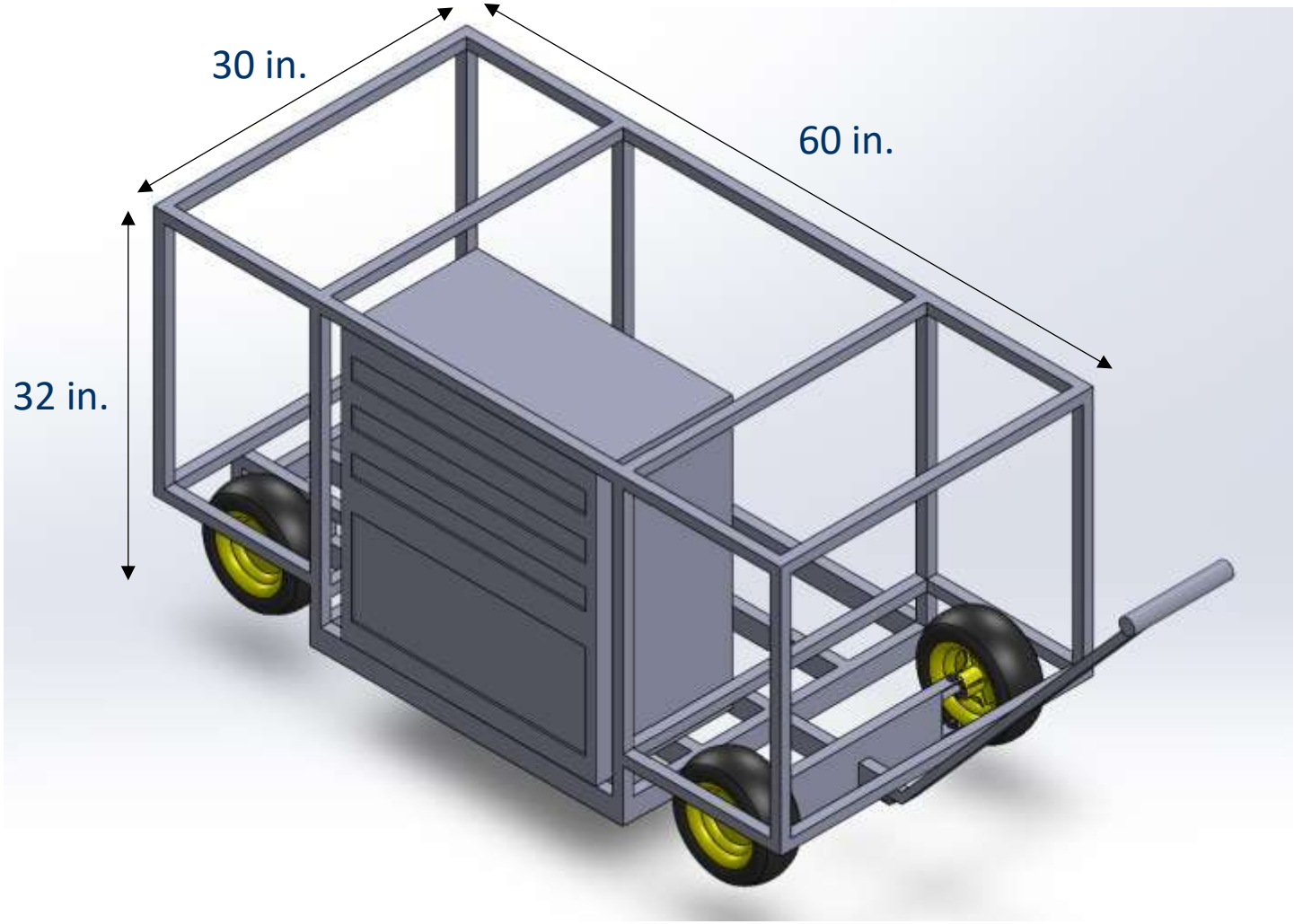


Figure 11: Current Concept CAD Render

Specification Table

Table 6: Customer Need Checklist

Customer Need	Part Creation/Implementation	Status
Minimal footprint in trailer	Small frame dimensions	Met
Braking	Rotor and caliper on rear axle	Active
Locking drawers on toolbox	Outer locking system, not integrated into toolbox	Active
Power Supply	Inverter implementation to battery for extra life	Active
Built in Shade	Attached rollout car awning with legs	Active
Driver equipment storage	Two outer cabinets with shelves	Met
Stable	Heavy equipment stored low, good track width	Met
Roll on rough terrain	10” Casters designed in with HD bearings	Met
Mounted/Included Tools	BOM includes vice, tools, chargers	Active
Mounted Fire Extinguisher	BOM includes fire extinguisher + mount on exterior	Active
Add NAU/Sponsor logos	File of sponsor logos for printing and applying	Active
Tool organization	Toolbox w/tools and foam sourced in BOM	Active
Steering	Tie-rod steering system with handle for leverage	Met
2nd Tailgate for the trailer	Sourcing in the BOM	Active

Schedule

Table 7: Updated Gantt Chart Weeks 7-9

	Gantt Chart SAE Toolbox										
	ACTIVITY	PLAN START	PLAN DURATIO	DUE DATE	ACTUAL DURATION	PERCENT COMPLETE	Week 7/7/2025	7/14/2025	7/21/2025	7/28/2025	8/4/2025
All	Peer Eval 2	17-Jul	1	16-Jul	1	100%					
Derek	Brake System Prototype	17-Jul	7	24-Jul		25%					
Hailey	VR CAD Prototype	17-Jun	7	24-Jul		75%					
Yanbo	Website Check #1	8-Jul	21	24-Jul		10%					
All	Peer Eval 3	19-Jun	6	24-Jul		0%					
Haoran	2nd Prototype	18-Jul	10	30-Jul		0%					
All	Presentation 3	18-Jul	20	31-Jul		0%					
All	Final BOM	24-Jun	15	1-Aug		60%					
Yanbo	Website Check #2	8-Jul	1	1-Aug		0%					
All	Report #2	18-Jul	20	1-Aug		5%					
All	Peer Eval 4	25-Jul	1	1-Aug		0%					
Hailey	Final CAD	17-Jul	20	5-Aug		25%					

Fundraising

- Emails sent to 67 companies
- Tier system for logo size/placement
- In-kind parts sponsorships
- 2 for sure sponsors
- **$501/1000** Raised

Figure 12: SAE Toolbox Sponsorship Tier

Bill of Materials

Table 8: Portion of the Bill of Materials

Subassembly	Part #	Description	Qty	Price	Total	Manufacturer	Website
Toolbox	B0C3VDMJWW	7-Drawer Toolbox 24.2"Lx13"Wx34.6"H	1	$ 125.99		Seizeen	
		7-Drawer Toolbox 12.9"Dx24.2"wx29.9"H	1	$ 139.99		Artman	
		5-Drawer Toolbox 18"Dx37.5"Hx26"W	1	$ 269.00		Craftsman	
		13"Dx24.25"Wx29.33"H Box with 238 tools	1	$ 169.99		Campfun	
		Fire extinguisher mount for 2.5lb extinguisher	1	$ 18.99		MANNIFEN	
		3in table-top swivel vice	1	$ 19.97		Central Machinery	
		4in table-top swivel vice	1	$ 34.99		Central Machinery	
Tools		244 pcs Tool kit in foam inserts	1	$ 189.00		Husky	
		171 pcs tool set in foam tray	1	$ 134.99		JZD	
		290 pcs tools in foam trays	1	$ 249.00		Husky	

Budget

Anticipated Expense Ranges:

- Toolbox ($125-250)
- Tools ($130-250)
- Casters ($50-200/4)
- Brakes ($20-100)
- Power Supply ($320-500)
- Frame Steel ($50/6ft)
- Shade ($120-250)
- Aluminum Panels ($15/12x24in)

Actual expenses:

- Toolbox + Tools ($170)
- Vice + Extinguisher ($54)
- Casters + Frame + Steering ($645)
- Inverter Power Supply ($320)
- Shade ($120)
- Aluminum panels ($120)
- Steel tubing ($200)
- Brakes ($60)

Resulting Balance:

$2501-1689 =$812

References

[1] D. Pree and H. Rückert, “The functional black box model of the brake,” *ResearchGate*, [Online]. Available: https://www.researchgate.net/figure/The-functional-black-box-model-of-the-brake_fig16_339009653. Accessed: Jul. 8, 2025.
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Thank You

Questions?