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Design & Development of Four-Wheel Steering Mechanism for Minimum Turning Radius: A Case Study of CM Transportation Trolley

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ABSTRACT

The main intent of this research is to discuss the benefits, applications, and implementation of four-wheel steering mechanism over two-wheel steering mechanism on CM Transportation trolley. Based on a review of the relevant academic journals, books, and textbooks investigation concludes that two-wheel steering is more commonly used than four-wheel steering because of its lower steering efficiency. Turning radius is decreased at low speeds, steering reaction is enhanced, and vehicle stability is maximized with four-wheel steering. Because of the limited space available in the magazines, the only feasible alternative for designing a trolley to transport canisterized missiles is to equip it with four-wheel steering. Explosion-proof prime movers are required for usage on the CM transportation trolley, which moves CM containers containing items from the magazine to the loading/unloading bay and back again. To accomplish this tighter turn, the rear wheels has to rotate counter to the front wheels which is arranged by a system composed of intermediate linkages and rotating components thus, transmits entire relative motion to the rear wheels. The design and development of the linkage mechanism and chassis frame was accomplished with the help of Creo v7, and Safety margins were determined by structural analysis performed in Ansys 21. The turning radius of the CM Transportation trolley was found to be reduced by roughly 48% when compared with a two-wheel steering system after which a prototype was built and tested with a constant radius.

***Keywords**: Four Wheel Steering, Turning radius, CM transportation Trolley*

NOMENCLATURE:

C_1 = Front Axle to Instantaneous Centre Distance	T = Track Width of the vehicle
C_2 = Rear Axle to Instantaneous Centre Distance	L = Wheel Base of the vehicle
a_2 = Distance of CG from Rear Axle	δ_{if} = Front Inner Wheel Steering Angle
θ = Front Inner Wheel Steering Angle	δ_{ir} = Rear Inner Wheel Steering Angle
Ø = Front Outer Wheel Steering Angle	δ_{of} = Front Outer Wheel Steering Angle
T_f /T_r =Front/Rear Track Width	δ_{or} = Rear Outer Wheel Steering Angle
R_1 = Distance from Instantaneous Centre to Centre of the vehicle	

1. INTRODUCTION

Four-wheel steering improves vehicle maneuverability and turning. With a normal two-wheel steering system, the rear wheels do not revolve in the curve, reducing steering efficiency [1]. Four-wheel steering reduces vehicle turning radius by rotating the rear wheels with the front [2]. Four-wheel steering improves active safety by stabilizing overtaking maneuvers, reducing vertical axis oscillation, reducing lateral wind sensitivity, and neutralizing cornering [3,12]. Four Wheel Steering offers cornering, high steering reaction, straight line stability, lane change, and low speed maneuverability. 4-Wheel Steering is complicated and costly despite its advantages over two-wheel steering [4,11]. Operating factors determine rear-wheel steering compared to front-wheel steering. At low speed, rear wheels steer opposite front wheels. When steering is slight at high speed, the front and rear wheels turn the same way [5-7]. Reversing the rear wheels reduces the vehicle's turning radius, making parking, low-speed cornering, and high-speed lane changes easier [8-10]. In this study, four-wheel steering is used to lower the trolley's turning radius and improve its maneuverability.

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2. Literature Review

Most vehicles use steering to regulate the movement. Figure 1 shows the steering mechanism's essential components: the steering wheel, steering column, steering rack, and vehicle wheels.

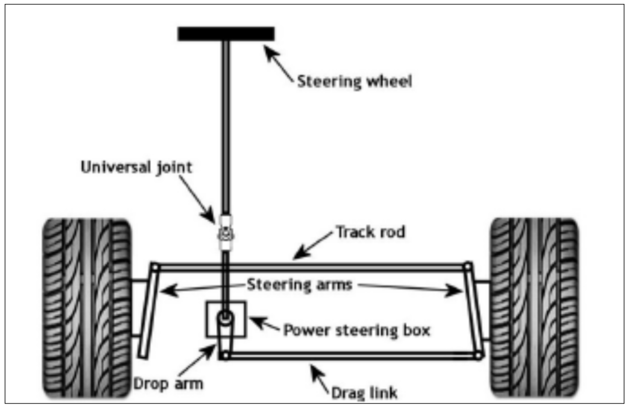

Figure 1: Main Components in Steering System [17]

Four-wheel steering, which uses all four wheels for steering, is the most effective. The intricacy of typical mechanical four-wheel steering systems makes this technology unpopular. The Honda Prelude and Nissan Skyline GT-R have four-wheel steering systems that spin the rear wheels to help the front wheels steer. These systems only guided the rear wheels by 2 or 3 degrees since they assisted the front wheels rather than steering themselves.

Modern four-wheel steering systems have completely electronic steer-by-wire systems, equal front and rear steer angles, and sensors to monitor vehicle dynamics and modify steer angles in real time. Many experimental models using these technologies have been developed and tested, but a complicated four-wheel steering model has not been produced.
Four-wheel steering has several benefits over two-wheel steering.

(a) Smaller Turns – With four-wheel steering, the vehicle can turn with a tighter radius than with two-wheel steering since the rear wheels may pivot in the opposite direction of the front wheels. This allows you to make turns without widening your turn.

(b) Good Stability – Stability helps you drive smoothly. While rounding corners or driving in the rain, a four-wheel steering system helps you manage and stabilize your car. Even in strong gusts or potholes, a straight route will keep your automobile straight.

(c) Smooth Steering – Unresponsive steering wheels are the worst. Four-wheel steering responds faster than two-wheel steering. You'll be able to steer more precisely, making driving more comfortable.

(d) Faster Lane Changes – If you often change lanes or overtake people on the road, a four-wheel steering system will help you accomplish this quickly and efficiently. With solid and steady steering control, you can change lanes faster than with a two-wheel steering system.

(e) Better Terrain Performance – Four-wheel steering is better for tougher terrains like rainy, snowy, or dirt roads. Your car won't get stuck on these terrains.

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3. Applications of Four-Wheel Steering

(a) Gentle curve: Rear-wheel steering on mild bends Stabilizes vehicle.

(b) Parking: To minimize the car's turning circle when parking, the driver frequently spins the wheel across a wide arc.

(c) Junctions: At a crossroads or other intersection where roads converge at 90° or tighter angles, rear-wheel counter-phase steering aligns the front and rear wheels. The car can turn effortlessly at a function.

(d) Slippery road surfaces: Rear wheel steering prevents rear end sideways slide on snow, ice, mud, and other low friction surfaces. Hence, automobiles are easier to steer.

(e) High-speed straight-line operation: While driving in a straight line at high speed, a driver often needs to make tiny steering corrections to maintain the intended direction. In phase steering of the rear wheels reduces these steering corrections.

(f) Narrow roads: On small roads with tight curves, rear-wheel counter-phase steering reduces the vehicle's turning radius, minimizing steering wheel rotation and making the vehicle simpler to turn.

(g) U-Turns: Counter-phase steering of the rear wheels allows U-turns on small highways by reducing the vehicle's turning radius.

4. Case Study of CM Transportation Trolley using Four Wheel Steering System

A trolley is a mechanical device used to transfer weights or convey materials. Based on the application, we must choose a trolley from the market or design a new one. Due of their two-wheel steering mechanisms and wider turning radius, present trolleys are unsuitable. According to investigations of the relevant literature, the only alternative that can fulfill the requirements for mobility within magazines is a trolley with four wheels steering system. CM Transportation Trolleys have three primary sub-assemblies are Suspension System, Chassis and Steering Mechanism.

4.1. Design Specifications

(a) Design, Development and Delivery of CM transportation Trolleys with Minimum Turing Radius available in Storage Magazines

(b) The payload carrying capacity is 1 ton

(c) Explosives Proof, Anti-Static and Shall be grounded.

(d) Low speed, Light Weight and Towing type.

(e) Easy to maintenance and Space Parts Shall be available freely outside the market.

4.2. Methodology

The design methodology of CM transportation trolley for minimum turning radius as shown in figure 2. It includes comparison of two and four-wheel steering mechanism, CAD modelling, Finite Element Analysis, Porotype development and experimental validation of design.

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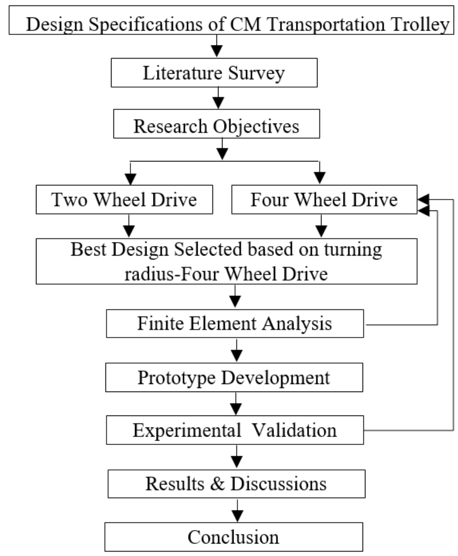

Figure 2: Design Methodology of Trolley

4.3 Steering Mechanism

4.3.1 Ackerman steering mechanism

Most four-wheeled vehicles employ four-bar linkages, often known as Ackermann-type steering mechanisms, to turn the wheels. Ackermann steering linkage is commonly seen on stiff steering axles in trucks and off-road vehicles [16]. With perfect Ackermann, the perpendicular line across the centers of all the wheels always converges on a single point, regardless of the direction in which the vehicle is being steered. The problem is that this can be hard to construct in practice with only linking objects together. While the Ackermann theory is sound for low speed movements, current automobiles do not employ pure Ackermann steering since it overlooks significant dynamic and compliant effects.

4.3.2 Steering wheel configuration

- **(a) Two Wheel Steer:** The front wheels are free to spin in the direction of the steering wheel, while the rear wheels are locked, requiring a large turning radius to turn.
- **(b) Four Wheel Steer:** Rear and front wheels are opposite in directions. This allows sharp turns with little turning radius at a slow speed.
- **(c) Crab Steer:** Both front and rear wheels face the same direction during high-speed lane changes.
- **(d) Zero turn:** The car moves in a circle of "zero radius" since the front and rear wheels are aligned as shown in figure 3.

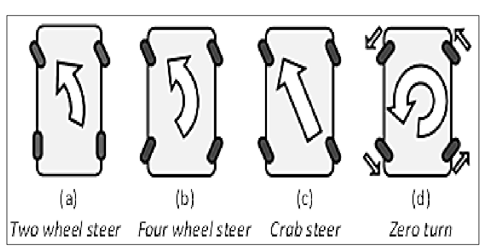

Figure 3: Types of Steering wheel configuration [6,11,17]

4.3.3 TURNING RADIUS

A vehicle's turning radius, sometimes called its turning circle, is the lowest diameter at which it can complete a full circle turn [17].

Turning circle radius = (Wheelbase/ sin (average steer angle)) — (Track width / 2)

4.3.4 CALCULATIONS TO FIND OUT TURNING RADIUS

(i) ***Two Wheel Steer Mechanism:*** From the benchmark Ackerman Steering Mechanism as shown in the figure 4, we have

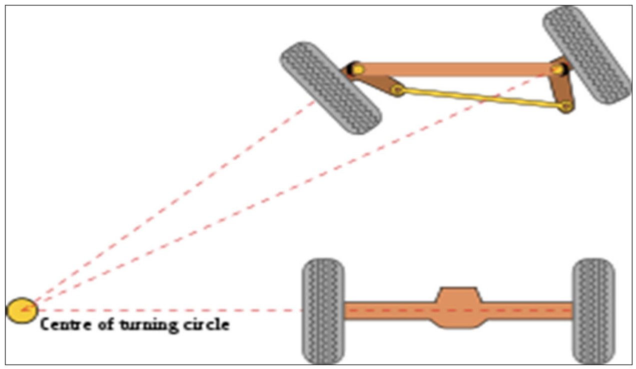

Figure 4: Two Wheel Steer [8,10,12,15]

From the figure 5 of Two-wheel steer of CM Transportation Trolley, assume front inner wheel steer angle $\delta_{if} = 30°$

$$\text{Cot } \delta_{of} - \text{Cot } \delta_{if} = T / L \quad (1)$$

$$\text{Cot } \delta_{of} = (1582 / 5000) + \text{Cot } 30°$$

$$\delta_{of} = 26.0204°$$

To find Turning Radius of two-wheel drive

we have equation

$$R^2 = a_2^2 + L^2 \times \text{Cot}^2\delta \quad (2)$$

$$\text{Cot } \delta = (\text{Cot } \delta_{if} + \text{Cot } \delta_{of}) / 2 \quad (3)$$

$$\text{Cot } \delta = 1.890251$$

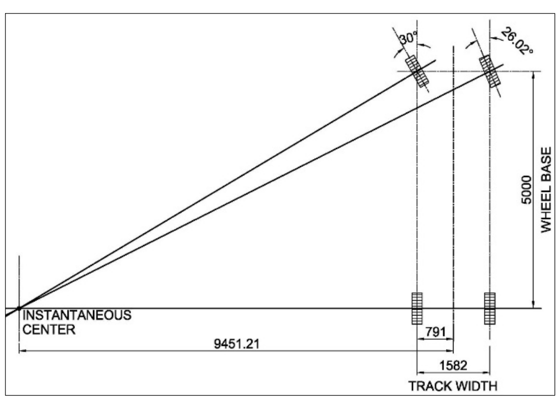

Figure 5: Two Wheel Steering in Transportation Trolley

Therefore, from equation 2, we have

$$R^2 = 2800^2 + 5000^2 \times Cot^2\delta$$

$$R = 9857.29 \text{ mm}$$

Therefore, the Turning Radius (R) of the two-wheel steering is = 9857.29 mm

(ii) ***Four Wheel Steer Mechanism:*** Four-wheel steering (4WS), sometimes termed rear-wheel or all-wheel steering, actively steers the rear wheels during turns. Four-wheel drive, which powers all four wheels, is different. It enhances handling and tightens corners.

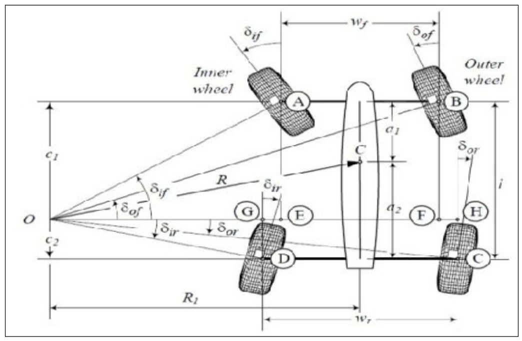

Figure 6: Steering angles position of Instantaneous Centre for Turning Radius 4.4 m [4,7,10,13,14]

From the figure 6, we know that

$$R^2 = a_2^2 + R_1^2 \tag{4}$$

From the figure 7 Four-wheel steering of CM Transportation Trolley, R_1=5121.13 mm

$\therefore$ from the eq.4, we have, $R^2= a_2^2+R1^2$

$$R^2 = 300^2 + 5121.13^2$$

$$R = 5129.90 \text{ mm}$$

To find the Steering Angle assume front inner wheel δ_{if} = 30°

$$Tan(\delta_{if}) = C_1 / (R_1 - T_f / 2) \tag{5}$$

$$C_1 + C_2 = L \tag{6}$$

Where,

$C_1 = C_2 = 2500$, Tr = 1582, L = 5000 mm

T = 1582 mm, R_1 = 5121.13 mm, R = 5129.9 mm

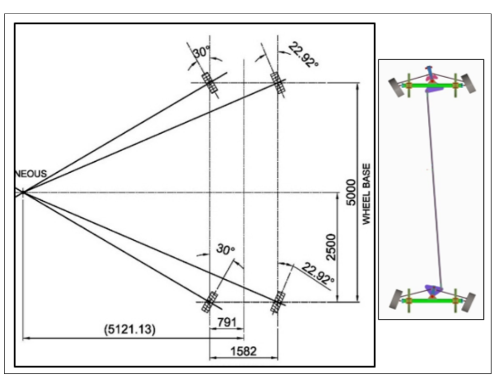

Figure 7: 4WS in CM Transportation Trolley [8]

From Eq.5, we have, $\tan(\delta_{if}) = C_1 / (R_1 - T_f / 2)$

$\therefore C_1 = 2500$ mm

From Eq.6, we have, $C_1 + C_2 = L$

$\therefore C_2 = 2500$ mm

To Find δ_{of} = Front Tyre Outer Angle

$\tan(\delta_{of}) = C_1 / (R_1 + T_f / 2)$

$\delta_{of} = 22.92°$

To Find δ_{ir} = Rear Tyre Inner Angle

$\tan(\delta_{ir}) = C_2 / (R_1 - T_r / 2)$

$\delta_{ir} = 29.99°$

To Find δ_{or} = Rear Tyre Outer Angle

$\tan(\delta_{or}) = C_2 / (R_1 + T_r / 2)$

$\delta_{or} = 22.91°$

Therefore, the Turning Radius (R) of the four-wheel steering is = 5129.90 mm

The purpose of this article is to outline plans for creating a four-wheeled trolley designed specifically for transporting CM containers. This device is used to enhance responsiveness of the steering, enhance stability during high-speed maneuvers, or reduce turning radius in low-speed situations as shown in figure 8.

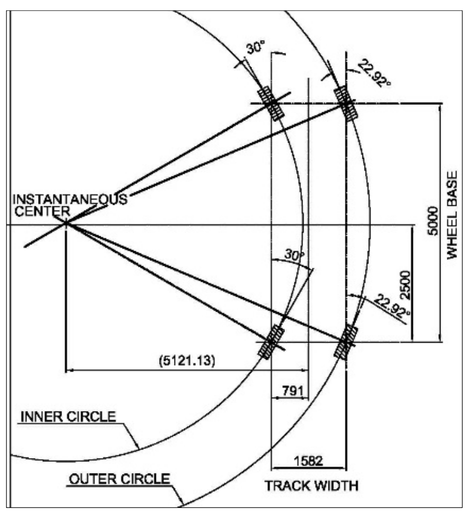

Figure 8: 4WS Turning Radius for Inner and Outer Wheels

With four-wheel steering, the rear wheels aren't always required to follow the front ones. The rear wheels may turn in the same way (same-side steering) as the front wheels, or in the opposite direction, depending on the speed of the vehicle (counter steering). Most modern four-wheel-steer vehicles may be navigated in either a counterclockwise or clockwise direction. With counter steering, a regular automobile may reduce its turning radius by a whole yard while making tight, low-speed bends. Yet, at high speeds, counter steering can make an automobile dangerously unstable, whereas same-side steering actually enhances the ride quality as shown in the figure 9.

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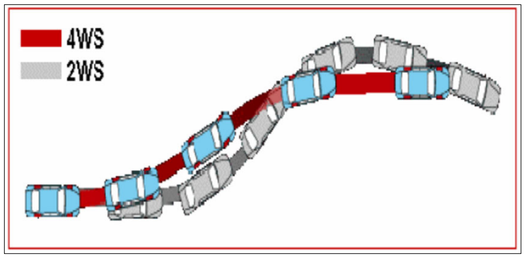

Figure 9: Wheel Steer under 2 Wheel Steer and 4 Wheel Steer [13]

4.4.DESIGN OF CM TRANSPORTATION TROLLEY

4.5. CHASSIS

The term "chassis" refers to the primary framework of a vehicle. A chassis resembles the skeleton of an organism since it is composed mostly of the supporting structure of the vehicle to which all of the other components are linked. You might say that it's the "spine" of the car, or the main support for the weight of the vehicle. Side and cross members form the chassis frame. Based on boundary conditions and loads, Finite Element Method (FEM) stress analysis determined the chassis' critical point of maximum stress. The trolley FOS is calculated from the maximum stress.

4.5.1. LADDER FRAME CHASSIS

The ladder chassis is widely regarded as one of the oldest types of automotive chassis or car chassis, and despite its age, it is the type of chassis that the vast majority of SUVs utilize even now. As depicted, it resembles a ladder with two longitudinal rail sinters joined by multiple lateral and cross bracing as shown in the figure 10 and Table 1 shows key dimensions, pay load, and other characteristics that help determine max. stress.

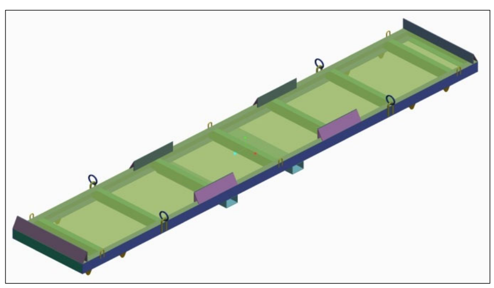

Figure 10: Chassis of Transportation Trolley

Table 1: Design Parameters of the Chassis [3,13]

Sl No.	PARAMETERS	VALUE
1.	Total Chassis length	6110 mm
2.	Width of the chassis	1080 mm
3.	Wheel base (L)	5000 mm
4.	Track width (T)	1582 mm
5.	Front over hang	365 mm
6.	Rear over hang	745 mm
7.	Ground clearance	200 mm
8.	Capacity (gvw)	5000 kg's
9.	Kerb weight	4000 kg's
10.	Pay load	1000 kg's
11.	C Channel Dimension	150H x 75W x 6.5t

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4.6. SUSPENSION SYSTEM

Spring, shock absorbers, and linkages connect a vehicle's wheels to its suspension, allowing relative motion. It helps with the vehicle's handling and braking for good active safety and driving pleasure, and it also keeps the passengers comfortable and relatively well separated from road noise, bumps, and vibrations, among other things. The suspension model is shown in the figure 11 & 12.

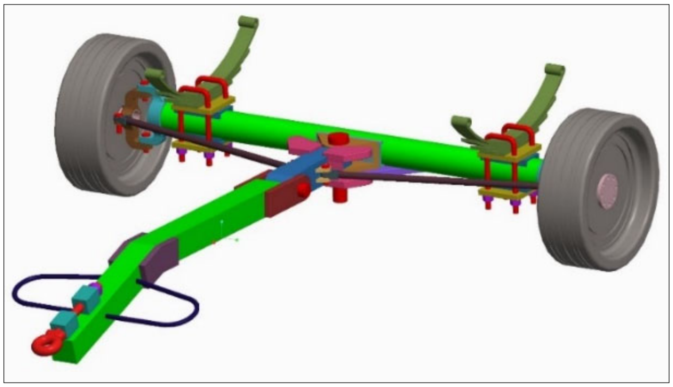

Figure 11: Front suspension of trolley

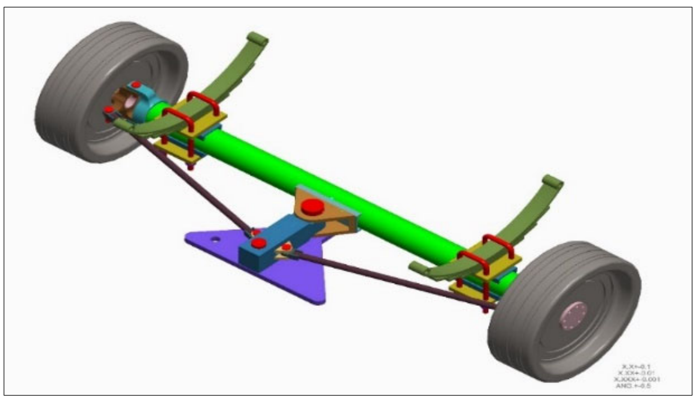

Figure 12: Rear suspension of trolley

4.7. FINITE ELEMENT ANALYSIS

The suspension pieces are welded to the chassis frame, and the chassis frame also serves as the support structure for the steering column and the linkage body. While designing the chassis frame, we take the length and passage dimensions of the CM container into account. The chassis structure is responsible for supporting the vehicle when it is moving, including the weight of the vehicle, the driver, and the road surface. C-Channel is used for Chassis frame. The material chosen for it is structural steel, the Ultimate Tensile Strength and the Yield Strength of the materials are 460 MPa & 250 MPa. A Payload of 1 ton is applied as a uniform pressure on chassis frames and all DOF are fixed at eight points where four-leaf springs are connected to the chassis frame. The maximum von-misses stress on chassis frame is 32.27 MPa and the deformation is 0.0056 mm as shown in the figure 13.

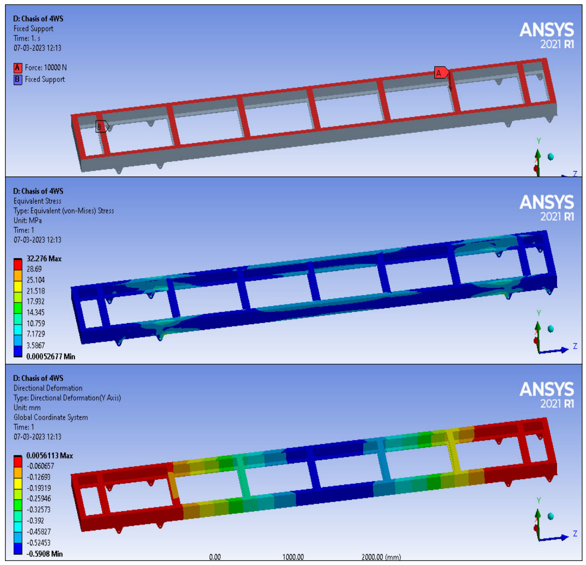

Figure 13: Applied Load & Boundary Conditions, Von-Misses Stress and Deformation along Y axis direction of Chassis

A hallow tube with four welded plates (for supporting the leaf springs) are used for axle. The material chosen for axle is alloy steel, the UTS and Yield Strength of the material is 450 MPa & 250 MPa as shown in the figure 14.

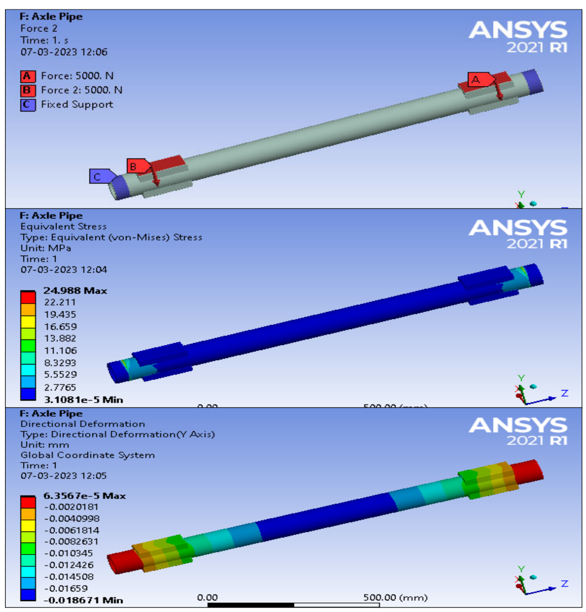

Figure 14: Applied Load & Boundary Conditions, Von-Misses Stress and Deformation along Y axis direction of Axle

Load of two tons (1 Ton of payload + 1 Ton of chassis weight) is applied on the welded plate surfaces where leaf springs are connected. Fixed boundary conditions are applied at both end portions of the axle where the hubs are connected. The maximum Von-Misses stress on axle is 24.98 MPa and the deformation is 0.0187 mm.

A hub is designed with a hole to fix the axle both ends and two hinge joints at top and bottom molded to the Knuckle of the wheel. The material chosen for hub is cast iron, the UTS and Yield Strength of the material is 415 MPa & 276 MPa. Load of two tons (1 Ton of payload + 1 Ton of chassis weight) is applied on the two surfaces of the hub where knuckle is connected. The fixed boundary conditions are applied at the end portions of the axle where the hubs are connected. The maximum Von-Misses stress on axle is 55.98 MPa and the deformation is 0.036566 mm as shown in figure 15.

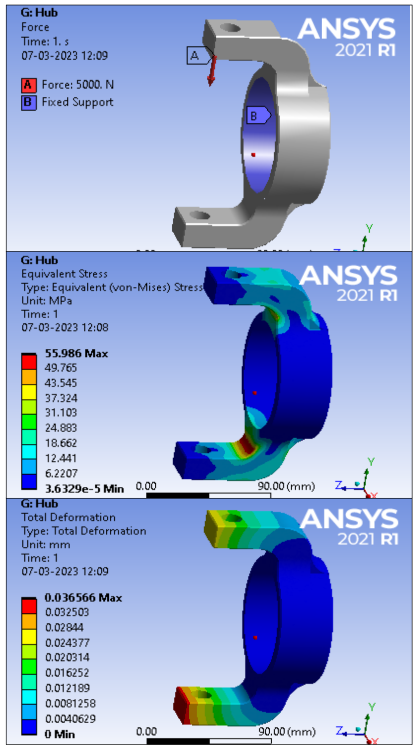

Figure 15: Applied Load & Boundary Conditions, Von-Misses Stress and Deformation of Hub

5. Prototype Development

Complete CM Transportation Trolley was modeled in Creo v7 software and structural analysis was carried out using Finite Element Analysis Ansys 21 and updated CAD model based on stress analysis to maintain the factor of safety & Prototype was Developed, load test and min. Turning Radius test conducted at vendor premises and it was operated at a low speed of 15kmph with CM Container as a pay load on the Transportation trolley shown in the figure 16.

Figure 16: CM Transportation Trolley

Four-wheel steering mechanism is designed using linkages directly connected to front wheels and the rear wheels. The design is aimed to turn the front wheels at a maximum angle of 30° and the stopper is provided at an angle of 35° as to stop the over turn of the wheels. The Chassis Frame was able to withstand the entire CM Container load during its testing on the road with bumps and found satisfactory. The operating instructions of trolley is shown in the figure 17.

Figure 17: Operating instructions of CM Trolley

6. Experimental Validation

Experiment carried out on developed prototype with payload of 1 ton at rated speed using prime-mover on the normal road and measured the minimum turning radius possible.

7. Results and Discussion

Analytical and experimental results of two-wheel steer and four-wheel steer turning radii as shown in table 2. The experiment result of four-wheel steering turning radius decreased by 48% and analytically reduced by 51.26% over two-wheel steering. Four Wheel Steering has several benefits and may successfully replace two Wheel Steering Mechanism for less turning radius. Consequently, the four-wheel steering system has cornering, high steering reaction, straight-line stability, lane shifting, and low-speed maneuverability.

Table 2: Comparison minimum turning radius of Two- & Four-Wheel Steer [10, 17]

Turning Radius (R)	Two Wheel Steer	Four Wheel Steer
By Analytical	9.87 m	5.12 m
By Practical	--	5.31 m

8. Conclusion

Canisterized Missile (CM) Transportation trolley is designed and developed using Creo and Ansys workbench for Finite Element Analysis. Structural analysis was carried out to verify stresses and deformation of the chassis, axle, hub and all other components, the results are within the safety margins. Analytically and Graphically validated the mechanism to suit the minimum turning radius available in the Magazines. Load test was carried out on realized CM Transportation Trolley for minimum turning radius and found satisfactory. Four-wheel steering mechanism worked effectively in reducing turning radius of CM Transportation Trolley and Cleared for further production.

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