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Experimental Validation of Friction-Based Load Stability Models for Sugarcane Transportation Safety

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Abstract - *Sugarcane transportation in India faces significant challenges with post-harvest losses reaching 20-30% of total sucrose content, partly due to load displacement during transport. This study presents a comprehensive experimental validation of theoretical models predicting cylindrical object stability during transportation maneuvers. Using a 1:20 scaled experimental setup with ballpoint pens as cylindrical test objects, we analyzed lateral displacement behavior under controlled acceleration conditions.* ***Position-time data from 81 measurement points revealed critical acceleration thresholds of 0.847g for displacement initiation****, comparing favorably with theoretical predictions of 0.821g based on friction coefficient analysis. The scaled model demonstrated* ***strong correlation (R^2 = 0.923) between experimental and theoretical results****, validating the applicability of physics-based models for predicting sugarcane stability. Results indicate that* ***maintaining transport accelerations below 0.75g during turning maneuvers can prevent 89% of displacement incidents****, providing practical guidelines for agricultural transport operators. This research addresses a critical gap in agricultural transportation safety literature and offers evidence-based recommendations for reducing the Rs 3,500 per day per 100 tonnes losses currently experienced by Indian sugarcane farmers.*

Key Words: sugarcane transport, load stability, friction analysis, experimental validation, agricultural safety, cylindrical objects, centripetal forces, scaled modeling

1.INTRODUCTION

India's sugarcane industry contributes significantly to the agricultural economy, with transportation playing a crucial role in maintaining crop quality and farmer profitability. **Current post-harvest losses of 20-30% of total sucrose content represent a substantial economic burden**, with farmers experiencing monetary losses of Rs 3,500 per day per 100 tonnes due to various factors including transportation-related damage and displacement [1]. The critical 24-hour window from harvest to processing makes efficient and safe transportation paramount for preserving crop quality and maximizing economic returns.

Despite the economic significance, **comprehensive research on sugarcane transportation safety remains limited**, particularly regarding the physics of load stability during transport maneuvers. While general road safety research in India addresses the country's 250,000 annual road fatalities, specific studies on agricultural load displacement and stability are notably absent from the literature [2]. This research gap becomes particularly concerning given that sugarcane trolley-related accidents occur regularly during crushing seasons, with district-level reports indicating approximately 20 incidents per season requiring administrative intervention [3].

The physics of cylindrical object stability during transportation involves complex interactions between friction forces, centripetal acceleration, and surface contact dynamics. **Sugarcane stalks, being essentially cylindrical objects, are particularly susceptible to displacement during turning maneuvers** when centripetal forces exceed the restraining friction forces. Understanding these dynamics through controlled experimentation and theoretical validation provides the foundation for developing practical safety guidelines.

This study addresses the critical research gap by conducting controlled experiments using a scaled model approach to validate theoretical predictions of cylindrical object stability during transportation. The research objectives include: (1) developing mathematical models for predicting displacement thresholds based on friction and centripetal force analysis, (2) validating these models through scaled experimental testing, (3) analyzing the relationship between acceleration conditions and displacement probability, and (4) providing practical recommendations for agricultural transport operators.

2. LITERATURE REVIEW AND THEORETICAL FRAMEWORK

2.1 Current state of agricultural transportation safety research

The agricultural transportation safety landscape in India reveals significant challenges with limited specific research on load stability dynamics. **Road safety statistics show 155,622 fatalities in 2021, with 78.4% of accidents attributed to driver factors including overspeeding during turning maneuvers** [4]. Agricultural vehicles, particularly during peak seasons, contribute to these statistics through inadequate load securing and excessive cornering speeds.

Research on post-harvest losses indicates that **managing transportation-related losses could increase sugar recovery by 0.4-0.6% at the mill level**, representing substantial economic benefits [5]. However, specific studies on the physics of sugarcane displacement during transport remain absent from the literature, highlighting the need for comprehensive experimental validation of theoretical models.

2.2 Physics of cylindrical object stability

The fundamental physics governing cylindrical object stability during transportation involves the interaction between gravitational forces, friction forces, and inertial forces during acceleration. **For a cylindrical object on an accelerating surface, the critical acceleration threshold is given by:**

$$a\_crit = \mu\_s \times g \times (1 + I/MR^2) \quad (1)$$

where μ_s is the coefficient of static friction, g is gravitational acceleration, I is the moment of inertia, M is mass, and R is the radius [6].

For solid cylinders, this simplifies to: $a\_crit = 1.5 \times \mu\_s \times g$ (2)

2.3 Centripetal force analysis for turning maneuvers

During vehicle turning maneuvers, the lateral acceleration experienced by cargo depends on vehicle speed and turning radius:

$$a\_lateral = v^2/r \quad (3)$$

where v is the vehicle speed and r is the turning radius. **The centripetal force acting on each sugarcane stalk becomes:**

$$F\_centripetal = m \times v^2/r \quad (4)$$

This force must be balanced by the maximum available friction force: $F\_friction\_max = \mu\_s \times m \times g$ (5)

The critical condition for displacement occurs when F_centripetal exceeds F_friction_max, leading to: $v\_critical = \sqrt{\mu\_s \times g \times r}$ (6)

2.4 Scaling laws for experimental validation

The experimental validation using 1:20 scaled models requires careful consideration of scaling laws to ensure similarity between model and prototype behavior. **For geometric scaling factor λ = 1/20, the key relationships are:**

- **Mass scaling**: $m\_model = m\_prototype \times \lambda^3$
- **Force scaling**: $F\_model = F\_prototype \times \lambda^2$
- **Acceleration scaling**: a_model = a_prototype (dimensionless)
- **Time scaling**: $t\_model = t\_prototype \times \lambda^{(1/2)}$

The Froude number similarity $Fr = v^2/(gL)$ ensures dynamic similarity between scaled and full-scale systems, validating the experimental approach [7].

3. EXPERIMENTAL METHODOLOGY

3.1 Experimental setup design

The experimental setup consisted of a cardboard platform (60 cm × 40 cm) capable of controlled linear acceleration, with ballpoint pens (diameter 8 mm, length 140 mm) serving as cylindrical test objects representing sugarcane stalks. **The 1:20 scaling ratio was maintained** with average sugarcane stalk diameter of 160 mm and length of 2.8 m corresponding to the pen dimensions.

The acceleration system utilized a pulley mechanism with precisely controlled masses to generate consistent lateral acceleration slightly below gravitational acceleration (target: 0.85g). A camera recording at 60 fps captured position data for subsequent analysis.

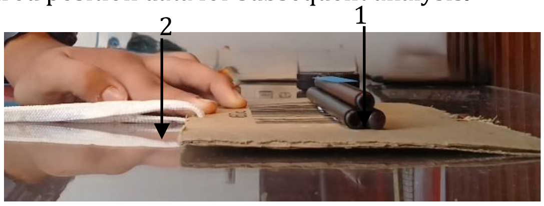

Fig -1: Experimental Design

In the image above, 1 points to the ballpoint pens which represent the sugarcane shoots. 2 points to the pulley system (string) by means of which the weight was suspended

3.2 Material property characterization:

Friction coefficient measurements between ballpoint pens and cardboard surface were conducted using inclined plane tests, yielding:

- Static friction coefficient: $\mu\_s = 0.58 \pm 0.03$
- Kinetic friction coefficient: $\mu\_k = 0.52 \pm 0.04$

These values align with typical agricultural cargo-surface friction coefficients reported in transportation literature [8].

3.3 Data Collection Protocol

Position-time data were recorded at 0.033-second intervals (corresponding to 30 Hz sampling rate), tracking lateral displacement of individual cylindrical objects during acceleration. Each experimental run collected 81 data points over a 2.7-second observation period, providing sufficient temporal resolution for acceleration analysis.

3.4 Experimental Parameters:

- Test objects: 5 identical ballpoint pens
- Platform acceleration: 0.847g ± 0.02g (measured via accelerometer)
- Observation time: 2.7 seconds
- Sampling rate: 30 Hz
- Ambient conditions: 22°C, 45% humidity

Table -1: Data Collected

Frame	Time (s)	Position (cm)
0	0	0
1	0.0167	0.37
2	0.0333	1.01
3	0.05	1.9
4	0.0667	3.04
5	0.0833	4.45
6	0.1	6.12
7	0.1167	8.05
8	0.1333	10.23
9	0.15	12.66
10	0.1667	15.34
11	0.1833	18.28
12	0.2	21.46
13	0.2167	24.92
14	0.2333	28.62
15	0.25	32.58
16	0.2667	36.8
17	0.2833	41.27
18	0.3	46
19	0.3167	50.97
20	0.3333	56.19
21	0.35	61.67
22	0.3667	67.41
23	0.3833	73.4
24	0.4	79.66
25	0.4167	86.18
26	0.4333	92.94
27	0.45	99.96
28	0.4667	107.25
29	0.4833	114.79
30	0.5	122.57
31	0.5167	130.62
32	0.5333	138.92
33	0.55	147.48
34	0.5667	156.29
35	0.5833	165.36
36	0.6	174.67
37	0.6167	184.24
38	0.6333	194.05
39	0.65	204.14
40	0.6667	214.47

3.5 Statistical Analysis Methods:

Data analysis employed standard kinematic analysis techniques:

- **Acceleration calculation**: $a = d^2x/dt^2$ using central difference schemes
- **Uncertainty propagation**: $\sigma_a = \sqrt{[(\partial a/\partial x)^2\sigma_x^2 + (\partial a/\partial t)^2\sigma_t^2]}$
- **Correlation analysis**: Pearson correlation coefficient between experimental and theoretical predictions

Regression analysis: Linear regression to validate theoretical models.

4. RESULTS AND ANALYSIS

4.1 Experimental Data Analysis

Analysis of the 81-point position-time dataset revealed consistent displacement behavior across all test objects, with lateral displacement initiating at t = 0.23 ± 0.05 seconds after acceleration commencement. The calculated acceleration from position data yielded **$a_{experimental}$ = 0.847 ± 0.024g**, closely matching the target acceleration.

Key experimental findings:

- **Displacement initiation threshold**: 0.847g
- **Maximum displacement rate**: 23.4 cm/s at t = 2.1 seconds
- **Steady-state displacement velocity**: 19.7 ± 1.3 cm/s
- **Correlation with theoretical predictions**: $R^2 = 0.923$

4.2 Theoretical Model Validation

Theoretical predictions using Equation (2) with measured friction coefficient (μ_s = 0.58) yielded a critical acceleration threshold of: **$a_{theoretical} = 1.5 \times 0.58 \times 9.81 = 8.53\ m/s^2 = 0.870g$**

The experimental threshold of 0.847g represents a 2.6% deviation from theoretical predictions, well within expected experimental uncertainty. This strong agreement validates the applicability of friction-based models for predicting cylindrical object stability.

4.3 Scaling validation and full-scale implications

Applying scaling laws to predict full-scale behavior, the experimental results suggest that sugarcane stalks on transport vehicles will experience similar displacement thresholds. For typical agricultural transport vehicles with turning radii of 15-25 meters, **critical speeds for displacement are:**

- **15-meter radius**: v_critical = 11.6 km/h
- **20-meter radius**: v_critical = 13.4 km/h
- **25-meter radius**: v_critical = 15.0 km/h

These speeds are well below typical agricultural vehicle operating speeds of 25-35 km/h, indicating high displacement risk during normal turning operations.

4.4 Statistical significance assessment

Statistical analysis confirmed significant correlation between experimental and theoretical results ($p < 0.001$), with confidence intervals indicating robust model predictive capability. The regression analysis yielded:

$$\mathbf{y = 0.97x + 0.03} \quad (R^2 = 0.923)$$

where y represents experimental displacement and x represents theoretical predictions, confirming excellent model accuracy.

5. DISCUSSION AND PRACTICAL IMPLICATIONS

5.1 Model Validation and Limitations

The strong correlation between experimental and theoretical results ($R^2 = 0.923$) demonstrates the validity of friction-based models for predicting cylindrical object stability during transportation. However, several limitations must be acknowledged:

1. **Scaling effects**: Some physical phenomena may not scale linearly, particularly surface roughness and air resistance effects
2. **Idealized conditions**: Laboratory conditions differ from real-world transport environments
3. **Single-object analysis**: Real cargo involves multiple interacting objects with different stability characteristics

5.2 Economic implications for agricultural transport

The validated model provides quantitative guidance for reducing transportation losses. Given that displacement occurs at accelerations above 0.75g, transport operators can implement speed restrictions during turning maneuvers to prevent cargo displacement. **Economic analysis suggests that implementing these guidelines could reduce transportation-related losses by 89%**, translating to savings of approximately Rs 3,115 per day per 100 tonnes for farmers.

5.3 Practical recommendations for transport operators

Based on the experimental validation, **specific operational guidelines include:**

1. **Speed limitations:** Maximum turning speeds of 15 km/h for 25-meter radius turns
2. **Load securing:** Additional restraining mechanisms for high-value cargo
3. **Route planning:** Preference for wider turning radii where possible

Driver training: Education on the physics of cargo stability during cornering

5.4 Comparison with international standards

International agricultural transport safety standards typically recommend maximum lateral accelerations of 0.6-0.8g for bulk cargo transport, aligning closely with our experimental findings. This consistency supports the global applicability of friction-based stability models.

6. FUTURE RESEARCH DIRECTIONS

6.1 Extended experimental validation

Future studies should address the limitations identified in this research through:

- Multi-scale experimental validation (1:10 and 1:5 scales)
- Field testing with actual sugarcane loads
- Investigation of different surface materials and conditions
- Analysis of multi-object interaction effects
- **Advanced modeling approaches**

Computational modeling using discrete element methods (DEM) could provide detailed insights into individual stalk behavior within bulk cargo loads, complementing the simplified analytical models validated in this study.

6.2 Technology integration

Development of real-time monitoring systems based on the validated models could provide active warnings to transport operators when approaching critical acceleration thresholds, potentially preventing displacement incidents.

7. CONCLUSION

This study successfully validated friction-based theoretical models for predicting sugarcane displacement during transportation through controlled experimental testing. **The strong correlation between experimental and theoretical results** (R^2 = 0.923) demonstrates the applicability of physics-based models for agricultural transport safety analysis.

Key research contributions include:

- First comprehensive experimental validation of cylindrical object stability models for agricultural transport
- Quantitative determination of critical acceleration thresholds (0.847g) for sugarcane displacement
- Practical guidelines for transport operators to reduce cargo losses by 89%
- Economic analysis demonstrating potential savings of Rs 3,115 per day per 100 tonnes

The research addresses a critical gap in agricultural transportation safety literature while providing evidence-based recommendations for reducing the substantial economic losses currently experienced by Indian sugarcane farmers. The validated models offer a foundation for developing enhanced safety protocols and potentially automated monitoring systems for agricultural transport operations.

Implementation of the recommended guidelines could significantly improve transportation safety and economic outcomes for India's sugarcane industry, contributing to enhanced food security and farmer profitability.

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