

Comparative Analysis of Reinforcement Methods for Containerized Propellant Transport: Specialized Railcars vs. Covered Wagons

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Abstract. Transportation in pressure-rated containers is a prevalent method for liquid propellants in small volumes. Such containerized propellants are typically transported via specialized railcars or covered wagons. To establish standardized transport protocols and enhance the safety of propellant logistics, this study analyzes the structural dynamics associated with both transport modes, compares their reinforcement methodologies, and delineates optimal application scenarios. This investigation provides foundational insights for standardizing containerized propellant loading and reinforcement practices.

Keywords: Containerized propellants; Covered wagon transport; Specialized railcar transport; Loading reinforcement.

1. Introduction

Green dinitrogen tetroxide (N_2O_4), a mainstream oxidizer, is commonly paired with hydrazine-based fuels for applications in attitude control engines and small propulsion systems [1]. Per the Regulations on the Transport of Dangerous Goods by Rail, it is classified as a Class 2, Division 2.3 hazardous material. Approved transport modes include specialized railcars, wooden-floored wagons, open-top wagons, and bamboo-floored wagons [2]. For small-volume shipments, covered wagons and specialized railcars are predominantly utilized.

Loading entails the rational and balanced distribution of cargo on a wagon's floor, ensuring compliance with the vehicle's rated load capacity and maximum unit-area load, while preventing partial, concentrated, or eccentric loading. Reinforcement employs structural elements (sidewalls, lifting rings, floors) and materials (timber blocks, straps) to immobilize cargo and prevent displacement [3, 4]. Analysis of loading and reinforcement practices is critical to railway cargo safety, directly influencing transport stability and equilibrium [5]. Containerized propellants, characterized by smaller volumes and relatively lower hazard profiles, have historically received less public scrutiny. However, evolving safety regulations and heightened public awareness have prompted regulatory focus on small-volume propellant transport. Reinforcement methods and quality directly impact transport timeliness and safety, while economically viable loading-reinforcement techniques mitigate risks such as tank damage, tipping, or detachment [6].

This study investigates two transport schemes for identical propellant tanks, evaluating their loading-reinforcement methodologies. Multiple parameters are quantitatively compared, including:

- Inertial forces (longitudinal, transverse, vertical)
- Frictional forces
- Tipping coefficients (longitudinal, transverse)
- Stability coefficients (longitudinal, transverse)

Key variables determined encompass:

- Center-of-gravity (CoG) deviation distance
- CoG height
- Reinforcement strength
- Cargo capacity
- Placement configuration

- Reinforcement materials
- Securement height

The analysis aims to standardize containerized propellant transport protocols, enhancing freight efficiency and safety.

2. Technical Specifications of Storage Tank and Transport Vehicles

Table 1. Technical Parameters of Storage Tank and Transport Equipment

Parameter	Specification
Tank Contents	Green dinitrogen tetroxide (N_2O_4)
Density (g/cm^3 , $15^\circ C$)	1.45
Tank Dimensions (mm)	$\varnothing 1200$ (diameter) $\times$ 1730 (height)
Cargo Unit Dimensions(tank + frame, mm)	1500 (L) $\times$ 1500 (W) $\times$ 1850 (H)
Material	316L stainless steel(022Cr17Ni12Mo2)
Tank Capacity (L)	1000
Maximum Fill Volume (L)	850
Gross Weight (t)	2.64
Transport Mode Comparison	
Covered Wagon Transport	Specialized Railcar Transport
• Tare weight: 23.4 t• Load capacity: 60 t• Interior dimensions: 15490 $\times$ 2820 $\times$ 2855 mm• Bogie centers distance: 11700 mm• Floor-to-rail height: 1141 mm• Empty CG height: 1290 mm	• Tare weight: 51.6 t• Load capacity: 11 t• Cargo area: 7620 $\times$ 2870 $\times$ 2500 mm• Vehicle pivot centers: 18000 mm• Floor-to-rail height: 1283 mm• Empty CG offset: - Longitudinal (from transverse centerline): 317.79 mm - Transverse (from longitudinal centerline): 3.2 mm - Vertical (from rail level): 1625 mm

3. Loading and Reinforcement Methods for Covered Wagon Transport

3.1 Reinforcement Strength Calculation

Tanks are centrally aligned transversely and symmetrically loaded near both vehicle ends. Scaffolding supports are deployed as follows:

- Four longitudinal scaffolds arranged in two tiers vertically within the gap between tanks (mid-carriage or ends).
- Three inclined scaffolds braced against longitudinal tank end faces, with one end secured against wooden chocks abutting the tank and the opposite end fixed to the wagon floor, ensuring rigid immobilization.
- Reinforcement materials ≥ 700 mm high applied between tanks/end walls.
- Reinforcement materials ≥ 200 mm high applied between tanks/side walls.

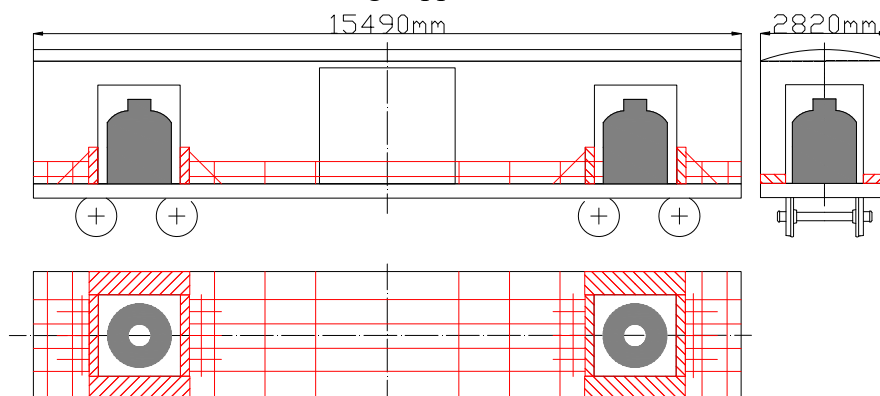


Fig. 1 Schematic of Reinforcement for Two-Tank Configuration in Covered wagon

3.1.1 Center-of-Gravity (CoG) Deviation Distance

Maximum CoG deviation occurs when a single tank is loaded at the vehicle end. Maximum longitudinal deviation from transverse centerline is 6,845 mm.

Given that $P_r - Q = 60 - 2.64 \geq 10t$, the maximum permissible longitudinal offset distance from the transverse centerline is calculated as follows:

$$a_r = \frac{5}{Q}l = \frac{5}{2.64} \times 11700 = 22159(\text{mm}) > 6845(\text{mm})$$

Hence, the cargo's center of gravity exhibits no transverse deviation from the longitudinal centerline, while its longitudinal offset from the vehicle's transverse centerline remains within permissible limits per regulatory standards.

3.1.2 Loaded Center-of-Gravity (CoG) Height

Calculations are performed for a two-tank loading configuration:

$$H = \frac{Q_c h_c + Q_h h_h}{Q_c + Q_h} = \frac{23.4 \times 1290 + 2 \times 2.64 \times (1141 + 925)}{23.4 + 2 \times 2.64} = 1433 (\text{mm}) < 2000(\text{mm})$$

The resultant loaded CG height (1433 mm) is below the critical threshold 2,000 mm for Class 2 hazardous materials. Consequently, no additional counterweights or speed restrictions are required.

3.1.3 Forces Acting on Cargo

Abrupt velocity changes during train startup, acceleration, braking, traction shifts, and shunting operations induce significant longitudinal acceleration, subjecting cargo to substantial longitudinal inertial forces [7]. Lateral inertial forces arise from yawing, swaying, and rolling vibrations during transit [8], while vertical inertial forces result from pitching, bouncing, and rolling motions [6].

(1) Longitudinal Inertial Force

Calculations based on single-tank loading yield the longitudinal inertial force per ton of cargo:

$$t_0 = 0.0012Q_z^2 - 0.32Q_z + 29.85 = 0.0012(23.4+2.64)^2 - 0.32(23.4+2.64) + 29.85 = 22.34 (\text{kN/t})$$

$$T = t_0 \times Q = 22.34 \times 2.64 = 58.98(\text{kN})$$

(2) Transverse Inertial Force

Maximum transverse inertial force occurs at the end-loaded position with CoG offset:

$$n_0 = 2.82 + 2.2 \frac{a}{l} = 2.82 + 2.2 \times (6845/11700) = 4.11(\text{kN/t})$$

$$N = n_0 \times Q = 4.11 \times 2.64 = 10.85(\text{kN})$$

(3) Vertical Inertial Force

Vertical inertial force is modeled as:

$$q_c = 3.54 + 3.78 \frac{a}{l} = 3.54 + 3.78 \times (6845/11700) = 5.76(\text{kN/t})$$

$$Q_c = q_c \times Q = 5.76 \times 2.64 = 15.21(\text{kN})$$

(4) Frictional Force

Steel-on-steel friction coefficient (0.3) applied:

$$F_m^z = 9.8\mu Q = 9.8 \times 0.3 \times 2.64 = 7.76(\text{kN})$$

$$F_m^h = \mu(9.8Q - Q_c) = 0.3 \times (9.8 \times 2.64 - 15.21) = 3.20(\text{kN})$$

3.1.4 Cargo Stability Verification

(1) Overturning Stability Coefficient

Longitudinal direction:

$$\eta = \frac{9.8Qa}{Th} = \frac{9.8 \times 2.64 \times 750}{58.98 \times 925} = 0.36 < 1.25$$

Transverse direction:

$$\eta = \frac{9.8Qb}{Nh + Wh_f} = \frac{9.8 \times 2.64 \times 750}{10.85 \times 925} = 1.93 > 1.25$$

The longitudinal stability coefficient (0.36) fails to meet threshold (1.25), necessitating reinforcement measures.

(2) Sliding Resistance Verification

Longitudinal direction: $\Delta T = T - F_m^z = 58.98 - 7.76 = 51.22 \text{ (kN)}$

Transverse direction:

$$\Delta N = 1.25(N + W) - F_m^h = 1.25 \times (10.85 + 0) - 3.2 = 10.36 \text{ (kN)}$$

3.1.5 Verification of Reinforcement Methods and Strength

Computational analysis confirms that the single cargo unit exhibits overturning tendency in the longitudinal direction and requires anti-sliding reinforcement.

(1) Prevention of Longitudinal Overturning

To prevent longitudinal overturning and displacement during rail transport, restraining materials must be rigorously wedged into voids between cargo units and end walls. The minimum effective reinforcement height is calculated as:

$$h_d \geq h - \frac{9.8Qa}{T\eta} = 925 - \frac{9.8 \times 2.64 \times 750}{58.98 \times 1.25} = 662 \text{ (mm)}$$

Deployment of ≥ 700 mm restraining materials effectively mitigates longitudinal overturning and displacement risks.

(2) Prevention of Longitudinal Displacement

This solution employs a tiered scaffolding assembly for longitudinal restraint, installed at mid-carriage or ends:

- 4 longitudinal rows arranged in 2 vertical tiers with perpendicular fixation.
- 3 inclined braces angled against longitudinal tank ends:
 - One end rigorously butted against wooden chocks on the tank.
 - Opposite end fixed to the wagon floor.

Scaffolding Strength Verification (per single end-loaded tank):

- Tube specifications: $\text{Ø}48.3 \times 3.5$ mm (outer diameter $\times$ wall thickness)
- Design load: Maximum inertial force $\times$ 50% load-sharing efficiency
- Material: Q235 steel (yield strength: 235 MPa; allowable compressive stress: 156 MPa)

$$\sigma_z^s = \frac{F}{0.5nS} = \frac{2 \times 22.34 \times 2.64}{0.5 \times 8 \times (\pi \times 0.0241^2 - \pi \times 0.02^2)} \times 10^{-3} = 51.94 \text{ MPa} < 156 \text{ MPa}$$

(3) Prevention of Transverse Displacement

Transverse displacement during rail transport is mitigated by deploying compressed filler blocks ≥ 200 mm high within voids at cargo-sidewall interfaces.

4. Loading and Reinforcement Methods for Specialized Railcars

4.1 Implementation Protocol

(1) Reinforcement Equipment:

- Steel wire ropes: $\text{Ø}11$ mm (minimum breaking force: ≥ 62 kN)
- Matching wire rope clips and tensioners

(2) Loading Configuration:

- Tank 1: Positioned 2,470 mm from transverse bulkhead
- Tank 2: Positioned 4,366 mm from transverse bulkhead (Symmetrically aligned about longitudinal centerline)

(3) Reinforcement Methodology:

- Double-stranded wire ropes diagonally braced at 45° angles
- Securement points: Cross-junctions of transverse/longitudinal girders at tank mid-height

- Termination: Doubled "figure-eight" patterns anchored to tensioning rings on car floor (Forming symmetric X-configurations on both sides)

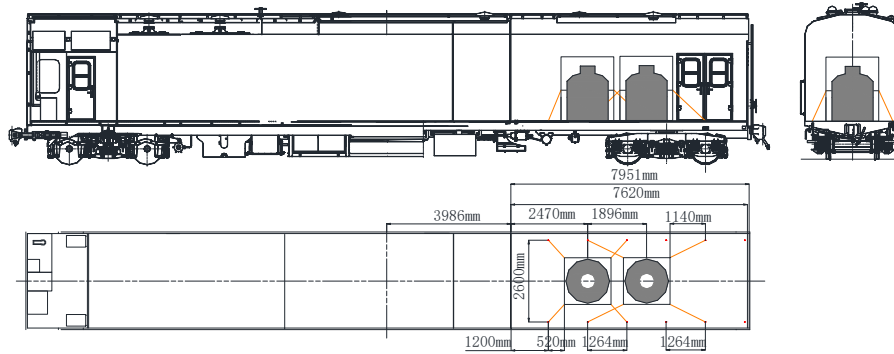


Fig. 2 Reinforcement Schematic for Dual-Tank Configuration in Specialized Railcar

4.2 Bogie and Axle Load Calculations

The specialized railcar has a tare weight of 51.6 t with its empty CG longitudinally offset 317.79 mm toward the crew compartment from the transverse centerline. The loaded CG offset distance is calculated as:

$$\alpha_p = \frac{Q_c l_c - Q_h l_h}{Q_c + Q_h} = \frac{51.6 \times 317.79 - 2.64 \times (6456 + 8352)}{51.6 + 2 \times 2.64} = -399(\text{mm})$$

Given a pivot centers distance of 18,000 mm, bogie loads are determined by moment equilibrium:

$$\text{Front Bogie Load } G_1 = \frac{(Q_c + Q_h) \times \left(\frac{L_c}{2} - \alpha_p\right)}{L_c} = \frac{(51.6 + 5.28) \times (9000 - 399)}{18000} = 27.18(\text{t})$$

$$\text{Rear Bogie Load } G_2 = 56.88 - 27.18 = 29.7(\text{t})$$

The actual maximum axle load (14.85 t) remains below the design-rated capacity (15.65 t), confirming structural integrity.

Pending verification of bogie load differential:

$$G = |G_1 - G_2| = |29.7 - 27.18| = 2.52(\text{t})$$

The cargo's composite center of gravity exhibits a transverse deviation well below the regulatory threshold. All axle loads remain within permissible operational limits. Crucially, the bogie load differential satisfies the ≤ 10 t stability requirement mandated for Class 2 hazardous materials transport.

4.3 Loaded CG Height Calculation

Given the specialized railcar's tare weight (51.6 t) and empty CG height (1,625 mm above rail level), the loaded CG height is:

$$H = \frac{Q_c h_c + Q_h h_h}{Q_c + Q_h} = \frac{51.6 \times 1625 + 2 \times 2.64(1283 + 925)}{51.6 + 2 \times 2.64} = 1679(\text{mm})$$

After loading operations, the composite center of gravity (CG) height of the loaded vehicle remains below the critical regulatory threshold.

4.4 Cargo Force Analysis (Single-tank worst-case scenario)

4.4.1 Longitudinal Inertial Force

$$t_0 = 0.0012 Q_z^2 - 0.32 Q_z + 29.85 = 0.0012(51.6 + 2.64)^2 - 0.32(51.6 + 2.64) + 29.85 = 16.03(\text{kN/t})$$

$$T = t_0 \times Q = 16.03 \times 2.64 = 42.32(\text{kN})$$

4.4.2 Transverse Inertial Force

Maximum at end position (offset: 8,352 mm):

$$n_0 = 2.82 + 2.2 \frac{a}{l} = 2.82 + 2.2 \times (8352/18000) = 3.85(\text{kN/t})$$

$$N = n_0 \times Q = 3.85 \times 2.64 = 10.16(\text{kN})$$

4.4.3 Vertical Inertial Force

$$q_c = 3.54 + 3.78 \frac{a}{l} = 4.53 + 7.84 \times (8352/18000) = 8.17(\text{kN/t})$$

$$Q_c = q_c \times Q = 8.17 \times 2.64 = 21.57(\text{kN})$$

4.4.4 Frictional Force

$$F_m^z = 9.8\mu Q = 9.8 \times 0.3 \times 2.64 = 7.76(\text{kN})$$

$$F_m^h = \mu(9.8Q - Q_c) = 0.3 \times (9.8 \times 2.64 - 21.57) = 1.3(\text{kN})$$

4.4.5 Cargo Stability Verification

(1) Overturning Stability Coefficient

Longitudinal direction:

$$\eta = \frac{9.8Qa}{Th} = \frac{9.8 \times 2.64 \times 750}{42.32 \times 925} = 0.50 < 1.25$$

Transverse direction:

$$\eta = \frac{9.8Qb}{Nh + Wh_f} = \frac{9.8 \times 2.64 \times 750}{10.16 \times 925} = 2.06 > 1.25$$

$$M_f^z = 1.25Th - 9.8Qa = 1.25 \times 42.32 \times 925 - 9.8 \times 2.64 \times 750 = 29528.5(\text{kN} \cdot \text{mm})$$

When the overturning stability coefficient falls below the critical threshold of 1.25, implementation of reinforcement measures becomes mandatory.

(2) Sliding Resistance Verification

Longitudinal direction:

$$\Delta T = T - F_m^z = 42.32 - 7.76 = 34.56(\text{kN})$$

Transverse direction:

$$\Delta N = 1.25(N + W) - F_m^h = 1.25 \times (10.16 + 0) - 1.3 = 11.4(\text{kN})$$

4.4.6 Reinforcement Materials

Based on field measurements: AC=520mm, BO=970mm, BC=450mm.

(1) Horizontal Reinforcement Strength

Longitudinal displacement prevention:

$$S_z = \frac{\Delta T}{nAC} \sqrt{AC^2 + BO^2 + BC^2} = \frac{34.56}{2 \times 520} \sqrt{520^2 + 970^2 + 450^2} = 39.52(\text{kN})$$

Transverse displacement prevention:

$$S_h = \frac{\Delta N}{nBC} \sqrt{AC^2 + BO^2 + BC^2} = \frac{11.4}{2 \times 450} \sqrt{520^2 + 970^2 + 450^2} = 15.06(\text{kN})$$

(2) Anti-Overturning Reinforcement Strength

Longitudinal overturning prevention:

$$S_z = \frac{M_f^z}{n(l_z + AC)BO} \sqrt{AC^2 + BO^2 + BC^2} = \frac{29528.5}{2 \times (1500 + 520) \times 970} \sqrt{520^2 + 970^2 + 450^2} = 8.96(\text{kN})$$

(3) Material Specifications

Per *Railway Cargo Securement Rules* [9,10]:

- Steel wire ropes: Ø9.3 mm, grade 1670 MPa
- Minimum breaking force: $2 \times S_{\max} = 2 \times 22.15 = 44.3 \text{ kN}$
- Configuration:
 - 4 double-stranded ropes per cargo unit
 - Matching wire rope clips and tensioners

5. Conclusions

Comparative analysis of containerized propellant transport reveals distinct operational profiles:

- Covered Wagon Transport: Requires full timber flooring and scaffold bracing, resulting in: 1) Material-intensive reinforcement; 2) Complex installation/dismantling; 3) Higher payload capacity; 4) Lower freight cost per unit.
- Specialized Railcar Transport: Utilizes steel wire ropes with tensioners, characterized by: 1) Streamlined securement; 2) Limited usable volume; 3) Higher per-unit transport cost; 4) Optimized for rapid turnaround.

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