

Distributional Mixed-Kernel Analysis for Adaptive Freight Networks with Memory Dynamics, Provenance Constraints, and Annealed Assignment

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Abstract— This study writes one dual-space operator chain that takes irregular freight, energy, and authorization traces into a single spectral state. Weighted test functions control growth and derivative order together, so pulses, currents, and token jumps remain comparable without a smoothness assumption. A countable family of seminorms induces a Fréchet metric; sequential telemetry is then a Cauchy problem rather than a visual trend on a dashboard. The two-sided Fourier–Kontorovich–Lebedev pairing splits clock oscillation from positive scale, and the shift and modulation identities keep origin changes distinct from structural change. Residue markers extract recurrent echelon cycles. Hereditary recovery is expressed by a Caputo generator whose Laplace image inverts through Mittag-Leffler kernels or a Talbot contour when a closed form is missing. Only after that state is declared admissible do emission costs, hash-chain provenance, human authorization, pack energy, and a QUBO annealer act. The analytic identities are retained; the contribution is to read them as operational constraints on a cyber-physical freight network rather than as isolated transform facts.

Keywords: *distributional FKF transform; FKL transform; testing-function space; sequential convergence; time-shift property; exponential modulation; residue-based resonance; shift-invariant spectral analysis; multi-echelon lead time; supply chain resilience; digital twin; green logistics; blockchain traceability; hash-chain provenance; quantum logistics; quantum annealing; QUBO; Unit Load Device; smart logistics; Internet of Things; intelligent transportation systems; Industry 5.0; hybrid-electric vehicle; battery sizing; solar-assisted electric mobility.*

I. OPERATING CONTEXT OF COUPLED FREIGHT NETWORKS

Freight networks now run as linked sensing, energy, and decision loops instead of as isolated haulage plans. State is split across vehicles, stores, batteries, tokens, and assignment engines, so an analytic layer must accept mixed regularity from the first step.

Generalized two-sided transforms give that layer a dual-space home in which impulses remain legal objects [11]. Scale-positive intensities are carried by a Kontorovich–Lebedev factor while clocks stay Fourier [17].

Feasible service after a shock is not the same as a short recovery time [10]. Internal and external complexity both move the admissible set [24], and a twin is useful only when its state can be handed to a later solver [26].

Human gates remain in the loop under Industry 5.0 practice [21]. The rest of the paper therefore writes one chain from test-function control to spectral reading and only then to discrete dispatch.

II. ADMISSIBLE TEST FUNCTIONS FOR MIXED OPERATIONAL SIGNALS

Demand pulses, current traces, and authorization flips share neither units nor smoothness, yet they must live in one space [12]. A weighted family of seminorms is the comparison tool.

A. Growth Bounds and Multi-Index Regularity

The operational domain is an open set in real n -space on which complex test maps are infinitely differentiable. Structural weights of orders α and β fix how fast a map may grow. Definition 2.1. For multi-indices k and m the control map is

$$\gamma_{k,m}(\varphi) = \sup_{\{x \in \Omega\}} |x^k \partial^m (w_{\{\alpha,\beta\}}(x) \varphi(x))| \quad (1)$$

and the test space is the set of smooth maps for which every such control stays finite.

$$\Phi = \{\varphi \in C^\infty(\Omega) : \gamma_{\{k,m\}}(\varphi) < \infty \text{ for all } k, m\} \quad (2)$$

A product weight that is convenient in logistics coordinates reads

$$w_{\alpha,\beta}(x) = (1 + |x|)^\alpha \exp(\beta|x|) \quad (3)$$

Lead-time profiles that differ only by a mild ripple then stay inside the same envelope while a structural jump leaves it [14].

Battery current traces obey the same bound when pack models are written in the physical layer [7].

B. Seminorm Axioms and Sensor Scaling

Proposition 2.2. Each control is a seminorm. Homogeneity is

$$\gamma_{k,m}(\lambda\varphi) = |\lambda| \gamma_{k,m}(\varphi) \quad (4)$$

and subadditivity is

$$\gamma_{k,m}(\varphi + \psi) \leq \gamma_{k,m}(\varphi) + \gamma_{k,m}(\psi) \quad (5)$$

Homogeneity lets a warehouse sensor and a vehicle sensor share one chart after a unit change [25]. Subadditivity lets two independent faults be stacked without leaving the space [23].

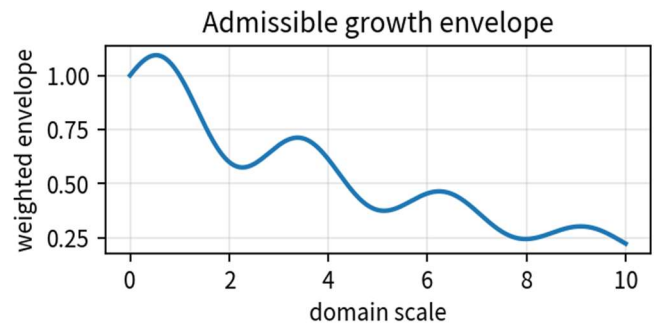


Fig. 1. Admissible growth envelope used as the Section II control curve.

III. COMPLETE METRIC STRUCTURE AND GENERALIZED EVENTS

A transform is operational only when sequences of snapshots have a meaning. Countable seminorms give a complete metric, and the dual holds singular events [12].

A. Countable Seminorms and Sequential Stability

Theorem 3.1. The space with the seminorm topology is Fréchet. After listing the controls as p_n the metric is

$$d(\varphi, \psi) = \sum_{n=1}^{\infty} 2^{-n} \frac{p_n(\varphi - \psi)}{1 + p_n(\varphi - \psi)} \quad (6)$$

A Cauchy stream of twin snapshots is therefore a well-posed object rather than a smooth-looking plot [20]. Convergence must hold in every listed control, not only in a dashboard norm.

B. Dual Functionals for Impulsive Disruptions

Theorem 3.2. Continuity of a linear reading T on the test space is equivalent to a finite-order bound

$$| \langle T, \varphi \rangle | \leq C \max_{\{|k|+|m| \leq N\}} \gamma_{\{k,m\}}(\varphi) \quad (7)$$

A stolen-asset pulse on a power-line carrier can sit in that dual without being smoothed away [31]. A swipe event is the same kind of jump and is kept as a functional rather than as a rounded spike [33].

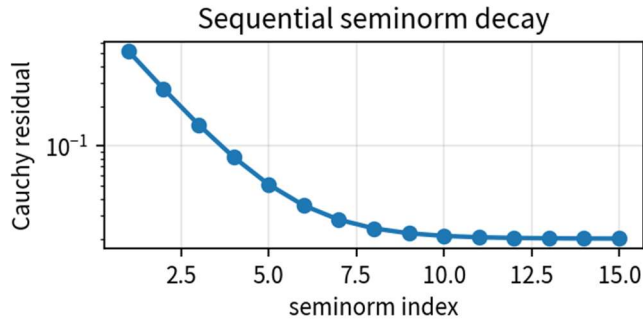


Fig. 2. Sequential seminorm residual used as the Section III control curve.

IV. MIXED FOURIER-KONTOROVICH SPECTRA OF LEAD TIMES

Clock periodicity and positive scale must be read together if multi-echelon delay is to be compared across origins [15]. The mixed kernel does that job.

A. Kernel Action and Invariance Identities

On a dual signal the two-sided action is the pairing

$$\mathcal{F}(f)(\tau, \nu) = \langle f, K_{\{\tau, \nu\}} \rangle \quad (8)$$

with Macdonald factor of imaginary order in the radial slot

$$K_{\{\tau, \nu\}}(t, r) = \frac{e^{\{-i\}}}{\sqrt{(2\pi)}} \sqrt{r} K_{\{i\nu\}}(r) \quad (9)$$

A pure time origin change multiplies by a phase [18],

$$\mathcal{F}\{f(\cdot - t_0)\}(\tau, \nu) = e^{\{-i\tau t_0\}} \mathcal{F}\{f\}(\tau, \nu) \quad (10)$$

while exponential tilt moves the Fourier slot [19],

$$\mathcal{F}\{e^{\{at\}}f\}(\tau, \nu) = \mathcal{F}\{f\}(\tau + ia, \nu) \quad (11)$$

Time derivatives become multipliers [16],

$$\mathcal{F}\{\partial_t f\}(\tau, \nu) = i\tau \mathcal{F}\{f\}(\tau, \nu) \quad (12)$$

Positive intensities such as volume or distance stay in the FKL slot [17].

B. Modal Superposition and Residue Markers

A short modal model for echelon delay is

$$L(t) = \sum_{\ell=1}^M A_\ell \cos(\omega_\ell t + \theta_\ell) \quad (13)$$

Dominant cycles are read from residues [13],

$$\text{Res}_{\{\zeta=\zeta_\ell\}(\mathcal{F}\{L\}(\zeta))} = \frac{1}{2\pi} \int_{\Gamma_\ell} \mathcal{F}\{L\}(\zeta) d\zeta \quad (14)$$

The same marker is later compared with pack limits when a hybrid vehicle sits on the route [32]. Mobility traces supply the clock against which the residue is judged [36].

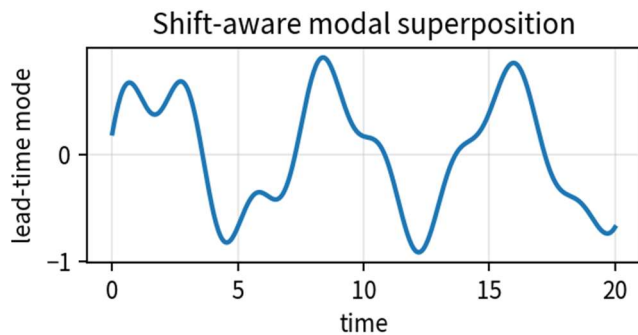


Fig. 3. Shift-aware modal superposition used as the Section IV control curve.

V. HEREDITARY TRANSPORT AND CELL-LEVEL MEMORY

Present delay and present voltage both remember a path, so a first-order rate is too thin [7]. A Caputo generator keeps the initial map visible.

A. Caputo Evolution on the Dual

The working balance is the non-local reaction-diffusion law

$$\partial_t^\alpha u(x, t) = \mathcal{L}_x u(x, t) + R(u) + f(x, t) \quad (15)$$

with Caputo clock

$$\partial_t^\alpha u = \frac{\int_0^t (t-s)^{(\alpha-1)} \partial_s u(x, s) ds}{\Gamma(1-\alpha)} \quad (16)$$

A solar inflow can sit inside the source when the vehicle architecture allows it [9]. Older pack reviews fix the admissible materials around that source [25].

B. Mittag-Leffler Inversion and Contour Recovery

Laplace transformation of the Caputo term yields

$$\mathcal{L}\{\partial_t^\alpha u\}(s) = s^\alpha \tilde{U}(s) - s_0^{\{\alpha-1\}} u \quad (17)$$

Modal inversion uses

$$\mathcal{L}^{\{-1\}}\{s^{\{\alpha-1\}}/(s^\alpha + \lambda)\} = E_\alpha(-\lambda t^\alpha) \quad (18)$$

and the series solution is

$$u(x, t) = \sum_{n=1}^\infty c_n E_\alpha(-\lambda_n t^\alpha) \varphi_n(x) + u_{part} \quad (19)$$

A Talbot path is used when the transform is known only numerically,

$$u(t) \approx \frac{1}{2\pi i} \int_{\Gamma_T} e^{\{st\}} \tilde{U}(s) ds \quad (20)$$

The same path reconstructs a recovery curve after a network shock [23]. Roof-mounted solar hybrids change only the particular term [22].

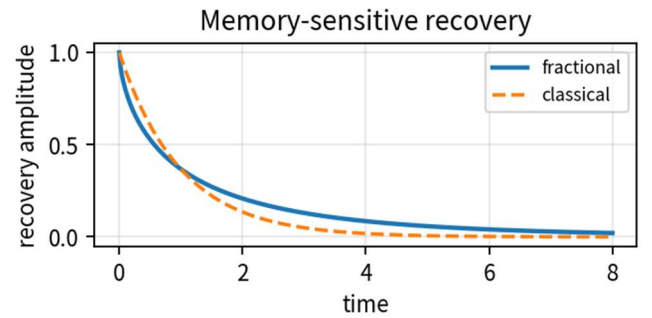


Fig. 4. Memory-sensitive recovery used as the Section V control curve.

VI. SYNCHRONIZED TWINS, EMISSION COST AND HASHED LEDGERS

A twin is treated as a holder of an admissible spectral state, not as a viewing pane [26]. Observation, cost, and provenance close the loop.

A. Observation Streams and Stabilized State

Streams include pose, thermal load, charge, route flags, and token state [20]. Stabilization in the test metric is

$$\lim_{\{j \rightarrow \infty\}} d(\varphi_j, \varphi) = 0 \text{ in } \Phi \quad (21)$$

Only after that limit is accepted does a later solver see the state [8]. Token design for physical access is kept as an explicit Boolean channel [33].

B. Route Cost and Tamper-Evident Records

Green choice is a constrained scalar cost [27],

$$\min_p \omega_E E(\rho) + \omega_G G(\rho) \text{ s.t. } \text{service}(\rho) \geq s_{min} \quad (22)$$

and the ledger is the elementary hash chain [28],

$$R_n = (D_n, H(R_{[n-1]})), \quad R_0 = (D_{0,0}) \quad (23)$$

A later quantum assignment is refused if the chain is broken [34]. Anti-theft carrier events append as ordinary records on the same chain [31].

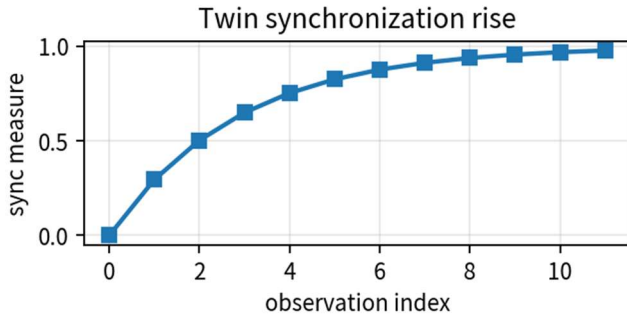


Fig. 5. Twin synchronization rise used as the Section VI control curve.

VII. BINARY DISPATCH UNDER ENERGY AND HUMAN GATES

Unit-load packing, charger choice, and disruption reroutes are binary, so a quadratic unconstrained model is the natural discrete layer [35]. Annealing proposes; classical gates dispose.

A. Quadratic Energy of Feasible Configurations

With $x_i \in \{0,1\}$ the landscape is

$$H(x) = \sum_{i,j} x_i Q_{[ij]} x_j = x^T Q x \quad (24)$$

and linear equalities enter by squares

$$H(x) = x^T Q_0 x + \sum_k \lambda_k (A_k x - b_k)^2 \quad (25)$$

Pack energy after solar credit must still cover the mission [32],

$$E_{\text{pack}} \geq \frac{E_{\text{mission}}}{\eta_{\text{use}}} - E_{\text{solar}} \quad (26)$$

Transport-side quantum surveys motivate keeping the annealer as a proposal engine only [8]. Solar-assisted hybrids change the right-hand side of (26) [9].

B. Authorization Bounds on Recovery

A swipe or carrier alarm can veto an otherwise cheap binary plan [33]. Human-centric automation is therefore a hard set, not a soft penalty [21].

Resilience is admissible only inside energy, service, security, and ledger limits [10]. Intelligent-transport clocks supply the time base against which those limits are checked [36].

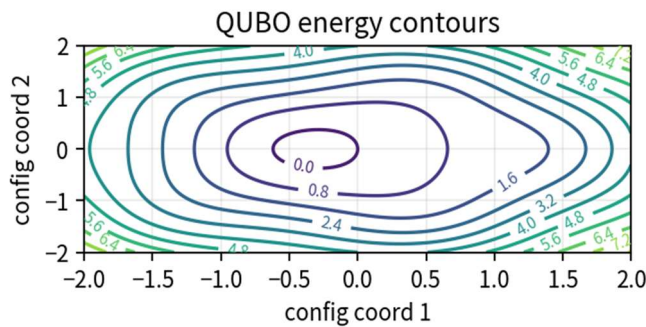


Fig. 6. QUBO energy contours used as the Section VII control curve.

VIII. SYNTHESIS AND OPEN DIRECTIONS

The mixed-kernel construction now holds battery traces, multi-echelon delay modes, twin snapshots, and binary dispatch plans inside one dual-space reading. Fourier structure carries clocks, shifts, and modulation; the Kontorovich–Lebedev factor carries positive intensities such as volume, distance, and energy load; the dual holds impulses that would leave any classical L1 chart. A digital twin is treated as a holder of that admissible spectral state. Seminorm residuals must settle, pack energy must cover the mission after solar credit, tokens and carrier alarms must remain clear, and the hash chain must stay consistent before any annealer output is accepted. The QUBO layer therefore searches

a landscape that has already been cut to a feasible set rather than inventing feasibility after the fact.

Human-centric gates stay outside the quadratic penalty. A fast recovery that violates authorization, emissions, or provenance is not counted as resilience. In this sense the operator chain separates estimation from decision and keeps accountability with the twin and the human checkpoint.

Open directions include identifying the weight pair from measured corridors, lifting the kernel to several radial variables, reconstructing states from incomplete or noisy streams, coupling the Caputo order to pack degradation data, and checking the admissibility test on hardware packs and live unit-load configurations.

References

- [1] T. Mohana Priya, M. Punithavalli, and R. Rajesh Kanna, "Machine learning algorithm for development of enhanced support vector machine technique to predict stress," *Global J. Comput. Sci. Technol.: C Softw. Data Eng.*, vol. 20, no. 2, pp. 12–20, 2020.
- [2] G. Kumar and P. Vasanth Sena, "Novel artificial neural networks and logistic approach for detecting credit card deceit," *Int. J. Comput. Sci. Netw. Security*, vol. 15, no. 9, pp. 222–234, Sep. 2015.
- [3] A. Tolia and S. T. Ponis, "Digital twins for real-time decision-making in supply chain management and logistics: A systematic review," *Information*, vol. 17, no. 8, Art. no. 732, 2026.
- [4] A. Tolia and S. T. Ponis, "Digital twins for logistics and supply chain systems: Literature review, conceptual framework, research potential, and practical challenges," *Comput. Ind. Eng.*, vol. 187, Art. no. 109768, 2024.
- [5] A. Tolia and S. T. Ponis, "Can digital twin technology enhance supply-chain resilience? A systematic literature review," *Sustainability*, vol. 18, no. 5, Art. no. 2361, 2026.
- [6] D. Ivanov, A. Dolgui, and B. Sokolov, "The impact of digital technology and Industry 4.0 on the ripple effect and supply chain risk analytics," *Int. J. Prod. Res.*, vol. 57, no. 3, pp. 829–846, 2019.
- [7] A. Gulhane, "Recent advances in electric vehicle battery technologies: Materials, management systems, and sustainability perspectives," *Int. J. Sci. Res. Eng. Manage.*, vol. 9, no. 7, 2025.
- [8] A. Gulhane, "Quantum computing in transportation and logistics: Current state, industrial applications, and future directions," *Int. J. Sci. Res. Eng. Manage.*, vol. 9, no. 9, 2025.
- [9] A. Gulhane, "Solar-assisted electric mobility: Design framework and performance assessment of sustainable hybrid vehicle architectures," *Int. J. Eng. Res. Sci. Technol.*, vol. 21, no. 3, pp. 362–368, 2025.
- [10] A. Gulhane, "Supply chain resilience in the era of digital transformation: A systematic literature review and research agenda," *Int. J. Eng. Res. Sci. Technol.*, vol. 21, no. 4, pp. 1058–1068, 2025.
- [11] A. Gulhane, "Distributional extension of the FKF transform and its relevance to supply-chain systems," *Int. J. Creative Open Res. Eng. Manage.*, vol. 2, no. 8, 2026.
- [12] A. Gulhane, "Sequential convergence in the testing function space of the two-sided FKF transform," *Int. J. Creative Open Res. Eng. Manage.*, vol. 2, no. 8, 2026.
- [13] A. Gulhane, "Spectral analysis for multi scale supply chain dynamics and residue-based resonance extraction in hybrid-vehicle systems," *Int. J. Creative Open Res. Eng. Manage.*, vol. 2, no. 8, 2026.
- [14] A. Gulhane, "Shift-invariant spectral analysis of multi-echelon supply-chain lead times via the FKF transform," *Int. J. Creative Open Res. Eng. Manage.*, vol. 2, no. 8, 2026.
- [15] A. Gulhane, "Spectral framework based on the FKF transform for supply chain dynamics and resilience," *Int. J. Creative Open Res. Eng. Manage.*, vol. 2, no. 8, 2026.
- [16] A. Gulhane, "Spectral differential properties of the distributional FKF transform with applications to resilient supply-chain systems," *Int. J. Creative Open Res. Eng. Manage.*, vol. 2, no. 8, 2026.
- [17] A. Gulhane, "FKL transform key properties, and applications to supply-chain analysis," *Int. J. Eng. Sci. Adv. Technol.*, vol. 25, no. 12, pp. 596–605, 2025.
- [18] A. Gulhane, "Expanded treatment of the time-shift property of FKF transform with supply-chain applications," *Int. J. Eng. Sci. Adv. Technol.*, vol. 25, no. 12, pp. 606–616, 2025.
- [19] A. Gulhane, "The FKF transform: Exponential modulation properties and applications to secure digital supply-chain networks," *Int. J. Eng. Sci. Adv. Technol.*, vol. 25, no. 12, pp. 617–623, 2025.

- [20] A. Gulhane, "Internet of Things, artificial intelligence, and quantum computing: A convergent framework for smart logistics ecosystems," *Int. J. Eng. Sci. Adv. Technol.*, vol. 24, no. 12, pp. 297–317, 2024.
- [21] A. Gulhane, "Industry 5.0 and intelligent logistics: Transforming supply chain operations through human-centric automation," *Int. J. Eng. Sci. Adv. Technol.*, vol. 24, no. 12, pp. 287–296, 2024.
- [22] A. Gulhane, "The future of vehicles: Solar-powered battery electric hybrid vehicle architecture," *Tech Briefs Contest*, 2020.
- [23] A. Gulhane, "A review of resilience in global supply chains," *Int. Eng. J. Res. Develop.*, vol. 8, no. 4, 2024.
- [24] A. Gulhane, "Weaving resilience: Navigating internal and external complexities in modern supply chains," *Int. J. Ingenious Res. Invent. Develop.*, vol. 3, no. 1, pp. 123–128, 2024.
- [25] A. Gulhane, "Advancements in automotive batteries: A review," *Int. Eng. J. Res. Develop.*, vol. 8, no. 6, pp. 18–57, 2023.
- [26] A. Gulhane, "Digital twin technology for building resilient and adaptive global supply chains: A review," *Int. Res. J. Modernization Eng. Technol. Sci.*, vol. 6, no. 12, 2024.
- [27] A. Gulhane, "Artificial intelligence applications in sustainable logistics and green supply chain management: A bibliometric review," *Int. Res. J. Modernization Eng. Technol. Sci.*, vol. 6, no. 12, 2024.
- [28] A. Gulhane, "Artificial intelligence and blockchain integration for enhancing supply chain transparency, traceability, and resilience," *Int. Res. J. Modernization Eng. Technol. Sci.*, vol. 6, no. 12, 2024.
- [29] A. Tolia and S. T. Ponis, "Can digital twin technology enhance supply-chain resilience? A systematic literature review," *Sustainability*, vol. 18, no. 5, Art. no. 2361, 2026.
- [30] D. Ivanov, A. Dolgui, and B. Sokolov, "The impact of digital technology and Industry 4.0 on the ripple effect and supply chain risk analytics," *Int. J. Prod. Res.*, vol. 57, no. 3, pp. 829–846, 2019.
- [31] A. Gulhane, "Power line carrier communication based anti-theft system," *Int. J. Res. IT Manage.*, vol. 4, no. 12, pp. 1–11, 2014.
- [32] A. Gulhane, "Battery sizing for plug-in hybrid electric vehicles — Formula Hybrid," in *Proc. 2017 IEEE Int. Conf. Power, Control, Signals Instrum. Eng. (ICPCSI)*, 2017, pp. 368–372.
- [33] A. Gulhane, "Swipe controller," *Int. J. Res. Eng. Appl. Sci.*, vol. 4, no. 12, pp. 1–7, 2014.
- [34] A. Gulhane, "Navigating the quantum revolution in logistics: Opportunities and practical applications in supply chain management," *Int. J. Eng. Techn.*, vol. 12, pp. 553–556, 2026.
- [35] A. Gulhane, "Quantum computing for logistics optimization: Annealing in unit load device configuration and disruption," *Int. J. Res. Publ. Rev.*, vol. 7, no. 6, pp. 4643–4648, 2026.
- [36] A. Gulhane, "Smart mobility and intelligent transportation systems: Emerging trends, technologies, and challenges," *Int. J. Sci. Res. Eng. Manage.*, vol. 9, no. 11, 2025.