NAU SAE

TOOLBOX

FINAL REPORT

Summer 2025 - Fall 2025

Derek Griffith: Prototype Engineer, Manufacturing Engineer 2

Hailey Hein: Logistics Manager Project Manager, CAD Engineer, Financial Manager, Manufacturing Engineer 1

Haoran Li: Test Report Engineer

Yanbo Wang: Website Manager, Report Engineer

Project Sponsor: NAU SAE
Faculty Advisor: David Willy
Instructor: Armin Eilaghi

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DISCLAIMER

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Executive Summary

The SAE Toolbox Capstone Project for the Northern Arizona University Formula and Baja teams centered on the creation of a durable, multifunctional toolbox cart that supports both race day operations and daily shop work. The objective of the project was to deliver a mobile platform capable of transporting tools, housing powered equipment, carrying driver gear, and securing essential safety items, all while remaining maneuverable across varied terrains. The final design provides a compact and robust system that fits within team trailers while maintaining high accessibility and organization.

Through extensive client feedback, engineering requirements development, iterative concept refinement, structural calculations, virtual simulations, and physical testing, the team produced a tool cart that satisfies all critical performance criteria. Sponsorships from NAU SAE, Findlay Toyota, Lane Automotive and Northern Arizona Signs played a significant role in ensuring that the project remained financially feasible. The completed system is expected to serve both SAE teams reliably for many seasons, improving efficiency, safety, and preparedness during competitions.

1. Introduction

The NAU SAE Toolbox Project was initiated to provide a single integrated cart that improves the mobility and accessibility of essential tools and equipment used by the NAU Formula and Baja teams. During competitions and on campus, students face challenges transporting tools across uneven ground, organizing equipment in high pressure environments, and maintaining readiness in limited pit space. The project goal was to design a cart that addresses these challenges through durable construction, organized storage, stable off-road movement, and the ability for a single team member to maneuver it safely. This report outlines the engineering process followed to develop the final design, including requirement development, concept selection, structural calculations, fabrication planning, and formal testing.

2. Background

The need for a new pit cart originated from the limitations of the team's existing small wagon, which lacked the storage volume, stability, and load capacity required for modern Formula and Baja race events. The teams regularly transport tires, power tools, safety gear, and repair equipment between pits and paddock areas. Commercial pit carts were evaluated, but none were configured for the team's storage needs or the rough terrain encountered during Baja competitions. The objective of the capstone project was to design a custom cart with increased durability, modular storage solutions, off road mobility, and an integrated power system that would support both routine maintenance and race day emergencies. The final system was expected to meet customer requirements while maintaining an appropriate size for trailer transport.

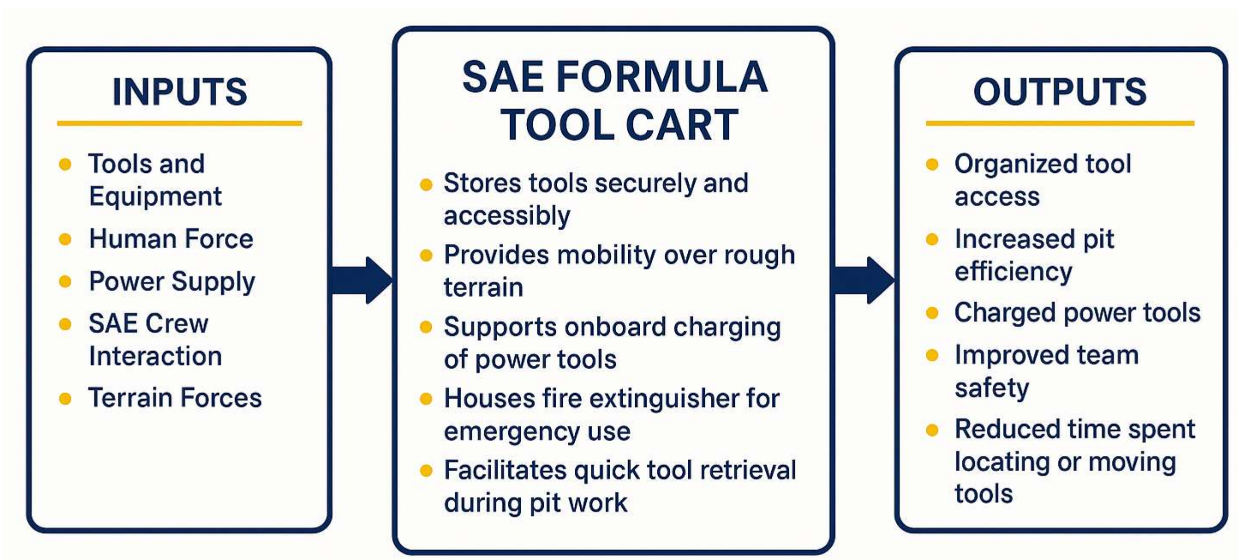


Figure 1: NAU SAE Toolbox Deliverable Breakdown

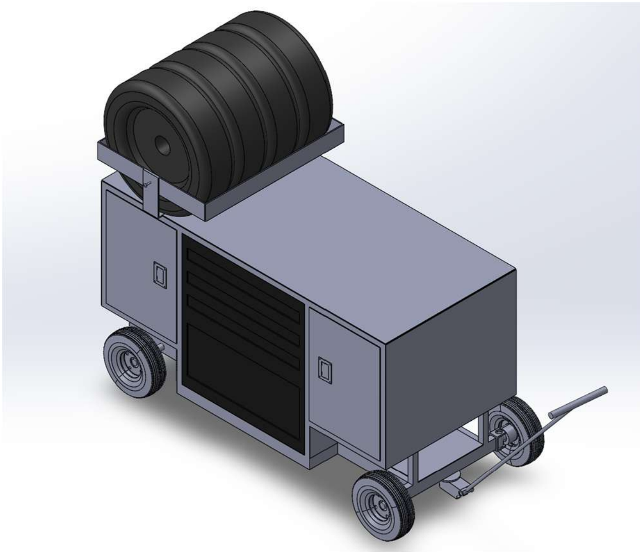


Figure 2: CAD Assembly Front

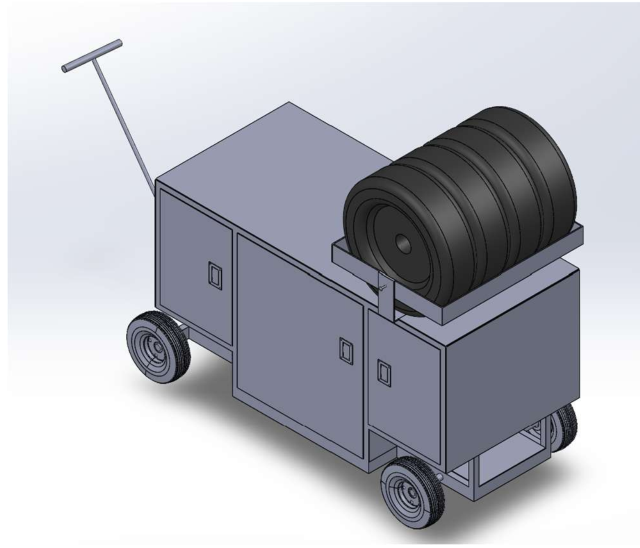


Figure 3: CAD Assembly Rear

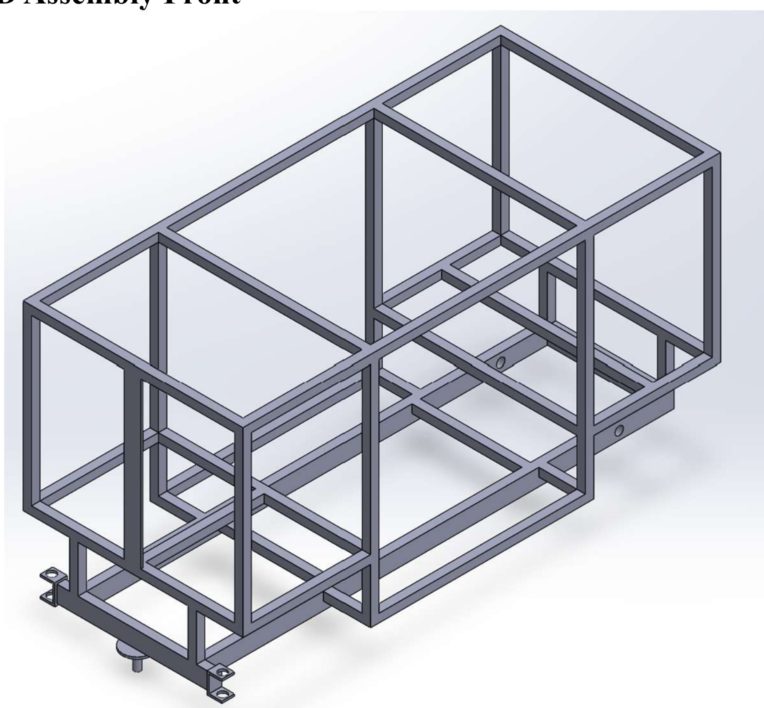


Figure 4: Raw Frame CAD Design

Success for this project was defined by the cart's ability to withstand rigorous physical testing and continue to operate without structural damage or functional failure. The cart needed to pass stability assessments, fit within competition pit spaces, and allow safe access to critical items such as the fire extinguisher and power tools. User satisfaction was considered a primary measure of success and was assessed through hands-on evaluations conducted by team members. Engineering performance was validated through SolidWorks simulations, strength calculations, prototype testing, and usability assessments.

3. Requirements

The design requirements for the NAU SAE Toolbox Cart were established through discussions with the NAU SAE teams, feedback from sponsors, and engineering analyses conducted during the early design phase. Customer requirements described the needs and expectations of the end users, while engineering requirements translated these needs into measurable, testable performance criteria. The most important requirements focused on mobility, braking, steering control, storage capacity, and overall durability. Each requirement was prioritized through a Quality Function Deployment process.

	Rubber Casters 6" to 10"	Integrated manual steering	Hand Braking/ Locking Wheels	Acceptable Volumetric Footprint in Trailer	Locking Drawers	3'x2'x1' Volume for Driver bag	Fire Extinguisher Mount	Integrated Power System for Tools	Charging Capability	Powered Tools Storage	Sound System (optional)	Mounting locations for vice, arbor press, etc	Shade	Welded Aluminum frame with bolted accessories
Rubber Casters 6" to 10"														
Integrated manual steering	9													
Hand Braking/ Locking Wheels	9	9												
Acceptable Volumetric Footprint in Trailer														
Locking Drawers				6										
3'x2'x1' Volume for Driver bag				6										
Fire Extinguisher Mount														
Integrated Power System for Tools														
Charging Capability								9						
Powered Tools Storage				6	3			9						
Sound System (optional)														
Mounting locations for vice, arbor press, etc				6										
Shade				6										
Welded Aluminum frame with bolted accessories				3	3					3				
Storage for saftey equipment, brake bleed kit, saftey wire puller				6	9									

Legend	
A	Redline 75" Pit Cart
B	Winter Pit Products
C	DK Hardware

Customer Needs	Customer Weights	Rubber Casters 6" to 10"	Integrated manual steering	Hand Braking/ Locking Wheels	Acceptable Volumetric Footprint in Trailer	Locking Drawers	3'x2'x1' Volume for Driver bag	Fire Extinguisher Mount	Integrated Power System for Tools	Charging Capability	Powered Tools Storage	Sound System (optional)	Mounting locations for vice, arbor press, etc	Shade	Welded steel frame with bolted accessories	Storage for saftey equipment, brake bleed kit, saftey wire puller.	1 Poor	2	3 Acceptable	4	5 Excellent
Large Toolbox	4	6	3	6	9	9					6		3		6	3			B		AC
Hold all of driver equipment/ spare wheels + rims	4	6			9		9												AC		B
Mounted items (arbor press, vice, grinding wheel,etc)	4	3			9				3	6	9		9					AC	B		
Price	5	3	3							3		6		6		3	ABC				
Brakes/ steering/ 6-10 inch casters	4	9	9	9															B		AC
Technical Requirement Units		inch	N/A	lbf/N	ft^3	N/A	ft^3	N/A	Watts	Watts	ft^3	N/A	N/A	ft^3	ft^3	ft^3					
Technical Requirement Targets		10 in	Y	2+	72 ft^3	Y	6 ft^3	Y			2ft^3	Y	3 locations	72 ft^3	Y	2 ft^3					
Absolute Technical Importance		50	50	50	50	30	50	50	30	30	50	10	50	30	50	30	Total Score				
Relative Technical Importance		8%	8%	8%	8%	5%	8%	8%	5%	5%	8%	2%	8%	5%	8%	5%	610				

Figure 5: SAE Toolbox QFD

A complete summary of customer and engineering requirements were compiled in requirement tables. This included the need for a large, organized storage space, transportation for driver equipment and spare tires, multiple mounting locations for tools such as a vice and arbor press, a manual steering mechanism, a reliable brake system, safe locations for emergency equipment, and an integrated power system capable of charging tools. The design also had to remain cost effective and fit within the dimensional limits of the team trailer.

Table 1: Customer Requirements

CR1	The cart must serve as a large, organized toolbox for use in pits and in the shop
CR2	The cart must hold all driver equipment, including spare wheels and rims
CR3	The cart must provide mounted locations for tools such as an arbor press, vice, and grinding wheel
CR4	The cart must include integrated braking and steering for safe and easy single-person operation
CR5	The cart must be affordable and cost-effective to build
CR6	The cart must include safe storage for essential equipment such as a fire extinguisher, brake bleed kit, and safety wire puller

Table 2: Engineering Requirements

ER1	Rubber casters are greater than 6 inches in diameter for stability and smooth mobility
ER2	Integrated manual steering system for controlled movement in tight spaces
ER3	Hand brake and locking wheel system to ensure the cart remains stationary when parked
ER4	Compact volumetric footprint (approximately 72 ft^3) to fit within a standard trailer for transport
ER5	Locking drawers to secure tools and prevent shifting during movement
ER6	A 3 ft × 2 ft × 1 ft storage volume minimum for the driver's bag and personal gear
ER7	Mounted fire extinguisher holder that is easy to access and meets safety standards
ER8	Integrated power system capable of supporting tool charging and electrical accessories
ER9	Dedicated powered tool storage area (about 2 ft^3) with charging capability
ER10	Optional sound system for communication or entertainment during competitions
ER11	Mounting points for accessories such as a vice, arbor press, or grinder (minimum of two locations)
ER12	Shade or canopy coverage for pit use in outdoor conditions
ER13	Welded aluminum frame with bolted accessories for strength, durability, and easy maintenance
ER14	Safe storage locations for emergency and safety-related equipment (minimum of 2 ft^3 total)

These requirements were prioritized through the QFD process. The most critical technical factors such as braking, steering, caster sizing, and internal storage, carry the highest relative importance due to their direct influence on mobility, usability, and safety. Lower-priority elements, such as the optional sound system and shade attachment, were included to enhance user comfort but are not essential for baseline operation.

Together, these customer and engineering requirements establish measurable performance standards that all testing procedures will be built around. The following sections describe how each requirement will be verified through physical and analytical testing.

Table 3: Client and Engineering Requirements Summary

Category	Client Requirements	Engineering Requirements	Solution
Mobility	Terrain capable tires	Rubber casters > 8" OD preferred, 6" Minimum	13" x 5.5" Casters
	Steering system	Integrated human operated steering system	Tie-rod + handle steering system
	Brake system	Human operated brake lever system	Exterior foot latch system
	Trailer footprint	Fits and can maneuver in the travel trailer	60 x 32 x 33.5" Frame (LWH)

Storage	General tool storage	Secure drawers and bins with latch systems	3D Printed add-on latches
	Ancillary equipment	Space to store required equipment per team	5 cabinet doors
	Driver gear storage	3'x2'x1' Internal cabinet volume minimum	21.6 ft^3 cabinet storage
	Fire extinguisher	External quick-access mount	Exterior un-latch mount
	Tire carrier	Storage for 4 Baja or Formula SAE Tires	30x25" Top mounted carrier
Power & Electrical	Integrated power system	Stand alone inverter generator that can handle loads	2500W Inverter generator
	Charging capabilities	Extension cord with power bank	25 ft extension cord
	Powered tools	Capacity for power tools to charge	13 outlet 120V power bank
Work Features	Mounted vice	Top mounted vice big enough for work	6” Table-mount vice
	Tabletop work area	Top panel doubles as the workspace	60 x 32” Top panel
Durability	Strong materials	2x1" and 1x1" steel frame construction	A36 welded steel
	Construction	Sufficient welds and mechanical fastening's	MIG welded material connections
Identity	Visual Branding	NAU, Lumberjack Motorsports, Sponsor logos	Sponsored vinyl wrap

4. Design Space Research

The design space research phase examined commercial pit carts, competitor systems, and literature relevant to mobile equipment transport. Benchmarking studies focused on commercially available pit carts from companies such as Redline and Winter Pit Products, with prices ranging from four thousand to seven thousand dollars. These products provided insight into common features such as modular drawer configurations, integrated power systems, and workspace surfaces. However, none aligned with the teams' combined requirements for off-road capability, compact volume, and tailored storage.

4.1 Literature Review

Derek Griffith

[4] **Braking of Road Vehicles, Elsevier BV, 2022**

This volume provides foundational insights into braking systems, detailing mechanical, hydraulic, pneumatic, and electronic brakes, along with their performance characteristics. It discusses the heat dissipation, friction behavior, and stability aspects that are essential in selecting and designing safe and efficient braking systems. For the SAE tool cart project, this reference offers a solid technical foundation for choosing an appropriate braking mechanism, ensuring that the tool cart can manage various loads and provide consistent stopping power in dynamic environments.

[5] **Energy Storage Systems for Electric Vehicles, 2020**

This book explores the wide range of energy storage methods used in electric vehicles, such as lithium-ion batteries and ultracapacitors, and explains their integration into vehicular power and braking systems. Key topics like charge/discharge cycles, power management, and regenerative braking directly inform how to size and wire power systems efficiently. For the tool cart, this source supports the design of a self-contained electrical power system by providing guidance on storage selection and power delivery.

[6] **Model-Based Range Extension Control System for Electric Vehicles With Front and Rear Driving–Braking Force Distributions, Fujimoto & Harada, 2015**

This paper presents a model-based control system that dynamically distributes brake and driving forces between front and rear axles in electric vehicles, improving stability and extending battery range. This research can influence how force is applied to each wheel of the cart to prevent skidding and improve maneuverability on slick or uneven pit lane surfaces.

[7] **Optimal Allocation Method of Electric/Air Braking Force of High-Speed Train Considering Axle Load Transfer, Guo & He, 2024**

This study introduces a method for optimally allocating braking force between electric and pneumatic systems in high-speed trains, considering axle load transfer during deceleration. For the SAE tool cart, which may experience varying loads and shifting weight distribution due to tool placement or movement, understanding how to balance braking force can improve both safety and wear characteristics. This source helps justify braking layouts that compensate for uneven loading and provide stable, controlled stops.

[8] **A New Model of Stopping Sight Distance of Curve Braking Based on Vehicle Dynamics, Xia et al., 2016**

Xia et al. presents a refined model of stopping sight distance (SSD) by accounting for vehicle dynamics like lateral forces and curve radii, which traditional models often overlook. For the tool cart, which may need to navigate tight corners or stop on variable terrain in crowded areas, this study helps estimate realistic braking distances and informs safer design of the brake system and operator control logic. It can also support decisions about maximum allowable speed in operational scenarios.

[9] **Fuzzy Scheduled Optimal Control of Integrated Vehicle Braking and Steering Systems, Mirzaei & Mirzaeinejad, 2017**

This research develops a fuzzy logic-based control system that integrates braking and steering, enabling real-time adjustments to improve handling and stability under dynamic conditions. While advanced, the approach offers insight into how to coordinate steering and braking in a compact, maneuverable platform like the tool cart.

[10] **R. G. Budynas, J Keith Nisbett, and Joseph Edward Shigley, Shigley's mechanical engineering design, 11th ed. New York, Ny: Mcgraw-Hill Education, 2020.**

Shigley's Mechanical Engineering Design will be used as a foundational reference for analyzing both compression and extension springs in the mechanical design process. This text provides detailed methodologies for calculating spring forces which is critical when selecting or designing springs for reliable performance under dynamic loads.

[11] **David Gordon Wilson, *Bicycling science*. Cambridge (Massachusetts): Mit Press, 2004.**

Bicycling Science will serve as a key resource for understanding the principles of bicycle braking systems, which are similar if not identical to the brakes used by the toolbox. The book explores the physics behind braking dynamics, including friction, weight transfer, and stopping distances, which are essential when analyzing or designing effective braking mechanisms.

Hailey Hein

[12] **"Vehicle Static Stability Factor," *Automotive Engineering Technical Article*, SAE International.**

This article introduces the Static Stability Factor (SSF), calculated as track width divided by twice the center of gravity (CG) height. The SSF helps estimate rollover thresholds on inclined surfaces. This is highly applicable to our cart design since it must remain upright and stable during transport on uneven terrain. The SSF equation is directly usable during our early CAD-based layout and during CG-height sensitivity analysis.

[13] **D. Raymer, *Aircraft Design: A Systems Engineering Approach*, American Institute of Aeronautics and Astronautics, 2012.**

Though focused on aircraft, this book provides valuable principles regarding center of gravity placement, mass distribution, and static margin stability. These concepts apply to our cart's loaded condition, especially when storing heavy parts such as tools and wheels. It reinforces the need to keep CG as low and centered as possible in the CAD model.

[14] **A. T. Jones, "Tip-Over Stability of Mobile Boom Cranes," M.S. thesis, Dept. Mech. Eng., Purdue Univ., 2018.**

This thesis models tip-over hazards in mobile cranes under dynamic and static conditions. Though larger in scale, its methodology, especially the use of free-body diagrams and moment equations—is transferable to our cart. I will apply this to simulate corner-case loading, such as placing a vice or jack stand near one side.

[15] **J. Martinez and S. Kim, "Tip-Over Stability Using Dynamic Simulation," *J. of Field Robotics*, vol. 33, no. 6, pp. 812–829, 2017.**

This paper describes multi-body simulation using MATLAB/ADAMS to evaluate orchard robot stability. It provides logic and modeling techniques for simulating movement across sloped or bumpy terrain. For our project, this supports the decision to use CAD motion simulation to visualize dynamic responses and test for critical angles of instability.

[16] **T. Kato and F. Miyazaki, "Analytic Solutions for Wheeled Mobile Manipulators," *IEEE Trans. on Robotics*, vol. 20, no. 2, pp. 378–384, Apr. 2004.**

This research provides exact solutions for wheel loading and tipping force thresholds when vehicles operate on inclines. Its load distribution equations are useful for calculating expected axle forces during worst-case braking scenarios. These formulas will be integrated into the hand calculations that verify my CAD design.

[17] **Hamilton Caster Co., "Tipping Hazards in Tool Carts,"** ***Hamilton Whitepaper*****, 2021.**

This industry whitepaper outlines practical safety concerns in mobile carts, including poor weight distribution, undersized wheels, and sudden stops. It includes general recommendations for CG height, wheel spacing, and slope handling. These industry guidelines reinforce our design constraints and serve as sanity checks for my structural and stability choices.

[18] **S. Blake, "Crane Tipping Theory Using CAD,"** ***Design World Case Study*****, 2020.**

This article discusses how to simulate tipping and load transfer directly within CAD platforms like SolidWorks and Fusion 360. It provides step-by-step instruction for simulating moment arms, center of gravity shifts, and static balance using real design geometries. This will be directly applied in my CAD analysis of the frame and wheel layout.

[19] **P. Black and E. Adams, "Finite Element Analysis of Mobile Structures,"** ***Mechanical Engineering Letters*****, vol. 14, no. 1, pp. 54–61, 2022.**

This paper explores stress and deformation in wheeled mobile frames under distributed and point loading. It presents FEA approaches ideal for analyzing the structural integrity of frame tubing—key for ensuring the cart's load-bearing capability meets our minimum safety factor.

Haoran Li

[20] **M. E. Cooper, "Rolling Resistance and Energy Losses in Manual Wheelchairs," Journal of Rehabilitation Research and Development, vol. 34, no. 3, pp. 289–298, 1997. (Paper)**

This article analyzes how wheel material and surface type affect rolling resistance due to hysteresis losses. The experimental data helps estimate the push force needed for rubber wheels, supporting our cart's maneuverability analysis and wheel selection.

[21] **"Rolling Resistance Coefficient Reference Table," The Engineering Toolbox. (Online)**

This webpage introduces the basic definition and formula of rolling resistance, $F_r = C_r * W$, and provides typical coefficient values for rubber, polyurethane, and steel wheels on various surfaces. These standardized values enable accurate estimation of rolling resistance for carts on different terrains, helping validate and refine the $F_r = C_r * W$ model. This supports performance evaluation of wheels and user effort estimation in our design.

[22] **D. Lippert and J. Spektor, Rolling Resistance and Industrial Wheels, Hamilton Caster White Paper No. 11, 2012. (Online)**

This white paper provides rolling resistance data for industrial wheels under various loads and surfaces. It introduces key influencing factors—wheel diameter, tread material, and floor roughness—and presents a calculation formula $F = f * \frac{W}{R}$. The content supports our toolbox design by guiding caster selection and push force estimation.

[23] **R. Zepeda, F. Chan, and B. Sawatzky, "The effect of caster wheel diameter and mass distribution on drag forces in manual wheelchairs," Journal of Rehabilitation Research and Development, vol. 53, no. 6, pp. 893–900, 2016. (Paper)**

This study investigates the effects of caster wheel diameter and load distribution on rolling resistance in manual wheelchairs. Experiments conducted using a treadmill and force sensors showed that small-diameter casters (4 inches) significantly increase resistance only when more than 40% of the total weight is placed over them. Weight distribution was found to have a greater impact on drag than wheel size. These findings support our toolbox design by emphasizing the importance of proper load placement and center-of-mass control to reduce push effort.

[24] **Z. Pomarat, T. Marsan, A. Faupin, Y. Landon, and B. Watier, "Wheelchair caster power losses due to rolling resistance on sports surfaces,"** ***Disabil. Rehabil. Assist. Technol.*****, vol. 20, no. 4, pp. 1176–1182, 2025. (Paper)**

This paper analyzes power losses from rolling resistance in different caster wheels under varying speeds, loads, and surfaces. It shows that caster type and floor material significantly affect energy loss, supporting caster selection decisions for improved toolbox mobility.

[25] **Darcor Ltd.,** ***Guide to Designing Manual Materials Handling Carts – Selecting Casters, Reducing Workplace Injury*****, 2018. (Book)**

This guide explains how caster diameter, material, and offset affect rolling resistance and push force. The "Caster Effects" section offers useful equations and design tips that support caster selection and handling performance in our toolbox project.

[26] **S. J. Khan, A. Ustun, and B. Venkatesh, Fundamentals of Smart Grid Systems, 1st ed., Elsevier, 2023, ch. 10. (Book)**

This chapter discusses the concept of rolling resistance and its impact on vehicle movement. It provides useful explanations for understanding how surface friction and load affect motion, which supports our toolbox design by helping evaluate caster performance under different loading conditions.

Yanbo Wang

This group of sources addresses practical power consumption parameters and efficiency considerations related to on-board electrical output systems, including AC outlets and USB interfaces.

[27] **Stanley Black & Decker, "DEWALT DCB112 12 V/20 V MAX Charger – Product Specification," DEWALT.com, accessed Jun. 2025.**

The spec sheet lists an AC input of 100–260 V and a peak draw of ≈ 80 W, giving a realistic figure-of-merit for one power-tool battery charger.

[28] **Greatatop, "UL-Certified 5 V 2 A (10 W) USB Wall Charger – Product Listing," Amazon Marketplace, 2024.**

Provides a concrete 10 W rating for a standard USB-A port, matching the 2 A@5 V assumption used in our load table.

[29] **M. Fedkin, "Efficiency of Inverters," EME 812 Utility Solar Power (Penn State Univ.), Lesson 6.5, 2024.**

States that high-quality pure-sine inverters achieve 90–95 % efficiency, while low-cost modified-sine models run 75–85 %; our 75 % system-loss factor adopts the conservative end of this range.

[30] **Battery University, "BU-403: Charging Lead Acid," BatteryUniversity.com, 2024.**

Notes overall charge/discharge efficiencies of 80–90 % for new VRLA batteries, validating the 90 % discharge-efficiency term in our calculations.

[31] **EnergySage, "Lithium-Ion vs. Lead-Acid Batteries – Efficiency & Cycle Life," EnergySage.com, 2023.**

Reports typical round-trip efficiencies: Li-ion ≈ 95 %, Lead-acid ≈ 80–85 %, supporting our chemistry-selection discussion and margin choices

[32] **USB Implementers Forum, "USB Power Delivery Revision 3.1 – Overview," usb.org, 2021.**

Defines USB-PD power profiles up to 240 W and confirms legacy USB-A/B ports remain limited to 5 V nominal, reinforcing the 10 W/port cap used here.

[33] **USB Implementers Forum, "USB 2.0 Specification," Release 2.0, Jun. 2025.**

Section 7.2.1 fixes VBUS at 4.75–5.25 V and 500 mA (2.5 W) for standard downstream ports; higher-current BC 1.2 charging logic scales to 1.5 A. Provides the regulatory ceiling for our USB-load envelope.

4.2 State-of-the-Art

To guide the SAE Toolbox design, we benchmarked three leading pit carts: the Redline 75" Mechanics Toolbox [1], Winter Pit Products Acceleration Cart [2], and Extreme Tools TXPIT7009BK [3]. These examples helped establish expectations for maneuverability, storage, and functionality.

The Redline 75" offers a rugged, simple design with large casters and a wide storage base but lacks modularity or onboard power, features we aim to add. The Winter Acceleration Cart stands out for its dual axle steering and flatbed layout, influencing our focus on off-road stability and control. The Extreme Tools TXPIT7009BK includes integrated brakes, secure storage, and a stainless-steel work surface, directly shaping our approach to safety and organization.

Figure 6: Benchmarked Redline 75" Cart [1]

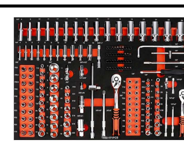
Figure 7: Winter Pit Products [2]

Figure 8: DK Hardware [3]

4.3 Subsystem Benchmarking

Subsystem-level comparisons, such as caster sizes, drawer locks, and power integration, further informed our decisions. For instance, 6–10" casters were standard across models, supporting our wheel size choice. Winter’s steering geometry and DK’s locking system were key inspirations. These benchmarks define our design priorities and highlight innovation opportunities in modular storage, power access, and off-road capability.

Table 4: Subsystem Benchmarking Breakdown

Subsystem	Benchmarked Part	Image	Price
Base Frame	Steel Roller Pit Cart Frame		$1,150.00 https://www.millercustomfabrication.com/store/p/roller-pit-cart-frame
Steel	1x2” 1/8” thick wall square steel tubing		$11.29 / Foot https://www.mcmaster.com/products/square-steel-tubing/steel-1~/outside-width~2/outside-height~1/
Toolbox	7-Drawer Toolbox		$148.99 https://www.walmart.com/ip/Seizeen-Rolling-Tool-Chest-on-Wheels-Metal-Tool-Cart-Toolbox-Storage-Cabinet-Organizer-W-4-Drawers-Red/1646253841
Tires	10” Pneumatic Casters		$8.99 / Tire https://www.harborfreight.com/10-inch-x-3-1-2-half-inch-pneumatic-tire-67465.html?gStoreCode=675&gQT=1
Power Supply	600W Portable Power Station		$246.99 https://www.amazon.com/DaranEner-299Wh-Portable-Power-Station/dp/B0D733VBQF/ref=sr_1_2_sspa?dib=eyJ2IjoiMSJ9.Au8rQRcSJ_tbfLJkT7k3O6jrn7NYW3DPEY5PrWCsRsxO56tw_KtzT5GSfHR21ajB64e2hahQGbkrk46ADzqsjKd-jBhO8QP3cCM6Fpxd7vd9CyuOwRvx2MyLETaIGo5K2suvQAIYvIGWesiDfLYot_T66nVIAJnvyAZejg-7ZVGhBlDSWSEPwNNBTPUsmzpcbLzZL_8ZP0FsXK4CufLiwaQ3ox9oIY_mK8NvPQ-KeKI.lOlVEy7rqjDFHu9Jz3SPoKAwuyKG6DynW3PV5LlxmH4&dib_tag=se&keywords=battery%2Bpower%2Bbanks&qid=1762373519&sr=8-2-spons&sp_csd=d2lkZ2V0TmFtZT1zcF9hdGY&th=1
Tools	171 Piece 3/8” Socket Tool Set		$139.00 https://www.amazon.com/Tool-Storage-Pieces-Socket-Mechanic/dp/B0CZKX8BC9/ref=asc_df_B0CZKX8BC9?mcid=396fe31db7413fc296435991f3bb9d1f&hvocijid=3917512610196015180-B0CZKX8BC9-&hvexpln=73&tag=hyprod-20&linkCode=df0&hvadid=721245378154&hvpos=&hvnetw=g&hvrand=3917512610196015180&hvpone=&hvptwo=&hvqmt=&hvdev=c&hvdvcmdl=&hvlocint=&hvlocphy=1013406&hvtargid=pla-2281435177338&th=1

Research into professional motorsport support equipment helped guide decisions regarding power integration, cabinet layout, and mobility. A literature review provided the theoretical basis for stability, mobility, and structural analyses. Stability research focused on the static stability factor and critical tipping angles. Mobility studies involved rolling resistance calculations and ergonomic limits for push forces. Structural design decisions were informed by beam bending theory, static strength equations, and fatigue considerations for tubular steel framing. The combination of analytical work and benchmarking helped define the bounds of feasible design directions before concept generation.

5. Concept Generation and Design Selection

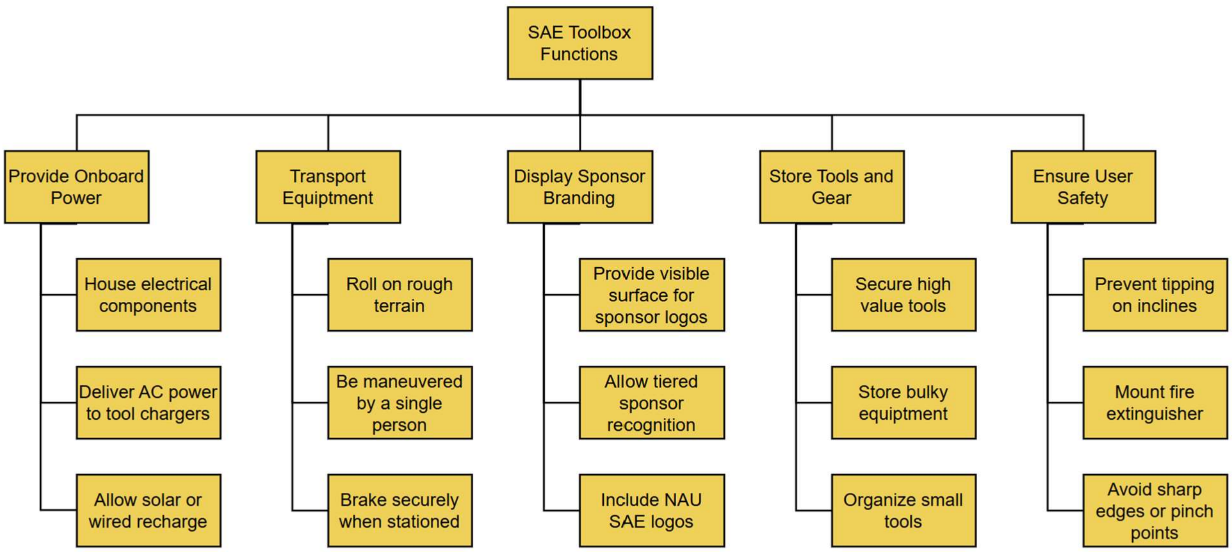
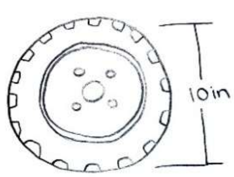
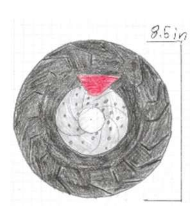
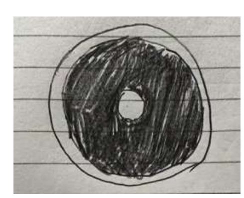
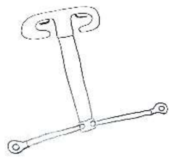
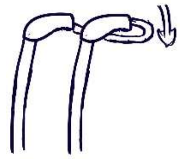
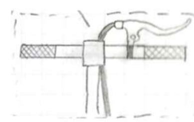
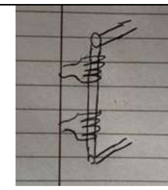
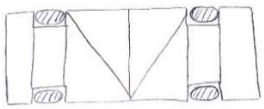
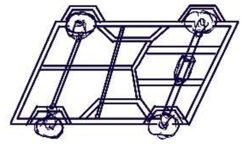
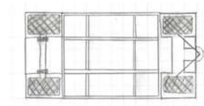
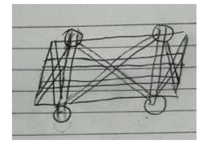
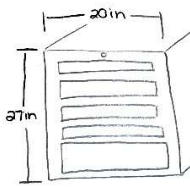
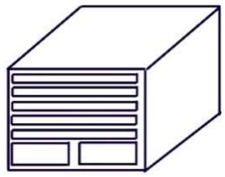
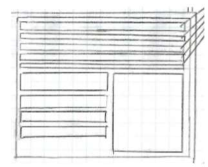
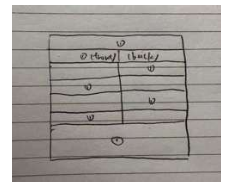
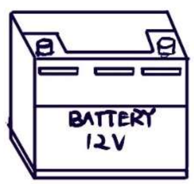
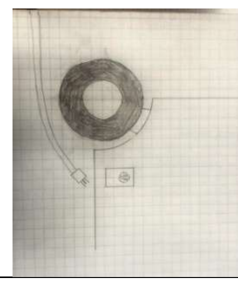
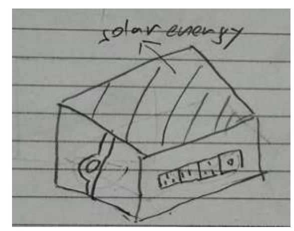
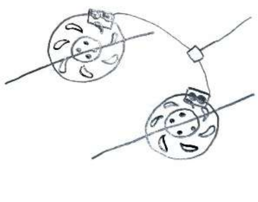
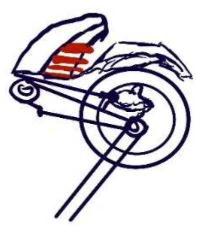
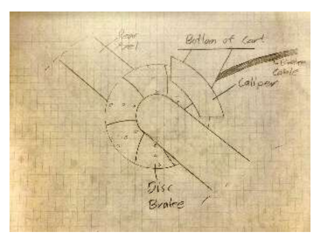
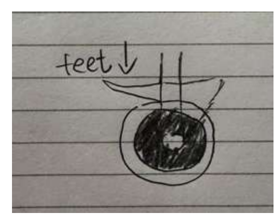
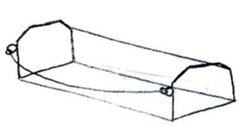
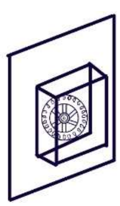
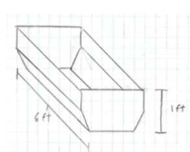
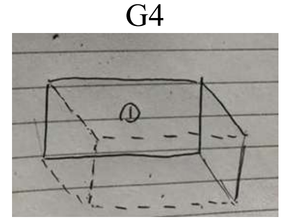


Figure 9: Sub-system Functional Decomposition

The team generated four primary design concepts during the brainstorming phase. These concepts differed in their frame geometry, steering systems, power system placement, and storage configurations. A formal Pugh Chart was used to compare concepts against a competitor baseline. Evaluation criteria included affordability, appearance, durability, weight, compatibility with add-on components, and material quality. Design three emerged as the strongest option through repeated comparison and scored the highest in the decision matrix analysis.

Table 5: Concept Generation

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 

A Pugh Chart was used to systematically evaluate the four concepts against the competitor datum based on criteria like Affordability, Aesthetic, Functionality, Durability, and Manufacturability. The final selected design adopted the features from the highest-ranking concepts shown below.

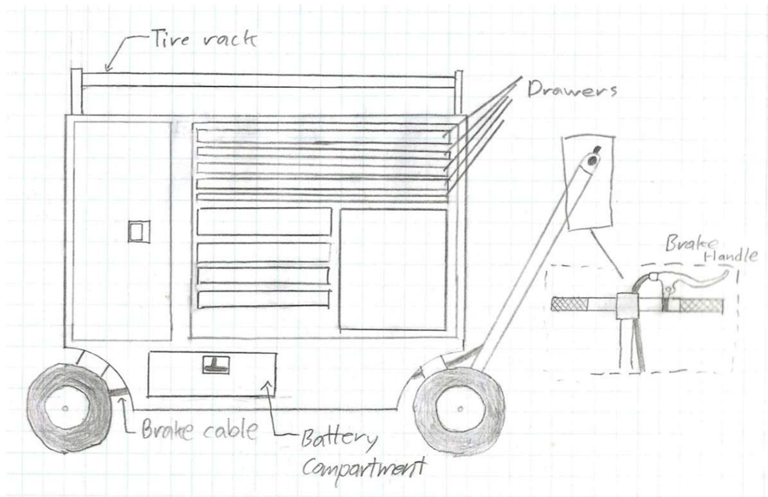


Figure 10: Design 1

Components: A3, B3, C3, D3, E2, F3, G1

Design 1 Description: This tool cart contains a forward mounted toolbox that has an empty compartment towards the rear for the driver's gear. The casters are 8.5 inches tall with a disc brake rotor mounted on the rear axle. The brake caliper will be mounted to the underside of the tool cart. The brake cable will be operated by a brake lever on the steering handle. The brake lever will be like levers seen on bicycles but work in a reversed fashion. For the cart to move the lever must be depressed.

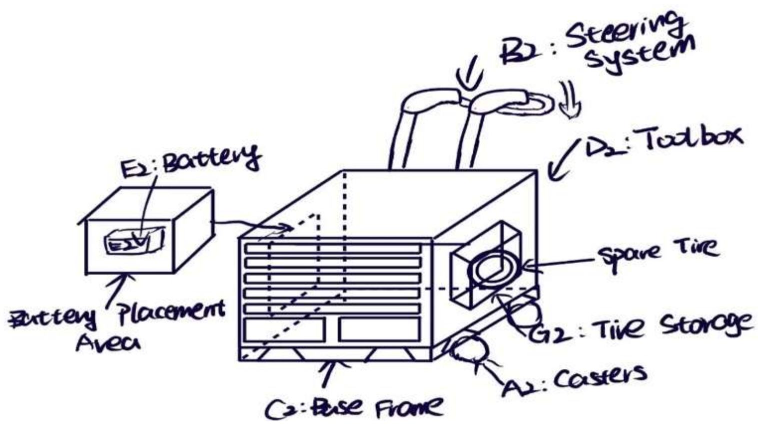


Figure 11: Design 2

Components: A2, B2, C2, D2, E2, F2, G2

Design 2 Description: This tool cart design incorporates a modular drawer-style toolbox (D2) mounted on the upper front section, allowing efficient access to tools during operation. A dual-handle steering system (B2), inspired by airport push carts, is attached to the rear and integrates a brake lever mechanism for enhanced control. The base frame (C2) adopts an outward-contoured profile with reinforced corner castors (A1), designed for stable mobility on varied terrain. A spare tire is stored in a dedicated side cavity (G2) to ensure rapid replacement during operation. The power system (E2) utilizes a portable 12V battery, which is placed in a clearly designated battery compartment at the rear of the cart. This layout ensures a compact, highly functional structure suitable for field engineering or maintenance work.

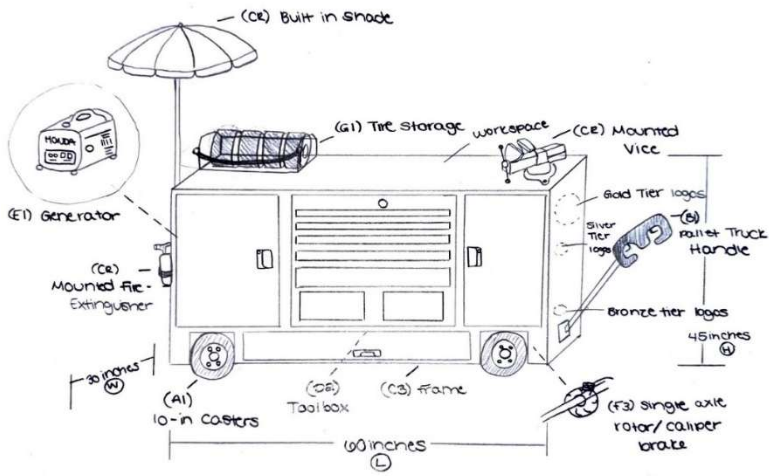


Figure 12: Design 3

Components: A1, B1, C3, D2, E1, F3, G1

Design 3 Description: This integrates a range of thoughtfully selected components to meet the demands of off-road environments and hands-on field work. It rides on large 10-inch axle-mounted casters (A1), which provide the necessary ground clearance and stability for rough terrain. Steering is managed through a pallet truck-style handle (B1) connected to a tie rod system, allowing for intuitive, controlled navigation. The main structure (C3) consists of a 60" long, 30" wide, and 45" high frame made from 1.5" x 1.5" square steel tubing, offering a durable and rigid platform for all mounted features. Tool organization is handled by a 5-drawer toolbox (D2) integrated into the frame, keeping essential items easily accessible. For portable power, a Honda EU2200i generator (E1) is securely stored in a side cubby, enabling on-site charging of tools and powering of auxiliary systems. Braking is achieved via a rotor and caliper (F3) installed on the non-steering axle, allowing the cart to be safely stopped and secured on uneven ground. Tire storage (G1) is located on top of the toolbox, featuring a chain-assisted access mechanism for quick loading and unloading. Additional features include customer-requested elements such as a mounted umbrella for shade, a fire extinguisher for safety compliance, sponsor branding areas with gold, silver, and bronze tier placements, and a bench-mounted vice on the top surface for field repairs and fabrication tasks.

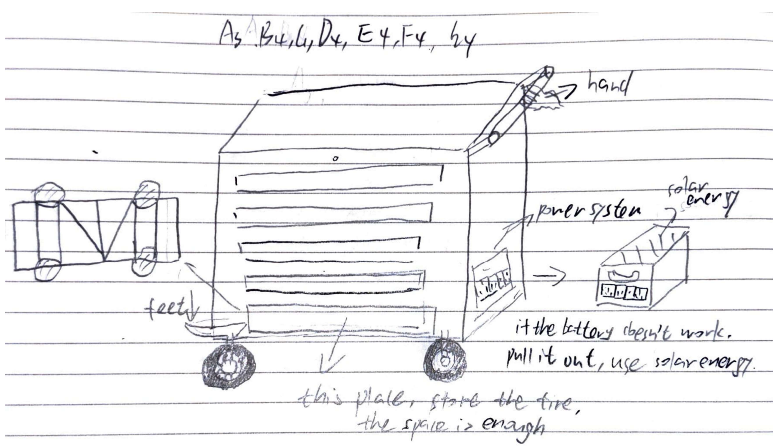


Figure 13: Design 4

Components: A3, B4, C1, D4, E4, F4, G4

Design 4 Description: This design presents a compact, functional tool cart ideal for rugged fieldwork and mobile service tasks. It runs on four 8.5-inch off-road casters (A3) with center-mounted hubs, ensuring stability on uneven terrain. Steering is handled via a standard two-hand grip bar (B4) for smooth directional control, while the base frame (C1) uses square tubing and inward-mounted wheels for strength and simplicity. The storage system (D4) features large top and bottom compartments and mirrored middle cabinets to maintain weight balance. All cabinets include locks for safety during movement. A solar-powered backup unit (E4) is housed in the right rear compartment and can be pulled out if the main battery fails. Braking is achieved using a foot-operated caliper above the wheel (F4), with an additional wheel lock to ensure stability. A spacious lower compartment (G4) stores larger items. Altogether, this cart balances durability, accessibility, and off-grid reliability.

Table 6: 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

An explanation of each criterion is as follows:

- **Affordability** – The toolbox should be cost-effective, ensuring accessibility without compromising performance.
- **Aesthetic** – The toolbox design should be visually appealing while maintaining functionality.
- **Durability** – The toolbox must be able to withstand rough terrain and heavy usage without significant wear or failure.
- **Lightweight** – The design must be lightweight to optimize efficiency and minimize added weight.
- **Add-on Components** – The toolbox must include all necessary components for pit usage.
- **Quality Materials** – The toolbox must use high-quality materials to ensure durability and reliability under various conditions.

This analysis ensures that each proposed design is judged on consistent, project-relevant metrics and that the final selected design reflects the optimal tradeoff between performance, cost, and manufacturability.

From the Pugh chart, designs 1 and 3 had the greatest number of “pluses” based on the criterion and the datum of the competitors toolboxes. After taking the top two designs from the Pugh Chart, they were evaluated in a Decision Matrix. This is displayed below in Table 7.

Table 7: 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%**

The selected design, design three, featured a sixty inch by thirty-two-inch footprint constructed from square steel tubing. Steering was achieved through a go cart style tie rod system connected to a long handle, which demonstrated smooth motion and a compact turning radius during SolidWorks motion studies. The design incorporated a central toolbox, large side cabinets, and a top work surface to maximize organization. The final configuration balanced strength, manufacturability, storage capability, and user friendliness.

6. Project Management

The project spanned the Summer 2025 and Fall 2025 semesters and followed a structured timeline that allocated phases for research, concept development, procurement, fabrication, and testing. Early project challenges included delays in updating the Gantt chart and uneven task delegation, which were later resolved through weekly meetings with assigned responsibilities for documentation, time management, and task tracking.

Table 8: Fall 2025 Gantt Chart

Owner	ACTIVITY	PLAN START	PLAN DURATION	DUE DATE	ACTUAL DURATION	PERCENT COMPLETE	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
							25-Aug	1-Sep	8-Sep	15-Sep	22-Sep	29-Sep	6-Oct	13-Oct	20-Oct	27-Oct	3-Nov	10-Nov	17-Nov	24-Nov	1-Dec	8-Dec
All	486C Kickoff	26-Aug	2	26-Aug	3	100%																
All	Academic Integrity	25-Aug	1	29-Aug	1	100%																
Hailey	Project Management	25-Aug	6	30-Aug	8	100%																
Hailey	Timecard Wk1	2-Sep	0.5	2-Sep	0.25	100%																
Hailey	Timecard Wk2	8-Sep	0.5	8-Sep	0.25	100%																
All	Engineering Calc Sum	1-Sep	5	10-Sep	7	100%																
All	Individual Analysis	1-Sep	8	12-Sep	9	100%																
Hailey	Timecard Wk3	15-Sep	0.5	15-Sep	0.25	100%																
Hailey	Timecard Wk4	22-Sep	0.5	22-Sep	0.25	100%																
All	33% Presentation work	19-Sep	8	23-Sep	10	100%																
All	Machine shop work day	20-Sep	6	21-Sep	7	100%																
All	33+% Presentation	20-Sep	5	23-Sep	7	100%																
All	Peer Eval 1	26-Sep	1	26-Sep	1	100%																
Hailey	Timecard Wk5	29-Sep	0.5	29-Sep	1	100%																
Hailey	Timecard Wk6	6-Oct	0.5	6-Oct	1	100%																
Yanbo	Website Check #1	10-Oct	6	10-Oct	4	100%																
Hailey	Timecard Wk7	13-Oct	0.5	13-Oct	1	100%																
Haoran	Inverter Load Testing	6-Oct	6	14-Oct	5	100%																
Derek	Brake CAD Building	6-Oct	7	14-Oct	8	100%																
Hailey	Sponsor frame tracking	29-Sep	1	14-Oct	2	100%																
SHOP	Frame Welding	13-Oct	6	16-Oct	4.75	100%																
All	67% Presentation Work	1-Oct	5	14-Oct	13	100%																
All	67+% Build Delivery	1-Oct	5	14-Oct	3.5	100%																
Hailey	Timecard Wk8	20-Oct	0.5	20-Oct	0.5	100%																
Derek	UGRADs Registration	1-Oct	2	23-Oct	4	100%																
All	Peer Eval 2	24-Oct	1	24-Oct	1	100%																
Hailey	Timecard Wk9	27-Oct	0.5	27-Oct	0.5	100%																
All	Draft of Poster	15-Sep	8	30-Oct	7	100%																
Derek	Physical Testing Part 1	15-Sep	15	30-Oct	3	50%																
Haoran	Finalized Testing Plan	5-Oct	4	31-Oct	6	100%																
HH & DG	Frame Manufacturing	20-Oct	12	26-Oct	18.5	100%																
Hailey	Misc tool mounting	24-Oct	2	3-Nov	7.75	100%																
ALL	Panel vinyl wrap	28-Oct	4	3-Nov	4.5	100%																
ALL	Panel mouting	28-Oct	3	3-Nov	6	100%																
Hailey	Timecard Wk10	3-Nov	0.5	3-Nov	0.5	100%																
All	100% Presentation Work	20-Oct	6	4-Nov	4	100%																
All	100% Build Delivery	6-Nov	8	4-Nov	3	100%																
Hailey	Timecard Wk11	11-Nov	0.5	11-Nov	0.1	100%																
All	Peer Eval 3	14-Nov	1	14-Nov	0.25	100%																
All	Final Poster and PPT	15-Oct	6	16-Nov	10.75	100%																
Hailey	Timecard Wk12	17-Nov	0.5	17-Nov	0.1	100%																
Derek	Initial Testing Results	5-Nov	8	20-Nov	12.5	100%																
Hailey	Final CAD Packet	15-Nov	15	21-Nov	22.25	100%																
Hailey	Timecard Wk13	24-Nov	0.5	24-Nov	0.1	100%																
Derek	Final Testing Results	5-Nov	8	26-Nov	8.5	100%																
Hailey	Timecard Wk14	1-Dec	0.5	1-Dec	0.1	100%																
All	Final Report	10-Nov	20	2-Dec	12	100%																
Yanbo	Final Website Check	3-Dec	5	3-Dec	7.75	100%																
Haoran	Final Product Demo	4-Dec	8	4-Dec	5	100%																
Derek	Assembly Manual	17-Nov	6	4-Dec	6.75	100%																
All	Poster Results	5-Dec	3	5-Dec	0.25	100%																
Hailey	Timecard Wk15	8-Dec	0.5	8-Dec	0.1	100%																
All	Client Handoff	1-Dec	4	10-Dec	5.25	100%																
All	(FINAL) Peer Eval 4	11-Dec	1	11-Dec	0.5	100%																

Team members held clearly defined roles throughout the project. Derek Griffith served as the primary prototype and manufacturing engineer. Hailey Hein led logistics, CAD modeling, and financial management while also supporting manufacturing. Haoran Li directed testing and timeline maintenance. Yanbo Wang managed the website and report development. The project was funded through two thousand dollars from NAU SAE, a discounted base frame from a sponsor, and a five hundred- and one-dollar contribution from Findlay Toyota. Northern Arizona Signs donated full vinyl wrap services.

Table 9: Order Form Tracker

Location	Parts	Price	Status	Method
Amazon	Extinguisher mount, 25 ft cord, safety wire pliers, power strip, brake bleed kit	$ 117.25	Delivered	Budget
Amazon	Inverter generator	$ 294.90	Delivered	Budget
Walmart	Toolbox	$ 284.39	Delivered	Budget
Summit	Formula push-jack	$ 290.84	Delivered	Budget
McMaster-Carr	1x1" steel bars + aluminum panels	$ 1,056.29	Delivered	Budget
Lane Auto	Base frame, wheels, steering	$ 403.87	Delivered	Discounted
Amazon	Magnet door latches	$ 17.87	Delivered	Budget
Home Depot	Diamond plate aluminum panels	$ 100.48	In-Person	Budget
Harbor Freight	Vice, super glue, bungees, safety wire	$ 77.59	In-Person	Budget
Harbor Freight	Rivets	$ 8.74	In-Person	Budget
Grainger	Brakes	$ 82.12	Delivered	Sponsored
Grainger	Spring-loaded handles	$ 98.22	Delivered	Sponsored
Home Depot	Handle hardware	$ 12.36	In-Person	Sponsored
McMaster-Carr	Drawer latch springs	$ 10.07	Delivered	Sponsored
Total Spent / $2,475.95		$ 2,534.97		
Over Budget /Leftover Funds		-$59.02		

Table 10: Full BOM

Subassembly	Part #	Description	Qty	Price	Total	Manufacturer	Status
Frame		Roller pit cart frame with casters	1	$ 695.00	$ 405.00	Lane Autmotive	Delivered
	6527K174	1x1" Steel Tubing 0.065" 6ft	18	$ 17.05	$ 306.90	McMaster	Delivered
	8973K258	36x96 Aluminum paneling 0.020"	4	$ 130.21	$ 520.84	McMaster	Delivered
Toolbox		13"Dx24.25"Wx29.33"H Box with 238 tools	1	$ 169.99	$ 276.36	Artman	Delivered
Tools		Fire extinguisher mount for 2.5lb extinguisher	1	$ 13.94	$ 13.94	Alert	Delivered
		9" Safety wire plier kit	1	$ 17.98	$ 17.98	Gunpla	Delivered
		Brake bleed kit	1	$ 19.99	$ 19.99	Wenzhon	Delivered
Power Supply		2500W Inverter Generator	1	$ 269.90	$ 286.58	Amerisun	Delivered
		120 V Power strip	1	$ 29.98	$ 29.98	Trond	Delivered
		25 ft Extension cord	1	$ 12.74	$ 12.74	Amazon	Delivered
Misc		Magnetic door latch	16	$ 16.99	$ 33.98	Amazon	Delivered
		6" Vice	1	$ 65.00	$ 65.00	Harbor Freight	Delivered
Completion		TOTAL TAX + SHIPPING	-	-	$ 279.80	-	-
					$2,534.97		
Extra Bonus Parts:							
Ancillary		Formula rear swivel lift jack	1	$ 265.88	$ 265.88	Summit Racing	Delivered

Trailer ramp		Hinged aluminum trailer ramp extension	1	$ 74.11	$ 74.11	Justsail	Cancelled
Shade		4.6x6.6ft Pullout sun shade with legs (55" L)	1	$ 89.99	$ 89.99	SKYSHALO	
Brakes		Brake kit for miller fab frame	1	$ 935.00	$ 935.00	Miller Fab	
		Umbrella	1	$ 39.99	$ 39.99	Amazon	
		Tie-down anchors 4 pcs	1	$ 14.99	$ 14.99	Pamazy	
		Brake kit (Calipers, handles, cords, rotors) x2	1	$ 26.99	$ 26.99	Amazon	Returned
Workspace		Fold down aluminum table tray to mount	1	$ 59.00	$ 59.00	Holzoffer	
Jacks		Race Ramps 10" Wheel lifts	2	$ 212.19	$ 240.00	Race Ramps	
Casters		Spare toolcart bolt on tire	1	$ 64.99	$ 64.99	Miller Fab	
Sound system		Bluetooth speaker	1	$ 19.98	$ 19.98	Chifenchy	
Misc		Door Handles	6	$ 44.29	$ 47.60	Amazon	Returned
		Door hinges	12	$ 5.99	$ 7.12	Amazon	Returned

Through sponsorship and careful budgeting, the project remained financially viable despite a final estimated cost that slightly exceeded the original budget. The team finalized all ordering during the fall semester and assigned subsystem leaders for the frame, braking system, power system, and cabinet structures to improve the efficiency of decision making.

The manufacturing plan for the tool cart included coordinated production and assembly of all structural and functional components. The two by one steel base frame was completed at the sponsor shop in approximately two hours, where it was delivered and assembled. The one-by-one steel frame shell required the most fabrication time, totaling eighteen and a half hours at the ninety-eight C machine shop where it was cut, fitted, and welded. Aluminum paneling was produced and installed over seven and a quarter hour, including cutting, wrapping, and mounting. The flat strap tire carrier was fabricated and mounted through joint work between the sponsor and the machine shop in two and a half hours. Additional components, including the steering handle and the extinguisher mount, were installed efficiently with under half an hour of labor each. Brake construction and mounting required two- and three-quarter hours and included iterative adjustments during testing. The door latch and handle installation took three and a half hours, and the three-dimensional printed toolbox drawer latch required one- and three-quarter hours to achieve a functional design that will be improved in future iterations.

Table 11: Manufacturing Plan

Part	Manufacture Status	Location	Hours	Comment
2x1” Steel Base Frame	100%	Sponsor Shop	2	Arrived/Assembled
1x1” Steel Frame shell	100%	98C Machine Shop	18.5	Cut & Welded
Aluminum Paneling	100%	98C Machine Shop	7.25	Cut, Wrapped & Mounted
3/16” Flat-strap Tire Carrier	100%	Sponsor/Machine Shop	2.5	Mounted
Steering Handle	100%	Sponsor Shop	0.25	Installed
Extinguisher mounting	100%	98C Machine Shop	0.25	Mounted
Brake Build/Mounting	100%	98C Machine Shop	2.75	Being tested/changed
Door latch/handle install	100%	98C Machine Shop	3.5	Mounted
Toolbox drawer latch 3D	100%	98C Machine Shop	1.75	Functional, redesigned

7. Final Hardware

Figure 14: Completed NAU SAE Toolbox Capstone

The completed tool cart integrates all major subsystems into a cohesive structure designed to withstand demanding competition environments. The frame consists of one-inch square steel tubing with welded joints and reinforced bracing to support a five-hundred-pound load. Structural calculations and early FEA work confirmed adequate strength for anticipated loads.

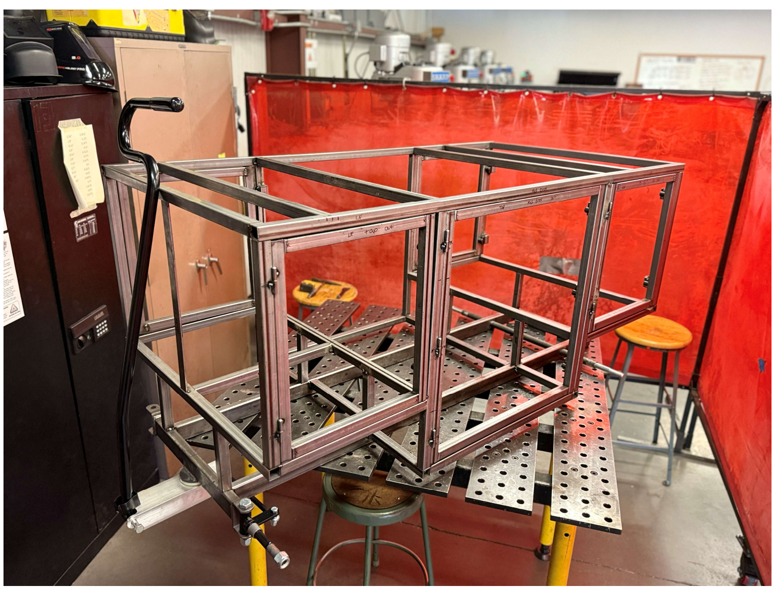


Figure 15: Raw Welded A36 Steel Frame

The steering system uses thirteen-inch pneumatic casters connected through two tie rods to a thirty-eight-inch steering handle. This configuration provides controlled maneuvering across gravel, asphalt, and packed dirt. Rolling resistance calculations confirmed the required push force remained within acceptable ergonomic limits for a single operator.

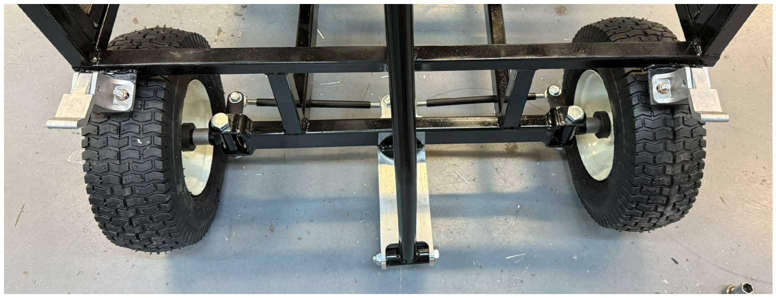


Figure 16: Steering Components and Handle

A foot operated brake latch provides reliable stopping performance. Structural and force calculations confirmed that the brake system can bring the fully loaded cart to a controlled stop within the target distance.

Figure 17: Rear Tire Brakes

Storage consists of a four-drawer locking toolbox mounted centrally, two side cabinets with hinged doors, and a large rear cabinet. All storage locations include secure latching mechanisms to prevent accidental opening.

Figure 18: Open Cabinet Space

Figure 19: Front Cabinet and Toolbox Space

A top mounted tire carrier holds four full size race tires. The power system bay accommodates a two thousand five-hundred-watt inverter generator and a power strip for charging tools.

Figure 20: Loaded Tire Carrier

Figure 21: Loaded Inverter Generator Power Source

8. Testing

Prototype testing included virtual simulation, analytical modeling, and physical validation of all major subsystems. The goal of testing was to verify that the toolbox cart met the engineering requirements (ERs) and customer requirements (CRs) established during the design phase. Testing was performed iteratively, informing component redesigns and modifications throughout the semester.

Table 12: Sub-system Prototype Overview

Sub-System	Question	Answer	Informed Design
Steering	Will the tie rod and handle steering system provide sufficient turning radius and mechanical advantage for off-road maneuverability?	The radius rods provide a sufficient turning angle for maneuvering.	The tie-rods moved from the front of the steering to the rear to prevent any bending from outside objects.
Tire Carrier	Is 6061-T6 aluminum sufficient to withstand deflection of bouncing tires?	0.0322” deflection from 4 25lb tires.	Manufactured the final carrier out of 3/16” steel flat strap to achieve 0” of deflection.
Handle Brake	Can we create a system that keeps the brakes engaged until pulled?	The bike brakes stay engaged until the handle is pulled.	Ideal, however, there is not a moving axle to mount this to.
Foot Brake	Can a push-on foot brake hold the cart at a stop?	The brakes hold the cart stopped when engaged.	There is rubbing that occurs when the cart is turning, this system was moved to the rear of the cart.
Scale Model	Can we reduce the height/width/length to better the center of gravity?	The height can be reduced to fit directly on top of the toolbox.	The center of gravity has reduced, increasing the stability and reducing the tipping angle.

8.1 Virtual Validation (CAD and FEA)

8.1.1 Steering Motion Study

Virtual validation began with a detailed steering motion study in SolidWorks. The analysis confirmed that the steering linkage produced smooth articulation through the full range of motion and generated wheel angles appropriate for Ackermann steering. At full lock, the left wheel reached approximately 27.4 degrees while the right wheel reached approximately 39.4 degrees, forming a turning radius that met the original maneuverability objectives. The motion study demonstrated that the tie-rod geometry operated without binding or interference and confirmed that single-person steering would be achievable during physical testing.

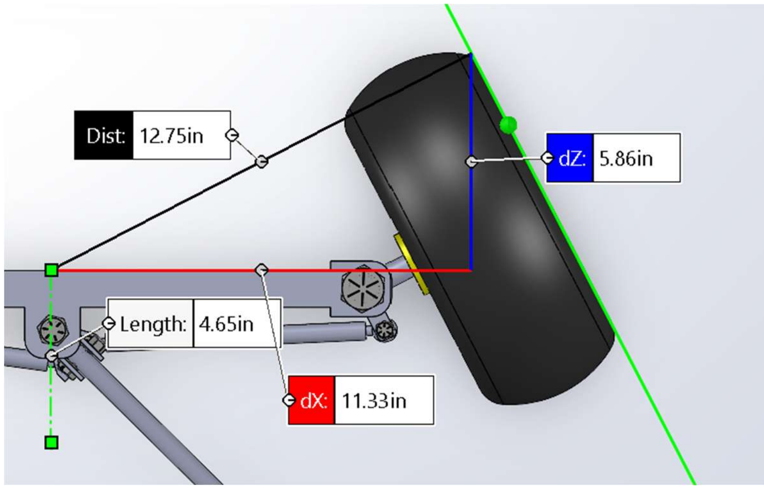


Figure 22: Turning Radius Measurements

8.1.2 Tire Carrier FEA Analysis

Finite element analysis was performed on the main frame and on the original 6061-T6 aluminum tire carrier to evaluate structural performance under the expected loads of four off-road tires. With approximately 444.8 N applied to each tire contact surface, the aluminum carrier experienced a maximum displacement of 0.0332 inches. Although stress remained below the material's yield strength, the measured deflection exceeded the acceptable limits for secure tire storage. This simulation prompted a redesign that replaced the aluminum tub with a 3/16-inch steel flat-strap carrier, which eliminated measurable deflection. Additional frame FEA indicated the need for reinforcement at key load-bearing areas of the 1×1-inch tubing, and strengthening these areas improved stiffness before physical testing commenced.

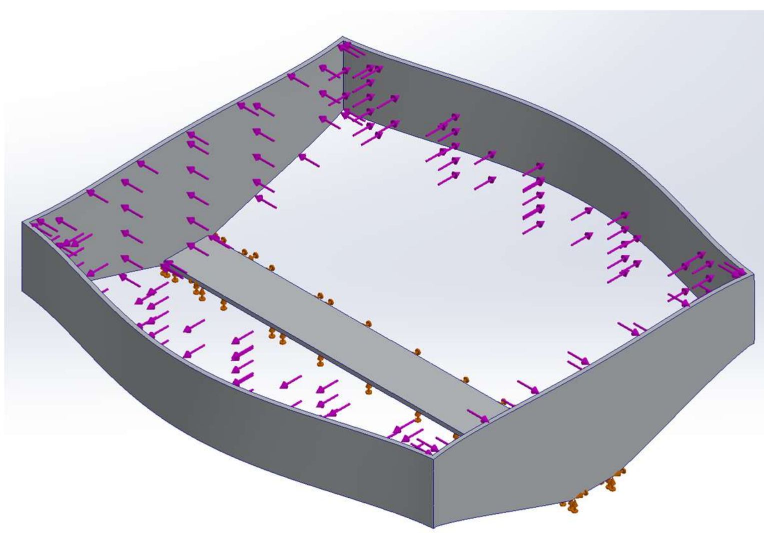


Figure 23: Aluminum Tire Carrier FEA Analysis

8.2 Physical Test Validation

Physical testing confirmed real world performance. Loaded maneuverability tests evaluated the ease of pushing the cart across uneven terrain. Brake testing demonstrated the carts ability to stop safely on inclines. A mock technical inspection ensured compliance with Formula and Baja team safety requirements. Storage testing verified the fitment of driver gear, fire extinguisher systems, and powered tool storage. All drawers and latches were checked under vibration and incline conditions.

Table 13: Testing Summary Breakdown

Experiment/Test	Relevant DR's	Testing Equipment Needed	Testing location/Other
1. Brake application	CR4 -Fast brake response ER3 – Wheel locking	Completed cart, installed brakes, wrenches	Inclined parking lot 98C
2. Power Supply	CR6 – Essential Equipment ER8 – Integrated Power Output ER9 – Powered tool storage volume	Inverter generator, gas, 10W-30 oil, tools	NAU Machine shop 98C
3. Turning Radius	CR4 – Single person steering ER2 – Steering system	Completed cart, SAE enclosed trailer	NAU Machine shop 98C
4. Weight capacity	CR1 – Large organized toolbox cart CR2 – Driver equipment CR3 – Ancillary equipment CR6 – Essential equipment storage ER4 – Volumetric footprint ER13 – Frame materials	Various heavy objects, all tooling, 4 scales	NAU Machine shop 98C
5. Equipment fitment	CR2 – Driver equipment CR3 – Ancillary equipment CR6 – Correct tooling ER7 – Fire extinguisher holder ER9 – Powered tool storage volume ER14 – Emergency storage volume	Completed cart, driver equipment, tools, tires	NAU Machine shop 98C
6. Correct tools	CR6 – Essential equipment ER6 – Driver gear storage volume	Tools and toolbox, SAE tech sheet, Baja car	NAU Machine shop 98C
7. Drawers/door latches	CR2 – Equipment holding ER5 – Drawer security	Drawer latches and magnets, blocks for incline	NAU Machine shop 98C

8.2.1 Brake Testing

The braking system was tested to determine whether the integrated foot brake could securely hold the fully loaded cart on inclined surfaces. With the cart loaded to approximately 500 pounds, the brake successfully held the cart stationery at a 13-degree incline but slipped at 17 degrees. Initial iterations of the brake were mounted at the front of the cart and experienced rubbing during steering maneuvers; relocating the brake assembly to the rear resolved the interference. Once relocated, the brake engaged reliably, provided consistent stopping performance, and met the requirement for safe, single-operator control on typical race-day and shop inclines.

Table 14: Detailed Brake Testing Plan

Test Experiment/ Summary	o **Question to be answered:** Will the integrated foot brake and wheel locking system reliably stop and secure the fully loaded cart, allowing for safe, single person operation and stable parking on inclined surfaces? o **DRs being tested:** CR4 (integrated braking for safe and easy single person operation) and ER3 (foot brake and locking wheel system to ensure the cart remains stationary when parked). o **Equipment needed:** Full load of tools and driver gear (to simulate maximum operating weight, estimated at 500 lbs), an inclinometer (or a digital level with angle function). o **Variables to be calculated:** The required brake engagement force (force applied to the foot handle/lever) to secure the cart and the required coefficient of friction (μ) between the wheels and the surface to prevent rolling on the measured incline.
Procedure	1. Fully load the cart to its maximum projected operational weight (500 lbs). 2. Identify an inclined ramp or surface. Using the inclinometer or phone, measure and mark the angle of the incline. 3. Push the cart onto the inclined surface, engage the brakes, and release the cart. Observe and record if the cart begins to roll down the incline. 4. Repeat step 3, incrementally increasing the incline angle (θ) until the cart just begins to slip. Record this maximum statiangle.θ_{max}).
Results	o **Kind of results looked for:** The cart must not move on the incline when the brake is engaged. o **Expected result:** The cart will remain stationary when brakes are engaged.

Figure 24: 13 Degree Incline – PASS

Figure 25: 17 Degree Incline – FAIL

8.2.2 Power Supply Testing

Testing of the inverter generator evaluated its ability to deliver continuous electrical power to onboard outlets and tool-charging stations. The generator was loaded incrementally and monitored for voltage stability, current draw, temperature rise, and signs of overload or thermal shutdown. The unit maintained stable output throughout all load steps, including at full capacity, and successfully powered chargers inside the tool storage compartment even when the generator was under heavy load. Operational measurements included an 11-hour runtime at 25 percent load, 5.5 hours at 50 percent load, and a noise level between 56 and 59 decibels from 23 feet away. The generator's consistent performance validated its suitability for powering tools, chargers, and auxiliary devices during competition.

Table 15: Detailed Power Supply Testing Plan

Test Experiment /Summary	o **Question to be answered**: Does the integrated power system deliver its rated continuous output and operate the powered-tool outlets reliably, to support charging in the powered tool storage? o **DRs being tested**: ER8, ER9 o **Equipment needed:** Resistive load bank (or combination loads such as tool chargers, phone chargers), true-RMS power meter (measuring V_{rms}, I_{rms}, P), multimeter, thermometer/thermocouple for inverter heat sink, stopwatch, extension cord to the powered tool storage outlet, representative battery charger/power tool. o **Variables isolated for measurement:** Output voltage, current, real power, outlet functionality inside storage, inverter surface temperature, breaker/fuse trip or alarms (Y/N). o **Variables to be calculated:**

	Output power: $P_{out} = V_{rms}I_{rms}$ (resistive loads), Voltage regulation: $\Delta V\% = \frac{V_{load}-V_{no-load}}{V_{nom}} \times 100\%$, Efficiency (if input is measurable): $\eta = \frac{P_{out}}{P_{in}}$, Energy delivered during a hold: $E = P_{out}t$.
Procedure	1. Safety & setup: Verify wiring/polarity, breaker rating, ventilation, and meter calibration. Connect the power meter at the inverter output; route a cord to the powered-tool storage outlet. 2. No-load baseline: Measure $V_{no-load}$ and ambient/inverter temperatures. 3. Step loading: Apply loads at 25%, 50%, 75%, and 100% of the nameplate rating. Hold 10 min at each step; log V, I, P every minute; note any alarms or sag. 4. Transient check: Switch from 0% → 100% → 50% → 100% (1–2 s transitions). Record minimum voltage dip and recovery time. 5. Full-power endurance: Operate at 100% for 30 min. Record steady P_{out}, voltage regulation and inverter temperature rise. 6. Powered-tool storage outlet (ER9): Plug a representative charger/power tool into the storage-area outlet. Confirm continuous charging/operation for 10 min while the main load is at 50% and then at 100%. 7. Documentation: Photos/video of meters and setup; complete the results table.
Results	**Kind of results looked for:** o At 100% load, the inverter provides stable output power with voltage within acceptable limits (no nuisance trips, alarms, or thermal shutdown). o Powered-tool outlet in the storage compartment operates the charger/tool without interruption at 50% and 100% system load. o Transient dips are modest and recover quickly; breaker/fuse status remains normal. o Endurance run shows temperature rise within manufacturer guidance.

8.2.3 Turning Radius and Steering Maneuverability Testing

A fully loaded cart was used to evaluate real-world steering performance, turning radius, and operator effort. Testing included navigating a marked S-curve, completing a 180-degree turn in a confined space, and traveling across uneven surfaces such as small hills and rough shop flooring. The cart produced a measured turning radius of 101.25 inches and a circular turning diameter of 202.5 inches, aligning with expectations from the motion study. Steering remained smooth throughout the tests and required minimal operator input, confirming the mechanical efficiency of the handle-and-tie-rod system. No interference occurred between the steering mechanism and the braking hardware, demonstrating successful packaging of both systems.

Table 16: Detailed Turning Radius Testing Plan

Test Experiment /Summary	○ **Question to be answered**: Will the manual steering system provide smooth, controllable motion in tight spaces and remain usable when the brake mechanism is present (no mechanical interference), enabling safe, single-person operation?
	○ **DRs being tested:** CR4 (integrated braking and steering for safe and easy single-person operation) and ER2 (integrated manual steering system for controlled movement in tight spaces). (Packaging/clearance cross-check with ER4.)
	○ **Equipment needed:** Fully loaded cart (projected operational weight), digital force gauge or spring scale (attach to push/steer handle), torque adapter for handle (optional), digital angle gauge or protractor, measuring tape, floor cones/tape to create a narrow corridor (tight-space course), chalk/marker for path tracing, camera/phone, wheel chocks.
	○ **Variables isolated for measurement:**
	  ○ Steering input at the handle: force F_{hand}.
	  ○ Maximum steering angle achieved at the wheels/handle(θ_{max}).
	  ○ Minimum turning radius of the cart R_{meas} and ability to follow an S-curve inside a marked corridor (tight-space controllability).
	  ○ Interference/binding with the brake hardware or cables (Yes/No) in both brake-released and brake-applied states.
	○ **Variables to be calculated:**
	  ○ Turning radius from path geometry. Trace a constant-radius arc; measure chord s and mid-ordinate (sagitta) d.
	  ○ Minimum aisle width for a 180° turn (no backing):
	  ○ Estimated steady pushing/steering force on smooth concrete using rolling-resistance:

Procedure	1. Load & safety: Fully load the cart to its maximum projected operating weight. Install wheel chocks when stationary.
	2. Static steering sweep (brake released): From the center position, sweep the steering/handle to left and right extremes three times. Record $\theta_{\max}$, note any binding or interference.
	3. Brake-applied clearance check: Apply the brake/lock. Repeat the sweep. Confirm there is no mechanical interference with brake linkages/cables and that the steering mechanism still moves freely (cart remains stationary).
	4. Tight-space course setup: Mark a straight corridor with floor tape (width chosen by the team to represent a pit/shop aisle). Place cones to form an S-curve and a 180° turn pad; chalk the cart path.
	5. Slow-speed steering test (brake released): A single operator pushes at walking speed and completes:
	  ○ One S-curve pass without touching the boundary lines.
	  ○ One 180° turn within the marked pad.

	6. Turning-radius data capture: On the 180° turn, mark three points along the inner wheel path and measure diameter to compute R. 7. Repeatability: Repeat Step 5–6 two additional times; record video/photos and all measurements. 8. Post-inspection: Check all steering fasteners, linkages, and casters for loosening or rubbing; document findings.
Results	**Kind of results looked for:** o Smooth, continuous steering range with no binding or brake-hardware interference. o Single-operator completion of the S-curve and 180° turn inside the marked corridor (tight-space controllability). o Recorded handle input F_{hand}, measured , computed R_{meas} and W_{min} .

Figure 26: Marked Turning Diameter

8.2.4 Weight Capacity Testing

To verify the load-bearing capacity of the cart, the structure was loaded with tools, equipment, and tires for a total measured weight of 386 pounds. The weight distribution across the four wheels measured 72 pounds at the right front, 96 pounds at the left front, 124 pounds at the right rear, and 94 pounds at the left rear. The frame showed no permanent deformation during or after loading, and welds remained intact with no signs of fatigue or cracking. Casters rolled smoothly under load, and no bolts loosened during travel over a one-inch floor threshold. This test confirmed that the cart frame and wheels safely support the operational payload.

Table 17: Detailed Weight Capacity Testing Plan

Test Experiment /Summary	○ **Question to be answered:** Can the cart withstand the full intended payload (tools, wheels, driver gear) without permanent deformation or loose joints, and are the casters and frame members adequately rated? (Supports CR3; checks attachment quality per ER13 welded frame with bolted accessories.) ○ **DRs being tested:** CR3, ER13. ○ **Equipment needed:** Full set of heavy objects/actual tooling (to reach maximum intended payload), floor scale (or scale + mass list) to obtain total weight W, dial indicators (or ruler/feeler) for deflection, tape measure, torque wrench, paint pen for bolt marks, camera/phone. ○ **Variables isolated for measurement:** 　○ Total loaded weight W. 　○ Static deflection at critical points (deck/frame mid-spans) δ_{meas}. 　○ Joint integrity (bolt loosening, weld cracks) Y/N; caster condition Y/N. ○ **Variables to be calculated:** 　○ Per-caster load (four casters assumed; use actual distribution if different) 　○ Caster safety factor
Procedure	1. Baseline: Empty cart; set dial indicators at selected mid-span points (deck center; long side rail mid-span). Zero readings; inspect and mark bolts. 2. Load-up: Place heavy objects/tools to reach the design maximum payload; record total W. If possible, weigh wheels/boxes as added to confirm tally. 3. Static check: With the cart stationery on level floor, record deflection δ_{meas} at all points. 4. Settle & roll: Slowly roll 10–15 m on level floor and traverse a 1 in threshold once to settle the load; re-check deflection and bolt marks. 5. Unload check: Remove the payload; read indicators to obtain residual set δ_{perm}. 6. Documentation: Photos/video and a results table (locations, readings, pass/fail).
Results	**Kind of results looked for:** 　○ No permanent deformation: $\delta_{\text{perm}} \approx 0$. 　○ Deflection within limit: $\delta_{meas} \leq \delta_{allow}$ at all points. 　○ Joints/casters sound: no bolt loosening (paint marks aligned), no weld cracking; casters roll smoothly and show no overload marks.

Figure 27: Loaded Toolcart on Scales

8.2.5 Equipment Fitment Testing

Fitment testing was conducted to ensure that all required tools, driver equipment, emergency supplies, and spare tires could be stored safely and efficiently within the designated compartments. Every required item fit securely in its intended location, and all drawers and doors latched properly even when loaded with gear. The driver-equipment bay exceeded the six-cubic-foot minimum requirement, and both the powered-tool storage area and emergency-equipment compartments met the volume specifications established by design requirements. The tire carrier accommodated multiple wheels with stable retention using straps. These results demonstrated that the organization and storage layout met all capacity requirements for competition use.

Table 18: Detailed Equipment Fitment Testing Plan

Test Experiment /Summary	○ **Question to be answered:** Do the designated compartments and mounts fit all required items; tools, spare wheels/tires, and driver equipment (suits/helmets), so they can be stored securely and accessibly without interference? This validates organization (CR1), capacity (CR2), safe storage (CR6), driver-gear bay volume (ER6), powered-tool storage volume (ER9), and emergency/safety storage volume (ER14).
	○ **DRs being tested:** CR1, CR2, CR6; ER6, ER9, ER14.
	○ **Equipment needed:** Completed cart; the full kit of required tools; 3-4 spare wheels/tires, driver suits/helmets, fire extinguisher, brake-bleed kit, safety wire puller, tape measure & calipers, clip-board checklist, camera/phone, labels/marker.
	○ **Variables isolated for measurement:**
	    ○ Net bay dimensions *L, W, H* and volume *V* (ft^3).
	    ○ Item fit in the assigned location (Y/N) with clearance margin *m* (in).

	○ Closure & security: door/drawer closes and latches; straps/holders engaged (Y/N). ○ Accessibility: retrieval without re-packing; optional pick time t_{pick} (s). ○ **Variables to be calculated:** ○ Driver-gear bay volume: $V_{driver} = LWH \geq 6\ ft^3$(ER6). ○ Powered-tool storage volume: $V_{power} \approx 2\ ft^3$ target (ER9). ○ Emergency/safety storage total:$\sum V_{emerg} \geq 2\ ft^3$ (ER14). ○ Coverage ratio: $C = \frac{N_{present}}{N_{required}}$ for each category (tools/tires/driver gear). ○ Tire rack capacity: count N_{tires} and side/front clearance margin m_{tire}
Procedure	1. Checklist & mapping: Create a table listing every required item and its intended location (drawer/compartment/rack). 2. Measure volumes: Empty each relevant bay; measure net L, W, H (clear of hardware) and compute V. Record photos of the interior and dimensions. 3. Place items: Load tools, tires, and driver gear into their assigned locations. Confirm doors/drawers shut and latch; verify straps/holders are engaged for tires, extinguisher, and other safety items. 4. Accessibility check: Remove and replace a representative subset (e.g., helmet, torque wrench, charger) to ensure no repacking is required; optionally time t_{pick}. 5. Documentation: Photograph each bay before/after loading; complete the fitment checklist and volume table.
Results	**Kind of results looked for:** ○ All required items are present and fit in their assigned locations; doors/drawers close and latch; straps/holders secure. ○ Driver-gear bay $V_{\mathrm{driver}} \geq\ 6\ \mathrm{ft}^3$; powered-tool storage $V_{power}\ \approx\ 2\ ft^3$; emergency/safety storage total $\geq 2\ \mathrm{ft}^3$. ○ Tire rack holds the planned number of wheels with measurable side/front clearance; straps reach and tension correctly. ○ Coverage ratio C=1.00 (100%) for tools, tires, and driver gear.

Figure 28: Spare Hardware and Oil

Figure 29: Various Equipment

8.2.6 Tool Usage and Technical Inspection Readiness Testing

A complete mock SAE technical inspection was performed using only the tools stored on the cart. All required hand tools, measurement devices, and safety-related items were present, organized, and easily accessible. Team members were able to retrieve and return critical tools quickly due to clearly labeled compartments and predictable layout. This testing confirmed that the cart contained the necessary equipment to support both Baja SAE and Formula SAE technical inspections without requiring borrowed tools, validating that the design met its operational purpose.

Table 19: Detailed Tool Usage Testing Plan

Test Experiment /Summary	○ **Question to be answered:** With only the tools on the cart, can the team complete SAE tech inspection and routine pit work without borrowing tools, and can a single operator locate & return critical tool quickly?
	○ **DRs tested:** CR1 (organized toolbox), CR6 (safe storage).
	○ **Equipment needed:** Official/team tech-inspection tool checklist; toolbox, labels/foam cutouts, stopwatch, camera, calibration references (for torque wrench, calipers).
	○ **Variables isolated for measurement:**
	    ○ Presence & condition of each required tool (Y/N).
	    ○ Labeling/organization (slot/foam present) (Y/N).
	    ○ Retrieval time t_{pick} for critical tools (s).
	    ○ Calibration/accuracy status (Y/N).
	    ○ Consumables stock vs minimum list (Y/N).
	○ **Variables to be calculated from results:**
	    ○ Overall coverage: $C_{total} = \frac{N_{present}}{N_{required}}$.
	    ○ Critical-set coverage: $C_{crit} = \frac{N_{crit,present}}{N_{crit,req}}$.
	    ○ Spare ratio: $Rspare = \frac{Q_{on-ha}}{Q_{min}}$.
	    ○ Time metrics: median retrieval time t_{med} and 95th-percentile t95 .

Procedure	1. Prepare the inspection checklist and map each tool to a labeled slot/foam. 2. Inventory drawers: verify presence, condition, and labels; photograph. 3. Retrieval drill: One operator retrieves and returns 5 critical tools (e.g., torque wrench, 10–19 mm sockets, calipers, multimeter, safety-wire pliers) three times each; record t_{pick}. 4. Verify calibration/accuracy (certificate date or quick check). 5. Count consumables vs minimum list.
Results	**Kind of results looked for:** All required and critical tools present, labeled, functional drawers close/lock, retrieval is fast, consumables meet minimums.

Section	Rule	TM	TI	TIL	Failed Items	RC
	Cockpit					
B.8.3	This firewall must be metal, and at least 0.508 mm (0.020 in) thick. Large cutouts, including those for CVT and engine air intakes are explicitly prohibited. Drivetrain clearances are permitted per B.9.1 and have no gaps larger than 6.35mm (0.25in)			1		
B.8.7	Open universal joints in steering system near drivers feet shall be covered to prevent entanglement. Steering linkages shall be properly shielded and covered with a sturdy, full-width cover.			1		
B.8.6	Skid plate material must be metal, fiberglass, plastic, or similar material. Skid plates shall extend the length of the cockpit and prevent debris and foreign object intrusion into the cockpit.			1		
B.8.8	Fire extinguisher mounted on the right side, easily accessible, with the top below the driver's eye, and the top half above the SIM. Mounting bolts must meet B12 and match hole geometry. The pull knob shall be free and clear of any access obstructions. ***Radial clearance to the pull knob shall be 2.5 in.***			1		
B.12.2	The fire extinguisher may be mounted with traditional 0.125 in thick tabs per B.12.2, or by fuel tank style tabs per B.6.5.1.			1		
B.8.8.4	Mount must resist shaking loose, but the extinguisher must be easily removable.			1		
B.8.8	Two extinguishers with a Minimum UL rating of 5 B C; must be equipped with a **manufacturer installed dial gauge**; gauge must be **readable and properly charged**. Must have OEM pin retainer. No zip ties or tape.			1		
B.8.8.3	Fire extinguisher mount is the approved Drake or DV8 quick-release mount. No other mounts are acceptable.			1		
B.8.8.1	All extinguishers must be labeled with school name and car number.			1		
B.7.2	Only foot operated, cable throttle controls are allowed. Wide open throttle stop is required (at the pedal).			1		
B.7.2	Throttle cable cannot be bare from the forward mounting point to the firewall.			1		
B.8.3	The firewall shall separate the cockpit and engine area, covering the entire plane of the RRH. Pass throughs for 4WD equipment are permitted if sealed.			1		
B.8.5	Body panels must cover the area between LFS member and SIM. The material must be plastic, fiberglass, metal or similar material. No gaps can exist that are larger than 6.35 mm (0.25 in). Must use quick-disconnect methods.			1		

Figure 30: Baja SAE Tech Sheet Portion

8.2.7 Door/Drawer Latch Testing

Drawer latch performance was evaluated under vibration, shock, and incline conditions to ensure reliable closure during transport. Fully loaded drawers were subjected to rough-surface movement that generated approximately one to one-and-a-half g of continuous acceleration and short-duration shock pulses up to three g. None of the drawers opened during testing, and displacement remained minimal. Earlier latch designs experienced fatigue cracking, but the updated, reinforced latch withstood more than fifty open-and-close cycles without damage. The drawers also remained closed on a 13-degree incline, confirming that the new latch design provided reliable and secure storage protection.

Table 20: Detailed Latch Testing Plan

Test Experiment /Summary	o **Question to be answered:** Will each drawer remain securely latched (i.e., no self-opening and no excessive shift) under transport bumps and on inclines, thereby ensuring safe storage of critical equipment? o DRs being tested: CR6 (safe storage for essential equipment such as a fire extinguisher, brake bleed kit, and safety wire puller); ER5 (locking drawers / drawer security). o **Equipment needed:** Rated drawer payload (tools + weights); rough-track/speed-bump course or vibration/impact setup (≈ 1.0–1.5 g along drawer axis; optional short-pulse 2–3 g shock); steel ruler/feeler gauge or dial indicator; force gauge (opening/closing forces and latch holding force); labels/marker; camera; data sheet. o **Variables isolated for measurement:** • Drawer displacement Δx (mm) after test • Opening and closing forces F_{open}, F_{close} (N) • Latch holding force F_{hold} (N) • Qualitative: self-opening, binding, looseness (Y/N) o **Variables to be calculated from results:** • Inertial pull during bumps: $F_{inertia} = m_d a_{peak}$ • Slope pull (static): $F_{slope} = m_d g\sin\theta - \mu m_d g\cos\theta$

Procedure	1. Load & Baseline**:** Load the drawer to its rated payload (record mass m_d). Close and latch. Mark reference lines on the drawer face and cabinet; record initial position x_0 and gap with a ruler/indicator. 2. Continuous bump test**:** Drive the cart over a rough-track/speed-bump course (or use a shaker) targeting axial $a_{peak,cont} = 1.0 - 1.5\ g$ for 5–10 min. If using a logger, verify peak-g. 3. Shock test (short pulse): Perform 3–5 controlled impacts/drop equivalents to achieve $a_{peak,shoc} = 2 - 3\ g$ for 20–50 ms (half-sine or equivalent). 4. Incline hold (static): Park the cart on a 10° ramp for 5 min with the engaged latch. 5. Post-test measurements: Record final position x and compute displacement $\Delta x = x - x_0$. Note any self-opening, binding, or looseness (Y/N). 6. Force measurements: Using a force gauge, measure opening and closing forces F_{open}, F_{close} (5 trials each). Then pull along the drawer axis to measure latch holding force F_{hold} just before release (use guarding). 7. Repeatability: Repeat Steps 1–6 on a second drawer of the same type.
Results	**Kind of results looked for:** ○ Displacement: Δx ≤ 5 mm; no self-opening and no binding. ○ Ergonomics: F_{open}, F_{close}= 10–40 N. ○ Strength:$F_{hold} \geq F_{hold,req}$ with safety margin SM ≥ 1.3.

Figure 31: Tilted Drawer and Latch Test

9. Risk Analysis and Mitigation

A full Failure Modes and Effects Analysis was conducted to identify and address risks associated with steering, braking, storage, structural components, and tire mounting. Steering risks related to tie rod bending and fastener loosening were mitigated through rod end bearings and reinforced mounting plates. Frame cracking concerns were addressed through welded steel tubing and the addition of cross bracing in high stress regions. Drawer latch failures were mitigated with locking mechanisms designed for vibration. Brake system fatigue was reduced through spring selection and mechanical stops that prevent overload.

Table 21: FMEA Analysis

Failure Mode	Cause / Effect	Mitigation Strategy
Steering System Failure	Tie rod bending, fastener loosening, handle deformation → Loss of control	SolidWorks motion study validated geometry; reinforced mounts; rod-end bearings tested
Tire Mount/Carrier Failure	Bolt shear or fatigue cracking in steel → Tire loss	FEA simulates ~40 lb load w/ vibration; steel or gusseted aluminum considered
Frame Cracking/Weld Failure	Dynamic loads over rough terrain → Structural collapse	Welded steel tubing with cross-bracing under heavy load zones
Drawer Latch Failure	Latches open during motion → Tool ejection, shifting load	Locking latches designed for vibration, like Redline unit
Brake System Fatigue	Spring or lever failure → Inability to hold on slopes	Foot brake-style locking lever w/ fatigue-tested springs and rubber stop

Strength and weight considerations guided material selection with steel used for structural components and aluminum used for paneling. Cost and reliability tradeoffs were evaluated to ensure all decisions aligned with the project budget while protecting safety and functionality.

10. Looking Forward

The project team identified future improvements that would enhance the carts long term usability. These include the addition of a shade structure for outdoor pit operations, interior wheel brakes for increased safety, and a hitch attachment to tow additional carts or equipment. A trailer flip ramp would simplify loading and unloading procedures. Additional mounting points and tool holders could streamline technical inspections and improve workflow during high pressure repairs.

Table 22: Future Additions Breakdown

Components to Add	Benefits of Addition	Estimated Cost
Shade	Provides team members with a break from the sun in competition settings	$39.98
Interior wheel brakes	Enhances the safety of the carts braking abilities	$134.99

Hitch	Allows further carts or tools to be mounted from the cart	$43.97
Trailer Flip Ramp	Allows for easy loading of all equipment	$99.48
Various tools/ equipment	Streamlines the ease of technical inspections/race-day repairs	$35-$100
Mounting points	Allows for ancillary equipment/tools to be mounted for easy access	$16.99

Future work should include long term durability testing to evaluate how the cart performs after extended use under realistic shop and paddock conditions. Additional braking fatigue testing should be conducted to confirm consistent performance during repeated stops and high-load maneuvers. Battery cycle testing would help verify the reliability of the onboard power system across many charging and discharging cycles. Finally, weather exposure testing should be completed to determine how the structure and components respond to sun, rain, and temperature variation over time.

11. Conclusion

The SAE Toolbox Capstone Project has successfully delivered a complete design for a multifunctional tool cart capable of supporting the operational needs of the NAU Formula and Baja teams. The final design meets all critical requirements including stable mobility, secure storage, integrated power capability, and structural durability beneath heavy loads. The combination of detailed engineering analysis, CAD modeling, physical testing, and sponsorship support ensured that the cart remained cost effective and fully realizable. The system will provide a significant improvement to team logistics, safety preparedness, and efficiency for future competition seasons.

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Appendix

Appendix A: Morphological Matrix Images

[A1] 10-inch caster with offroad tread and center hub mounted rim.

[A2] Off-road style tire designed to enhance the stability of the toolbox on uneven terrain.

[A3] 8.5-inch caster with offroad tread and center hub mounted rim.

[A4] Small hard plastic caster with off-road tread and central hub mounted rim.

[B1] Steering handle (pallet truck design) with two brake levers and tie-rod turning system.

[B2] Dual-handle design inspired by airport luggage carts, featuring a push-down mechanism to disengage the brake.

[B3] Standard handle with bicycle style brake lever mounted to one side.

[B4] Standard handle with a single bar for two-hand grip, used for directional control with rotatable wheels.

[C1] Simple supported base frame design with tucked in wheels and square metal tubing to build upwards from.

[C2] Outwardly contoured frame with corner-mounted casters; compact layout optimized for mobility and ground clearance.

[C3] Simple rectangular base frame for tool cart. Part of the frame also incorporates housing for front and rear axles.

[C4] Base frame structure of the toolbox cart: rectangular layout with steel rods welded into triangular patterns to enhance structural strength.

[D1] 5-drawer locking toolbox measuring 27x20 inches.

[D2] Six-drawer toolbox structure: five upper drawers for organizing small tools and two larger bottom drawers for storing bulkier equipment.

[D3] Toolbox with 5 upper wide drawers for socket sets, open closed wrenches, and smaller tools. Four deeper drawers below the wide drawers for larger toolsets. On the right side of the toolbox, there is space for the mounted items.

[D4] Except for the top and bottom large compartments, all other sections consist of paired cabinets arranged in a row with opposite opening directions. This design helps prevent weight from concentrating on one side, ensuring better balance. Each cabinet is equipped with a lock to prevent items from falling out during turning.

[E1] Honda 2200i generator as power supply fit into a storage door.

[E2] 12V battery unit offering a portable and reliable power supply for short to medium-duration operations.

[E3] This power option is a simple 220 V outlet that will route power to a power strip on the tool cart.

[E4] 220V outlet with a solar panel mounted above it, serving as a backup power source in case of power failure.

[F1] Dual rotor in-line axle braking system with 4 piston mountain bike calipers per axle.

[F2] Motorcycle-style disc brake system with protective housing; emphasizes performance and sporty aesthetics.

[F3] This braking system is a simple rotor mounted to the rear axle of the tool cart. The caliper will be mounted to the underside of the cart.

[F4] Brake caliper is mounted above the wheel for convenient foot operation. An additional locking device can be added to the tire to prevent movement in case the caliper fails.

[G1] Metal frame with chain in front for easy access and security while in motion.

[G2] Protruding tire storage compartment designed to extend from the side of the cart, allowing for accessible and secure wheel placement.

[G3] Simple bucket style tire + rim holder.

[G4] Located in the largest bottom cabinet of the toolbox, this compartment offers significantly more space than other storage units, suitable for storing large items.