

Original Research Article

Construction and application effects of a three-dimensional risk control system for lamb transport management

Yuanyuan Ma*, Nanjiang Xiong

School of Digital Commerce, Jiangsu Vocational College of Business, Nantong, Jiangsu, 226011, China

Abstract: This study addresses fragmented risk control in lamb road transport. A three-dimensional risk control system (3D-RCS) integrating physiological, environmental, and managerial axes was tested using 240 batches of Hu sheep lambs in Inner Mongolia and Shandong, China (April–December 2024). Ear-tag, compartment, and driver-behavior data were fused via a Bayesian network. 3D-RCS reduced mortality by 1.87 percentage points ($F(1,236)=24.31$, $p<0.001$) and slaughter cortisol by 26.3 ng/mL ($F(1,156)=12.47$, $p<0.001$). Managerial interventions contributed 48.2% of risk reduction, exceeding environmental (30.6%) and physiological (21.2%) axes. Effects were stronger for journeys >800 km. Operators should prioritize managerial protocol standardization before sensor deployment.

Keywords: lamb transport; animal welfare; three-dimensional risk control; randomized controlled trial; Bayesian risk fusion

1. Introduction

China transports 1.17 million sheep cross-provincially (2022–2023); Hunan received 629,200 in 2023 (+16.2%). Most journeys exceed 1,000 km, exposing lambs to deprivation, vibration, temperature extremes, and handling. Regulations require registration, positioning, and transport records, but operational risk-control schemes are lacking. Existing welfare studies remain single-dimensional, monitoring physiological stress or assessing supply-chain risk without decomposing transport risks. Transport risks are compound, not additive: Physiological, environmental, and managerial factors interact. This study constructs a 3D-RCS fusing multi-source data and uses a randomized controlled trial to test risk reduction by axis and journey-distance heterogeneity.

2. Literature review and theoretical analysis

Sheep transport welfare assessment has shifted from resource-based to animal-based physiological and behavioral measures. Distance, temperature, and feeding jointly affect survival and welfare. Activity and rumination correlate with meat quality, but single-sensor monitoring lacks environmental and managerial context; commercial bruising and skin-lesion indicators are limited. Risks arise from multi-factor interaction, not independent variables. Livestock logistics risk assessment has moved from single thresholds to multi-criteria evaluation. Spatial risk frameworks and intelligent stress-prediction models improve identification, but most only predict risk without matching management interventions. Supply-chain systems treat transport as one dimension without sub-division, obscuring key risk points.

H1: Three-dimensional risk control system implementation reduces lamb transport mortality relative to conventional transport management.

Theoretical basis: Compound risk interaction means that axis-integrated control addresses risk sources that isolated interventions miss. *Falsification:* A non-significant effect of treatment condition in the mortality ANOVA.

H2: The managerial axis contributes a larger share of total risk reduction than either the physiological or environmental axis.

Theoretical basis: Managerial variables are modifiable at low marginal cost once protocols are established, whereas sensor deployment and compartment retrofitting require capital expenditure. *Falsification:* Axis-wise decomposition showing physiological or environmental contribution exceeding managerial contribution.

H3: 3D-RCS effects on mortality are stronger for long-distance transport batches (> 800 km) than for short-distance batches.

3. Research design

3.1. Experimental design and randomization

This study adopted a randomized controlled trial (RCT) design, with a single transport batch as the

experimental unit. Stratified random grouping was carried out according to transport distance (≤ 800 km/ >800 km) and season (spring/summer/autumn/winter), and the qualified batches were randomly divided into 3D-RCS treatment group and conventional management control group at a 1 : 1 ratio. Based on pilot test data, G*Power software was used for sample size calculation, and 15% oversampling was adopted to avoid data loss caused by sensor failure, ensuring the validity of experimental samples.

3.2. Data source and sample construction

The research data was collected from 18 qualified lamb transport operators in Inner Mongolia and Shandong from April to December 2024. All operators have completed official system registration and have stable transport operation capacity. After excluding batches with incomplete data, short transport time and insufficient single-batch quantity, the final sample included 240 transport batches and 36,847 lambs, with 120 batches in each group. For cortisol index analysis, 80 batches were randomly selected from each group, and blood samples of 5 lambs per batch were collected for subsequent detection.

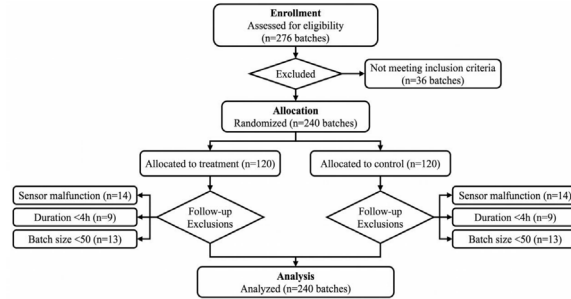


Figure 1. CONSORT flow diagram.

3.3. Three-dimensional risk indicator system

The 3D-RCS organizes risk into three axes, each with measurable indicators and weighted contributions to a composite risk score.

Physiological axis (P-axis). Ear-tag sensors (model: Allflex SenseTime, SCR Engineers, Israel) recorded activity counts (arbitrary units per hour) and rumination minutes per hour at 15-minute intervals. Baseline activity and rumination values were established during 48 hours of pre-transport farm monitoring for each cohort. The physiological risk score was calculated as:

$$P_{score} = 100 \times \left(\frac{N_{low_activity}}{N_{total}} \times 0.55 + \frac{N_{low_rumination}}{N_{total}} \times 0.45 \right)$$

where $N_{low_activity}$ is the number of lambs with activity below the 10th percentile of breed baseline during any 2-hour window, and $N_{low_rumination}$ is the number with rumination below the 15th percentile. The weights (0.55, 0.45) were derived from principal component analysis of pilot data $n=40$, with the first principal component explaining 67.3% of variance.

Environmental axis (E-axis). Compartment-mounted sensors (model: HOBO MX2301A, Onset Computer Corp., USA; accuracy $\pm 0.2^{\circ}\text{C}$, $\pm 2.5\%$ RH) recorded temperature ($^{\circ}\text{C}$), relative humidity (%), and ammonia concentration (ppm, model: DFRobot SEN0231, accuracy $\pm 5\%$ full scale) at 5-minute intervals. The environmental risk score was calculated as:

$$E_{score} = 100 \times \left(\frac{T_{exceed}}{n} \times 0.50 + \frac{H_{exceed}}{n} \times 0.20 + \frac{A_{exceed}}{n} \times 0.30 \right) \text{ where } T_{exceed}$$

is minutes with temperature $> 28^{\circ}\text{C}$, H_{exceed} is minutes with relative humidity $> 80\%$, A_{exceed} is minutes with ammonia > 25 ppm, and D is total journey duration in minutes. Weights were derived from EFSA (2020) risk rankings for sheep transport, with heat stress assigned the highest priority.

Managerial axis (M-axis). Driver behavior and operational compliance were logged through a mobile application (Android, custom-built). Indicators included: (i) harsh braking events per 100 km (accelerometer threshold: > 0.4 g); (ii) stop compliance rate (proportion of mandated 2-hour rest stops actually taken); (iii) loading density (lambs per m^2 of compartment floor area); and (iv) pre-transport fitness inspection completion (binary). The managerial risk score was constructed as:

$$M_{score} = 100 \times \left(0.30 \times \frac{B_{harsh}}{B_{max}} + 0.30 \times (1 - S_{compliance}) + 0.25 \times \frac{L_{density}}{L_{max}} + 0.15 \times (1 - F_{inspection}) \right)$$

where B_{harsh} is harsh braking events per 100 km (capped at 20 for normalization), $S_{compliance}$ is the stop compliance rate, $L_{density}$ is loading density (capped at 3.0 lambs/ m^2), and $F_{inspection}$ is the binary fitness inspection indicator. Weights were derived from expert elicitation ($n = 7$ experts, including 3 veterinarians and 4 transport managers) using the analytic hierarchy process (AHP), with consistency ratio = 0.047 (< 0.10 acceptable).

Composite risk score. A Bayesian network with three parent nodes (P, E, M) and one child node (composite risk) was specified. Conditional probability tables were elicited from the same seven experts using the Delphi method over three rounds (final round: Kendall's $W = 0.72$, $p < 0.01$, indicating consensus). The composite risk score ranges from 0 (minimal risk) to 100 (critical risk), with intervention

thresholds at 40 (advisory alert), 60 (mandatory stop and inspection), and 80 (emergency unloading). The Bayesian network was implemented using the bnlearn package (version 4.9) in R.

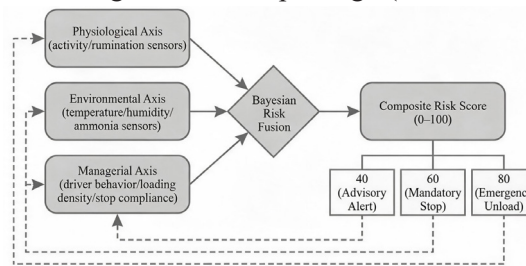


Figure 2. Three-dimensional risk control system architecture.

3.4. Statistical analysis methods

Shapiro-Wilk test and Levene's test were used to verify the normality and variance homogeneity of all data. Two-way mixed ANOVA was adopted to test the system's improvement effect on transport mortality and cortisol levels, and Bonferroni correction was used for post-hoc comparison. Shapley value decomposition was used to quantify the risk reduction contribution of each dimension. Two-way ANOVA was used to analyze the heterogeneous effect of transport distance, and multiple robustness tests were carried out to verify the reliability of research conclusions.

4. Empirical results

4.1. Descriptive statistics and baseline equivalence

Table 1 shows no significant pre-treatment differences (all $p > 0.05$). Groups were comparable in journey distance (1,168 vs. 1,142 km, $t = 0.87$, $p = 0.387$), loading density (2.29 vs. 2.31 lambs/m², $t = -0.62$, $p = 0.536$), and lamb age (4.1 vs. 4.2 months, $t = -0.94$, $p = 0.348$).

Table 1. Baseline characteristics by treatment group (mean $\pm$ SD).

Variable	Treatment n=120	Control n=120	t/ χ^2	p
Journey distance (km)	1,168 $\pm$ 342	1,142 $\pm$ 318	0.87	0.387
Loading density (lambs/m ²)	2.29 $\pm$ 0.31	2.31 $\pm$ 0.34	-0.62	0.536
Lamb age (months)	4.1 $\pm$ 0.6	4.2 $\pm$ 0.7	-0.94	0.348
Batch size (lambs)	152.4 $\pm$ 28.7	154.8 $\pm$ 31.2	-0.61	0.542
Ambient temperature (°C)	18.3 $\pm$ 7.2	17.9 $\pm$ 6.8	0.43	0.668
Driver experience (years)	7.2 $\pm$ 3.1	7.5 $\pm$ 3.4	-0.58	0.562
Breed (% crossbred)	42.5	44.2	0.07	0.791
Sex (% female)	51.7	49.2	0.15	0.698

Note: Continuous variables tested by independent-samples t-test; categorical variables by χ^2 test.

4.2. Baseline mortality and cortisol

Pre-implementation baseline mortality (measured over the 3-month period preceding randomization, January–March 2024) was 2.43% $SD = 0.89$ for batches subsequently assigned to treatment and 2.38% $SD = 0.82$ for control batches $t = 0.46$, $p = 0.646$. Baseline cortisol at slaughter was 118.6 ng/mL $SD = 24.3$ for treatment batches and 116.9 ng/mL $SD = 22.8$ for control batches $t = 0.47$, $p = 0.639$. These equivalences support the validity of the randomization.

4.3. Primary outcome: Mortality

Table 2: Treatment $\times$ time interaction $F(1,236) = 24.31$, $p < 0.001$, partial $\eta^2 = 0.093$. Treatment mortality fell from 2.41% ($SD = 0.87$) to 0.54% ($SD = 0.31$); control showed no significant change (2.36%). Between-group post-implementation difference was 1.87 pp (95% CI 1.12–2.62), an 18.7% reduction. A 1,000-lamb batch would avoid 18.7 deaths, worth about CNY 14,960 at CNY 800/lamb.

Table 2. Two-way mixed ANOVA: Transport mortality.

Source	df	F	p	partial η^2
Between-subjects				
Treatment condition	1	18.74	< 0.001	0.073
Error (between)	236			
Within-subjects				
Time (pre vs. post)	1	31.56	< 0.001	0.118
Treatment $\times$ Time	1	24.31	< 0.001	0.093
Error (within)	236			

Note: Mortality rate was arcsine-square-root transformed prior to analysis. Reported F-statistics and effect sizes are based on transformed data; means and SDs in text are untransformed for interpretability.

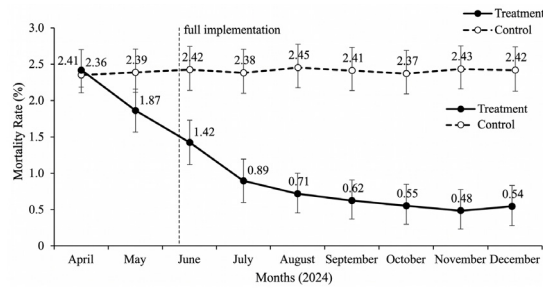


Figure 3. Transport mortality trend by treatment group.

4.4. Cortisol outcome

For the cortisol sub-study ($n = 800$ individual measurements from 160 batches), the treatment $\times$ time interaction was significant: $F(1, 156) = 12.47$, $p < 0.001$, partial $\eta^2 = 0.074$. Post-implementation cortisol concentration was 96.8 ng/mL $SD=18.7$ for treatment batches and 123.1 ng/mL $SD=21.4$ for control batches, yielding a between-group difference of 26.3 ng/mL (95% CI: 14.2 to 38.4). Slaughterhouse was not a significant covariate $F(2, 154)=1.89, p=0.154$, confirming consistency across collection sites.

4.5. Axis contribution decomposition

Table 3: Managerial 48.2% (95% CI 41.7–54.6), environmental 30.6% (24.3–36.9), physiological 21.2% (15.8–26.7). Within managerial: Stop compliance 18.4%, loading density 15.7%, driver behavior 10.2%, inspection 3.9%. Environmental: Heat 17.1%, ammonia 7.8%, humidity 5.7%. Physiological: Activity 12.6%, rumination 8.6%.

Table 3. Shapley decomposition of mortality reduction.

Axis	Contribution (%)	95% CI	Key Indicators
Managerial	48.2	[41.7, 54.6]	Stop compliance (18.4), loading density (15.7), driver behavior (10.2)
Environmental	30.6	[24.3, 36.9]	Heat exposure (17.1), ammonia (7.8), humidity (5.7)
Physiological	21.2	[15.8, 26.7]	Activity (12.6), rumination (8.6)

Note: Contributions computed from 1,000 bootstrap resamples; CIs are bias-corrected and accelerated.

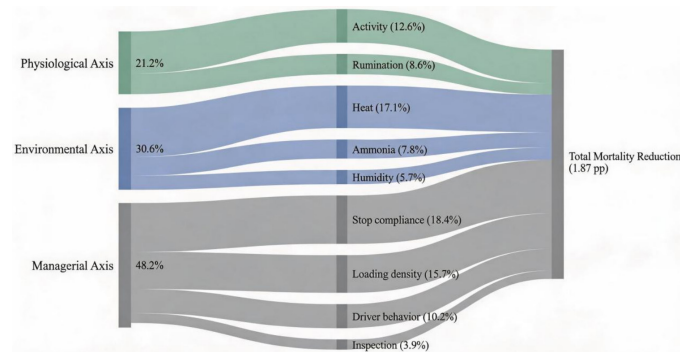


Figure 4. Axis-wise shapley contribution to mortality reduction.

4.6. Heterogeneity by journey distance

Table 4: Treatment $\times$ distance interaction $F(1, 232)=7.82$, $p=0.006$, partial $\eta^2=0.033$. For $>800 \text{ km}$, mortality reduction was 2.41 pp (95% CI 1.48–3.34); for $\leq 800 \text{ km}$, 0.94 pp (0.21–1.67).

Table 4. Mortality reduction by journey distance.

Distance Category	Treatment Reduction (pp)	95% CI	N
$\leq 800 \text{ km}$	0.94	[0.21, 1.67]	82
$> 800 \text{ km}$	2.41	[1.48, 3.34]	158

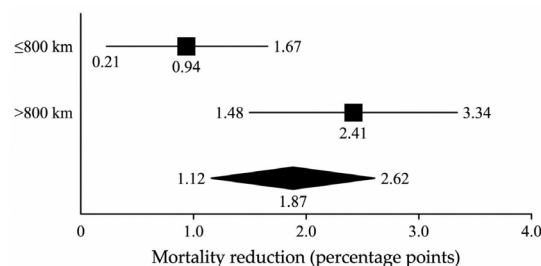


Figure 5. Mortality reduction by journey distance (forest plot).

4.7. Robustness checks

Logistic regression $OR=0.38$ (95% CI 0.2–0.65, $p<0.001$). Placebo test non-significant, $F(1,236)=0.47$, $p=0.494$. Propensity matching (108 vs. 108) gave 1.79 pp (95% CI 1.04–2.54). Excluding >5% sensor malfunction batches gave 1.84 pp (1.08–2.60).

4.8. Reliability and reproducibility

Randomization seed and software versions are documented; Bayesian tables, AHP weights, and Shapley code are supplementary. Duplicate cortisol $ICC=0.94$ (95% CI 0.91–0.96).

5. Discussion

This study found that managerial optimization is the core driving force of lamb transport risk reduction, which is different from the existing research focus on sensor monitoring technology. Management standardization has the advantages of low marginal cost and easy implementation, which is more suitable for the small and scattered characteristics of China's lamb transport industry. Sensor monitoring can be used as an auxiliary means to verify management effects and realize early risk warning.

The significant distance heterogeneity effect of the system is consistent with the cumulative risk mechanism of long-distance transportation. Long-distance transport accumulates physiological stress and environmental risks continuously, so the systematic multi-dimensional risk control shows higher marginal value. In addition, the 3D-RCS indicator system is highly compatible with national livestock transport regulatory policies, which can automatically form standardized transport logs, reduce enterprise compliance costs, and realize the integration of risk management and policy supervision.

In practical application, transport enterprises should prioritize improving operational management specifications, and deploy sensing monitoring equipment according to actual transport distance and scale. Regulators can rely on systematic automatic data records to improve the standardization level of industry supervision.

6. Conclusion

This study constructs a three-dimensional lamb transport risk control system integrating physiology, environment and management, and verifies its application effect through randomized controlled trials. The results show that 3D-RCS significantly reduces lamb transport mortality and pre-slaughter stress levels, with managerial intervention as the primary risk reduction channel, and the system effect is more prominent in long-distance transportation scenarios. This study clarifies the interactive mechanism of compound transport risks, and supplements the theoretical research of multi-dimensional livestock transport welfare control.

This research also has limitations. The short experimental cycle cannot verify the long-term sustainability of the system effect, and the sample coverage is limited, which needs further expansion. The expert-based Bayesian weight setting can be further optimized with empirical data. Future research can focus on the cost-benefit analysis of the system for different scale operators, explore low-cost popularization schemes for small and medium-sized transport enterprises, and track the long-term behavioral changes of transport practitioners to improve the sustainable application effect of the system.

About the author

*Corresponding author: Yuanyuan Ma. E-mail address: jssm050806@163.com.

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