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Synergy Mechanism of the Chinese New-Energy Vehicle Export to Belarus under the Belt & Road Initiative

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As the EU Carbon Border Adjustment Mechanism (CBAM) transitions from announcement to enforcement, Chinese new-energy vehicle (NEV) exporters face a dual shock: a €90 tCO_2e carbon tariff and winter-induced battery losses that inflate embedded emissions by up to 0.63 kg CO_2e per vehicle per degree below 0°C.

The purpose of the article is to integrate electrochemical and thermophysical physics into the stochastic trade and gravitation model and to jointly work out a set of Algorithm-Mechanism Synergy (AMS) that would optimize train schedule, previous battery charging load and stimulating contracts (transportation discounts, recycling credits or the hybrid).

Material and methods. *The system and institutional approaches, analysis, synthesis were used in the course of the research. The article material was scientific works by domestic and foreign scholars-economists as well as data of 847 China – Europe trains, 3,3 million cell telemetry minutes and random contract menu.*

Findings and their discussion. *The results show that AMS cuts landing cost by 8.4 %, reduces CBAM-declared emissions by 34 % and achieves a super-additive welfare index of 1.27 without new infrastructure.*

Conclusion. *It was shown that the turnkey dashboard is already piloted by two major OEMs and offers an immediate hedge against forthcoming carbon prices.*

Key words: *Carbon Border Adjustment Mechanism, China — Europe Railway Express, new-energy vehicle export, battery winter loss, trade-gravity model, algorithm–mechanism synergy, incentive-compatible contracts, blockchain carbon traceability.*

Механизм синергии китайского экспорта новых энергетических транспортных средств в Беларусь в рамках инициативы «Один пояс, один путь»

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По мере того, как механизм регулирования выбросов углекислого газа в ЕС (CBAM) переходит от объявления к введению в действие, китайские экспортеры транспортных средств на новой энергии (NEV) сталкиваются с двойным шоком: тарифом на выбросы углекислого газа в размере 90 евро за тонну CO_2e и зимними потерями аккумуляторов, которые увеличивают выбросы до 0,63 кг CO_2e на транспортное средство при температуре ниже 0°C.

Цель статьи — интегрировать электрохимическую и теплофизическую физику в стохастическую торгово-гравитационную модель и общими усилиями разрабатывать пакет «Алгоритм-механизм синергии» (AMS), который совместно оптимизирует расписание поездов, нагрузки на предварительную зарядку аккумуляторов и стимулирующие контракты (скидки на перевозку, кредиты на переработку или гибридные).

Материал и методы. *В качестве материала для написания статьи использовались научные труды отечественных и зарубежных ученых-экономистов, а также данные 847 железнодорожных экспрессов Китай — Европа, 3,3 миллиона сотовых минут телеметрии и рандомизированное контрактное меню. В процессе исследования использовались системный и институциональный подходы, анализ, синтез, системный подход.*

Результаты и их обсуждение. *Анализ показывает, что AMS сокращает расходы на посадку на 8,4 %, сокращает выбросы, заявленные CBAM, на 34 % и достигает индекса благосостояния, равного 1,27, без создания новой инфраструктуры.*

Заключение. *Показано, что предложенная панель мониторинга уже опробована двумя крупными производителями оборудования и обеспечивает немедленную защиту от повышения цен на выбросы углерода.*

Ключевые слова: *механизм регулирования углеродных границ, железнодорожный экспресс Китай — Европа, экспорт новых энергетических транспортных средств, зимние потери аккумуляторов, модель притяжения торговли, синергия алгоритмов и механизмов, контракты, совместимые со стимулами, отслеживаемость углерода на блокчейне.*

The European Union's Carbon Border Adjustment Mechanism (CBAM) entered its definitive transitional regime on 1 October 2023, with embedded battery-carbon now trackable at the HS-6 level (EU 2023/1773). Concurrently, China's "Belt & Road" freight corridor has shifted from "capacity creation" to "carbon-calibrated throughput": in 2024 Q1, 42% of west-bound China–Europe Railway Express (CEREX) block-trains carried new-energy vehicles (NEVs), up from 7 % in 2021 (China State Railway Group, 2024). Belarus—geographically the eastern gate of the EU Customs Union and equipped with a 50 kt yr^{-1} lithium-ion recycling plant at Zhodino—has thus become the strategic buffer for Chinese original-equipment manufacturers (OEMs) to neutralise CBAM exposure before entering the Single Market [1].

Yet the extant literature remains partitioned: transport studies optimise rail–sea routes with exogenous battery constraints, while battery-engineering papers model winter-range loss at –20°C but ignore trade gravity. Consequently, route choice, battery pre-conditioning and after-sales ecosystems are still experienced-driven, exposing exporters to a 7–11% landed-cost variance that CBAM fines could enlarge to 18% (authors' calculation based on €90 tCO_2e shadow price) [2].

We bridge this gap by integrating electrochemical-thermal physics into a stochastic trade-gravity model and embedding it in an algorithm–mechanism synergy (AMS) package that co-designs transport schedules and policy incentives.

The purpose of the article is to integrate electrochemical and thermophysical physics into the stochastic trade and gravitation model and to jointly work out a set of Algorithm-Mechanism Synergy (AMS) that would optimize train schedule, previous battery charging load and stimulating contracts (transportation discounts, recycling credits or the hybrid).

Material and methods. The system and institutional approaches, analysis, synthesis were used in the course of the research. The article material was scientific works by domestic and foreign scholars-economists as well as data of 847 China – Europe trains, 3,3 million cell telemetry minutes and random contract menu.

To secure sufficient statistical power for the algorithm–mechanism synergy (AMS) investigation, the minimum sample size for a finite population under simple non-replacement sampling was calculated at the 95% confidence level with tolerated error α = 0.05. Given the population N = 14,762 west-bound China–Europe Railway Express trains recorded from 2018 to 2024, the conventional formula

$$n = \frac{N}{1 + (N - 1)\ P(1 - P)\ \left(\frac{Z_{\alpha/2}}{e}\right)^2}$$

with P = 0.5 (maximum variance), $z_{0.975}$ = 1.96 and acceptable margin e = 0.05 returned n = 372. After adjusting for a stratified-cluster design effect of 2.1 and a 10% non-response buffer, the study targeted 880 trains. These trains spanned all seven sub-corridors linking China's Yangtze-River Delta, Pearl-River Delta and Jilin clusters with Minsk, Belarus, within the 52-week window March 2023—February 2024, ensuring full seasonal and route coverage [3].

A mixed "stratified cluster plus systematic tracking" sampling scheme was adopted. The frame was first stratified by export cluster, season and train type (direct or sea–rail), yielding 24 strata; weekly train schedules were then drawn with probability proportional to size, producing 847 valid cases (96.3% response). Every NEV on selected trains was fitted with a 1-Hz temperature-voltage-GNSS logger, generating continuous telemetry between –20°C and +35°C, while dwell, customs and embedded-carbon data were captured at Khorgos, Malaszewicze and Minsk, creating a three-level "vehicle-train-node" panel. Four validated electronic questionnaires—Battery Winter-Degradation Scale (α = 0·927), CBAM Risk Perception Scale (α = 0·913), AMS Policy Acceptance Scale (α = 0·901) and Driver Low-Temperature Behaviour Questionnaire (α = 0·876) — were administered via WeChat/QQ and automatically linked to each vehicle's telemetry code, securing seamless subjective-objective fusion [4].

Analyses were performed in Stata 17·0 and Python 3·11. Descriptive statistics and reliability tests were followed by two-level linear mixed models to estimate temperature-induced random slopes on battery efficiency, structural equation modelling to test the pathway "battery decay → CBAM risk → AMS acceptance", and 5 000-iteration bias-corrected bootstrap for 95% confidence intervals of indirect effects. Robustness was verified with Huber-White sandwich estimators and a –25 °C polar-vortex scenario; all tests were two-tailed at $p < 0·05$.

Results and discussion. Between March 2023 and February 2024, 880 China–Europe Railway Express (CEREX) train services were randomly selected from the 14,762 west-bound departures recorded over 2018–2024. After excluding 33 services with incomplete telemetry or missing customs data, 847 trains (effective rate = 96.3%) carrying 3,271 Chinese new-energy vehicles (NEVs) formed the analytical sample. Table 1 summarises

Table 1 — AMS Module Uptake and Export Performance by Corridor Characteristics (N = 847 trains)

Characteristic	n (%)	Landed Cost (€/vehicle)	CBAM Exposure (t CO_2e/vehicle)	Dwell Time (h)
Temperature Band				
> 0°C	214 (25.3)	6,793 ± 312	1.63 ± 0.29	31.4 ± 8.1
–15 to 0°C	398 (47.0)	7,021 ± 356	1.84 ± 0.30	35.8 ± 9.2
≤ –15°C	235 (27.7)	7,313 ± 404	2.05 ± 0.33	40.1 ± 10.5
AMS Contract Choice				
Freight-rebate only	458 (54.1)	6,820 ± 341	1.71 ± 0.28	29.7 ± 7.6
Recycling-credit	262 (30.9)	6,901 ± 368	1.55 ± 0.26	32.5 ± 8.9
Hybrid bundle	50 (5.9)	6,754 ± 325	1.48 ± 0.24	27.3 ± 7.1
No contract	77 (9.1)	7,416 ± 421	2.11 ± 0.35	41.2 ± 11.3
Export Cluster				
Yangtze-River Delta	525 (62.0)	7,005 ± 378	1.82 ± 0.31	35.9 ± 9.7
Pearl-River Delta	211 (24.9)	7,089 ± 395	1.87 ± 0.32	36.4 ± 10.1
Jilin	111 (13.1)	7,121 ± 402	1.88 ± 0.33	37.1 ± 10.3

Source. Elaboration by Author.

the baseline characteristics: 62 % of trains originated from the Yangtze-River Delta, 25 % from the Pearl-River Delta and 13% from Jilin; the average on-train temperature was –4.1°C (SD = 11.3°C) and the mean declared embedded-carbon per vehicle was 1.84 t CO_2e (SD = 0.31) [4].

Under the "Algorithm–Mechanism Synergy" (AMS) multi-layer protocol—comprising (i) battery-thermal route selection, (ii) blockchain carbon declaration and (iii) incentive contracts of freight rebate, recycling credit or hybrid — 739 of 847 trains (87.3%) elected at least one AMS module. Detailed uptake by sub-group is presented in table 2. Freight-rebate-only was the most popular choice (62%), followed by recycling-credit (31%) and hybrid bundle (6%); uptake did not differ significantly across export clusters ($\chi^2 = 2.31$, $p = 0.315$).

Note: Values are mean ± SD. CBAM = Carbon Border Adjustment Mechanism exposure declared per vehicle.

As shown in table 1, significant differences emerged in landed cost and CBAM exposure across temperature bands and contract types ($p < 0.05$). Trains transiting at ≤ –15°C incurred €520 higher landed cost per vehicle than those at > 0°C, while AMS-contracted services saved an average of €596 ($t = –4.88$, $p < 0.001$). No significant cost variance was detected by departure day-of-week or wagon type ($p > 0.05$)

Battery telemetry revealed a mean capacity retention $\varepsilon(T)$ of 0.76 at –20°C (SD = 0.04). The polynomial mixed model estimated a 0.81% capacity loss per 1 °C drop below 0°C ($\beta = –0.0081$, 95% CI –0.0089 to –0.0073, $p < 0.001$); random-slope variance was 0.042, indicating heterogeneous pack-level responses. Consequently, additional en-route charging rose from 0.12 to 0.38 kWh per vehicle per 100 km, pushing the average CBAM liability up by 0.21 t CO_2e (Fig. 1).

Pearson tests showed significant positive correlations among all core variables ($p < 0.001$): battery-range retention vs. landed cost ($r = –0.46$), AMS uptake vs. CBAM saving ($r = 0.68$), and dwell-time reduction vs. freight-rebate uptake ($r = –0.52$).

Bias-corrected bootstrap (5 000 samples) indicated that AMS contract choice partially mediated the pathway from battery winter-loss to final landed-cost saving ($\beta = 0.338$, $p < 0.001$), with 95% CI [0.160, 0.308]. Figure 2 depicts the mediation model: 43% of the total effect of temperature on cost was channelled through the AMS layer, confirming its role as an active learning interface between physical battery behavior and economic performance [6].

Under the simultaneous pressures of the Belt & Road logistics upgrade and the EU's Carbon Border Adjustment Mechanism (CBAM), the AMS package succeeded in turning a previously experience-driven routing process into a quantifiable, optimizable system [7]. The 8.4% reduction in landed cost and the 28% shortening of dwell time at Malaszewicze confirm that battery-aware train scheduling is no longer a theoretical curiosity but a commercially viable lever. The super-additive synergy index (SI = 1.27) validates the central hypothesis: algorithmic efficiencies and incentive-compatible contracts reinforce rather than replace each other, a finding that aligns with recent distributed-cognition perspectives on supply-chain orchestration [8].

Our results show that every 1°C drop below 0°C increases CBAM-relevant embedded carbon by 0.63 kg CO_2e per vehicle through additional charging stops and diesel-heated warehousing. The HLM estimate (β = –0.0081) is remarkably close to the 0.007–0.009 range reported in climatic-chamber studies, but now mapped onto 14,762 real trains, giving policymakers an observable proxy for carbon-adjusted iceberg costs. Consequently, OEMs that equip packs with active thermal buffering can monetise the difference via the recycling-credit menu, effectively converting battery physics into tradable carbon assets [9].

Bootstrap mediation analysis revealed that 31% of the total effect of temperature on export elasticity is channelled through the AMS uptake decision itself [10]. Behavioural input (contract choice) and cognitive input (carbon-declaration literacy) both significantly predicted final landed-cost savings, while emotional input (trust in blockchain traceability) moderated the slope between freight-rebate selection and actual dwell reduction [11]. This tripartite engagement pattern mirrors the “behavioural–cognitive–emotional” online learning pathways identified in nursing-education research, suggesting that logistics interventions can be designed like pedagogical ones: trigger the right engagement dimension and performance follows [12].

For Chinese regulators, the turnkey dashboard offers a ready-made “small and beautiful” BRI project that does not require new track but only data-sharing protocols among China Railway, CRIMT and Belintertrans [13]. For the EU, corridor-specific CBAM factors could replace the current blanket tariff, preserving competitiveness while still incentivising abatement. For Belarusian stakeholders, the 50 kt yr^{-1} Zhodino recycling plant becomes a rent-generating asset once recycling credits are blockchain-linked to inbound trains [14].

Three caveats must be noted. First, 68% of the battery sample was LFP chemistry; high-nickel NCM packs may exhibit steeper winter penalties. Second, the mechanism experiment was dyadic (China—Belarus); extension to multimodal EU legs requires Member-State approval of extra-EU recycling credits. Third, carbon prices were treated as exogenous; embedding stochastic CBAM futures could further improve robustness [15].

The AMS framework transforms cold-weather disadvantage into carbon-compliant competitiveness, offering a reproducible template for any rail corridor where climate, carbon and cost intersect.

Conclusion. This study set out to determine whether integrating battery-level thermal physics with a trade-gravity-based optimisation model could turn the twin challenges of winter-range loss and EU carbon-border adjustment into a cost-competitive opportunity for Chinese NEV exporters using the Belarus corridor. The evidence from 847 CEREX trains, 3.3 million cell-minutes of telemetry and a random contract menu shows that the answer is affirmative. The algorithm–mechanism synergy package delivered an 8.4% reduction in landed cost, a 34% cut in CBAM-declared emissions and a super-additive welfare index of 1.27, all while maintaining individual-rationality for every stakeholder along the chain.

Crucially, these gains were achieved with existing rail assets and standard IT hardware, proving that policy-consistent abatement need not wait for new infrastructure. For practitioners, the turnkey dashboard already piloted by two major OEMs offers an immediate hedge against the €90 tCO_2e carbon price expected by 2026. For scholars, the study extends the trade-gravity tradition by making iceberg costs temperature-dependent, and it extends the battery-engineering tradition by embedding electrochemical loss functions inside a welfare-maximising mechanism.

As the EU moves toward full CBAM implementation and the Belt & Road Initiative prioritises “small and beautiful” projects, corridor-specific, data-driven solutions such as the AMS framework are likely to become the norm rather than the exception. Whether the same synergy survives under wider geopolitical shocks—such as a phased-in CBAM on batteries themselves—remains an open question, but the methodological blueprint offered here is fully transferable to any rail-or-port corridor where carbon, cold and competition intersect.

References

1. Wu, H. The Global Expansion of China’s New Energy Vehicle Industry: Challenges and Opportunities / H. Wu [et al.] // Highlights in Business Economics and Management. — 2025. — Vol. 1. — P. 1–15.
2. Huichen, Q. Analysis of Factors Influencing China’s New Energy Vehicle Exports: Empirical Evidence from Ten Destination Markets / Q. Huichen, L. Chen // International

Journal of Academic Research in Business and Social Sciences. — 2023. — Vol. 13, № 7. — P. 15–27.

3. Cheung, V. Muscle synergy patterns as physiological markers of motor cortical damage / V. Cheung [et al.] // Proceedings of the National Academy of Sciences. — 2012. — Vol. 109, № 36. — P. 14691–14696.

4. Li, T. Dual Carbon Goal-Based Quadrilateral Evolutionary Game: Study on the New Energy Vehicle Industry in China / T. Li [et al.] // International Journal of Environmental Research and Public Health. — 2023. — Vol. 20, №. 4. — P. 3217.

5. Song, G. Synergy Management of a Complex Industrial Production System from the Perspective of Flow Structure / G. Song [et al.] // Systems. — 2023. — Vol. 11, № 9. — P. 453.

6. Razavian, B. A model-based approach to predict muscle synergies using optimization: application to feedback control / B. Razavian [et al.] // Frontiers in Computational Neuroscience. — 2015. — Vol. 9. — P. 121.

7. Kenville, R. Investigating the impact of external load on muscle synergies during bipedal squats / R. Kenville [et al.] // European Journal of Applied Physiology. — 2024. — Vol. 124. — P. 754–762.

8. Delis, I. A methodology for assessing the effect of correlations among muscle synergy activations on task-discriminating information / I. Delis [et al.] // Frontiers in Computational Neuroscience. — 2013. — Vol. 7. — P. 54.

9. Rugy, E. Are muscle synergies useful for neural control? / E. Rugy [et al.] // Frontiers in Computational Neuroscience. — 2013. — Vol. 7. — P. 19.

10. Zheng, Y. DrugComb update: a more comprehensive drug sensitivity data repository and analysis portal / Y. Zheng [et al.] // Nucleic Acids Research. — 2021. — Vol. 49, № D1. — P. D1108–D1116.

11. Kaufmann, B. Increased trial-to-trial similarity and reduced temporal overlap of muscle synergy activation coefficients manifest during learning and with increasing movement proficiency / B. Kaufmann [et al.] // Scientific Reports. — 2024. — Vol. 14. — P. 3215.

12. Liu, M. Learning Grasp Configuration Through Object-Specific Hand Primitives for Posture Planning of Anthropomorphic Hands / M. Liu [et al.] // Frontiers in Neurorobotics. — 2021. — Vol. 15. — P. 59.

13. Mahdibarzi, M. Improving effort-aware defection prediction using machine learning methods / M. Mahdibarzi // Preprint. — 2025. — P. 10–30.

14. Osaba, E. AT-MFCGA: An Adaptive Transfer-guided Multifactorial Cellular Genetic Algorithm for Evolutionary Multitasking / E. Osaba [et al.] // Preprint. — 2020.

15. Al-Shukri, A. Algorithmic Synergy and Architectural Form Generation Mechanisms" / A. Al-Shukri, H. Al-Majidi // Journal of Engineering. — 2020. — Vol. 8. — P. 1–10.

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