A Unified Framework Linking Transform-Electro Thermal Battery States and Quantum Logistics Optimization

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Abstract—
The framework combines the transform-domain treatment of time-dependent signals with electro-thermal battery-state modeling, multi-scale spectral analysis, intelligent transportation, digital-twin synchronization, artificial intelligence, blockchain-supported traceability, and quantum optimization. The mathematical emphasis is placed on admissible testing-function spaces, transform composition, time-domain operators, state estimation, energy constraints, and spectral signatures of operational disturbances. Battery sizing is formulated as a constrained energy-power problem in which state of charge, temperature, current demand, and auxiliary loads jointly determine feasible operating envelopes. Smart mobility is represented as an interconnected cyber-physical system in which vehicle telemetry, charging infrastructure, traffic conditions, and logistics demand form coupled dynamic signals. Resilience is treated as the ability of the network to detect, absorb, adapt to, and recover from disruptions while respecting physical and operational constraints. Quantum annealing and QUBO representations are introduced as optimization layers rather than replacements for continuous battery and network dynamics. The resulting architecture provides a coherent bridge between transform calculus, digital twins, sustainable mobility, and resilient logistics without altering the professional mathematical expressions retained from the source document.
Keywords: hybrid transform calculus; battery sizing; electro-thermal modeling; smart mobility; intelligent transportation systems; spectral analysis; digital twins; artificial intelligence; blockchain; supply chain resilience; quantum logistics; QUBO.

I. INTRODUCTION

Integral Battery-electric and hybrid mobility systems increasingly operate as components of larger logistics networks rather than as isolated vehicles. A useful mathematical model therefore has to connect cell-level electrical and thermal behavior with vehicle-level energy demand and network-level logistics states. Battery sizing establishes the feasible energy and power envelope, while intelligent mobility determines how that envelope is consumed under changing routes, traffic, charging availability, and freight demand. The literature represented by the supplied references supports this progression from battery engineering toward integrated mobility and logistics systems [11].

Automotive battery development includes electrochemical storage, thermal management, battery-management systems, charging strategies, degradation, safety, and sustainability. These aspects make a single static capacity number inadequate for planning. A practical sizing framework must distinguish energy capacity from peak power, account for usable state-of-charge limits, and include temperature and ageing effects [14]. Recent battery technology perspectives further motivate coordinated treatment of materials, management systems, lifecycle considerations, and electrified-vehicle operation [15].

Smart mobility adds another layer of coupling. Intelligent transportation systems combine sensing, communications, computation, routing, charging, traffic information, and human interaction. Mobility decisions can consequently be interpreted as control actions acting on a dynamic energy system rather than merely as route choices [16]. Solar-assisted hybrid architectures extend this perspective by introducing an additional renewable-energy input whose variability must be reconciled with vehicle demand and battery constraints [17].

The central proposition of this work is that transform methods provide a compact representation of these coupled dynamics. The Fourier component exposes temporal oscillations and recurring operating cycles, while a scale-sensitive transform component can characterize positive variables such as intensity, distance, or degradation-related state. The same representation can be propagated into logistics signals, where lead-time cycles, demand disturbances, and recovery signatures have different characteristic scales.

The source manuscript's Laplace-Weierstrass construction is retained as a mathematical bridge. Its test-function formulation and transform-domain operator rules motivate the broader hybrid calculus used here. The approach is deliberately layered: physical models generate admissible trajectories; transforms expose their spectral structure; estimation converts measurements into state information; digital twins maintain synchronized representations; and optimization selects feasible actions.

II. HYBRID TRANSFORM CALCULUS AND FUNCTION-SPACE FOUNDATIONS

2.1 test-function setting and transform composition

Let a>0 and A,B>0 denote fixed parameters. The testing-function construction in the source manuscript defines a smooth function class controlled by weighted seminorms. Such a space is useful because battery current, voltage, temperature, mobility demand, and logistics signals are not necessarily ideal square-integrable signals at every modeling stage. A testing-function framework permits generalized signals and supports sequential limiting arguments.

The seminorm family supplies a topology in which convergence can be expressed through controlled derivatives and weighted growth. This becomes important when telemetry is noisy, when a digital twin is updated sequentially, or when a finite observation window is extended toward a generalized signal representation. The two-sided FKF theory in the supplied references specifically motivates sequential convergence and shift-sensitive analysis [29].

2.2 operator rules and time-domain structure

The Laplace-side multiplication and differentiation rules retained from the source manuscript show how polynomial time dependence can be mapped into transform-domain differentiation and how time differentiation can be represented through multiplication by the transform variable. These identities form the algebraic core of the hybrid calculus.

For a generic transform pair, the time-shift operator can be represented schematically by an exponential factor. The supplied FKF time-shift study extends this idea to supply-chain applications, allowing delayed demand, transportation lead times, and delayed recovery effects to be treated as translated spectral signatures [28].

$$F\{f(t-\tau)\}(\omega,\kappa) = e^{(-i\omega\tau)}F\{f(t)\}(\omega,\kappa)$$

A hybrid representation can consequently be written as a composition of a temporal Fourier-type kernel and a scale-sensitive KL-type kernel. The purpose is not to replace the original transforms, but to place them in a common analytical pipeline for signals generated by mobility and logistics systems.

$$H(\omega,\kappa) = \int_0^{\infty}\int_{-\infty}^{\infty} f(t,y)e^{-i\omega t}K_{\text{i}\kappa}(y)dt\,dy$$

III. ELECTRO-THERMAL BATTERY MODELING AND STATE ESTIMATION

3.1 retained Thevenin model

The source document couples electrical and thermal dynamics through a Thevenin equivalent circuit. This model is retained as the physical plant because it provides a tractable relation among current, terminal voltage, polarization dynamics, and temperature. Battery parameters are allowed to depend on state of charge and temperature, consistent with the supplied battery literature [14], [15].

The RC polarization state captures transient voltage response, while the thermal balance accounts for internally generated heat and heat exchange with the environment. In a battery-management context, these states form the minimum physical layer required before an estimator can infer SoC or SoH from measurements.

3.2 noise-to-estimate pipeline

Measured voltage and current are affected by sensor noise, quantization, temperature variation, parameter uncertainty, and operating-history dependence. A robust estimation layer therefore combines model prediction with measurement correction. A generic continuous-time state model may be expressed as

$$\dot{x}(t) = A(\theta,T)x(t) + B(\theta,T)u(t) + w(t)$$
$$y(t) = C(\theta,T)x(t) + D(\theta,T)u(t) + v(t)$$

where x contains electrical and thermal states, u contains current and auxiliary inputs, y contains measured voltage and temperature, and w and v represent process and measurement uncertainty. The transform representation of residuals can then distinguish periodic driving components from transient estimation errors.

$$r(t) = y(t) - \hat{y}(t),\ \ R(\omega) = F\{r(t)\}(\omega)$$

IV. BATTERY SIZING, POWER LIMITS AND ENERGY FEASIBILITY

4.1 energy-capacity sizing

Battery sizing must satisfy both energy and power requirements. The energy condition integrates traction, accessory, conversion, and charging losses over the duty cycle. The battery-sizing reference in the supplied literature establishes the engineering relevance of sizing for plug-in hybrid vehicle operation [11].

$$E_{req} = \int_0^T [P_{trac(t)} + P_{aux(t)} + P_{loss(t)}]dt$$

$$E_{use} = V_{nom}Q_{nom}[SOC_{max} - SOC_{min}]se \geq E_{req}/\eta_{sys}$$

The usable energy is smaller than the nominal stored energy because reserve limits, conversion efficiency, temperature derating, ageing, and safety margins restrict the operating region. Power feasibility must be checked independently.

$$P_{batt(t)} = V_{batt(t)I_{batt(t)}}$$

$$P_{batt(t)} \leq P_{\max(SOC,T,SOH)}$$

A practical sizing margin can be represented by a multiplicative factor on the required capacity. The factor should absorb route uncertainty, degradation allowance, environmental variation, and reserve policy rather than being treated as an arbitrary constant.

$$Q_{design} = \gamma \frac{E_{req}}{[V_{nom}\eta_{sys}\Delta SOC]}$$

4.2 thermal and ageing constraints

Temperature affects both instantaneous power capability and long-term degradation. A sizing decision is therefore feasible only when the predicted temperature remains within its admissible interval.

$$T_{min} \leq T(t) \leq T_{max}(t) \geq SOH_{min}$$

This constraint-based formulation aligns battery engineering with resilient logistics: a route or dispatch plan is not feasible merely because its average energy consumption is acceptable; it must remain inside the physical battery envelope under transient demand.

V. SMART MOBILITY AND INTELLIGENT TRANSPORTATION DYNAMICS

5.1 mobility as a cyber-physical system

Smart mobility integrates vehicles, roads, charging infrastructure, communications, sensing, and decision support. The supplied intelligent-transportation reference identifies emerging technologies and challenges that make mobility a networked information-and-energy system [16]. A vehicle's route is consequently coupled to traffic state, charging opportunities, fleet demand, and logistics service requirements.

Let z(t) denote a vector containing speed, acceleration, traffic density, charging state, route position, and logistics demand. A generalized mobility model is

$$\dot{z}(t) = f[z(t), u(t), d(t), \eta(t)]$$

$$y_{m(t)} = h[z(t)] + \nu(t)$$

Here u represents control actions, d represents external demand or disturbance, η represents uncertain network conditions, and ν represents measurement error. The transform of z(t) can reveal recurring congestion cycles, charging patterns, and duty-cycle frequencies.

$$Z(\omega) = F\{z(t)\}(\omega)$$

5.2 renewable-assisted mobility

Solar-assisted electric mobility introduces a variable renewable input. The supplied solar-assisted architecture reference motivates treating renewable generation as a component of the vehicle energy balance rather than as an independent subsystem [17].

$$P_{net(t)} = P_{solar(t)} + P_{grid(t)} - P_{load(t)}$$

$$\dot{X}E_{b(t)} = P_{net(t)} - P_{aux(t)} - P_{loss(t)}$$

The hybrid transform framework can analyze the solar-generation spectrum and the mobility-demand spectrum jointly. Alignment between renewable availability and vehicle demand can reduce charging stress, while mismatches can be managed through storage, charging schedules, and route selection.

VI. MULTI-SCALE SPECTRAL ANALYSIS OF MOBILITY AND LOGISTICS SIGNALS

6.1 spectral decomposition of operational signals

Logistics networks exhibit multiple temporal scales: short-duration vehicle events, daily demand cycles, weekly schedules, lead-time variability, and slower recovery processes. The supplied spectral-analysis reference motivates a multi-scale treatment and residue-based resonance extraction for hybrid-vehicle and supply-chain signals [18].

A generic two-variable hybrid transform may be written as

$$F_H(\omega,\kappa) = \int_0^{\infty} e^{-i\omega t} \left(\int_{-\infty}^{\infty} e_i \kappa(y)\, K f(t,y)\, dy \right) dt,$$

The Fourier variable ω represents temporal frequency, while κ indexes the scale-sensitive transform dimension. Peaks or localized spectral structures can be interpreted as recurring operational modes, provided that their physical meaning is validated against the underlying telemetry.

$$|F_H(\omega,\kappa)|^2 = S(\omega,\kappa)$$

6.2 shift, convergence and resonance

A time displacement changes phase without changing the underlying spectral magnitude. This is valuable for logistics because the same operational event may occur at different locations or times. The supplied FKF work specifically develops the time-shift property and its application to supply-chain signals [28]. Sequential convergence provides the analytical basis for taking limits of approximating signal sequences in the testing-function setting [29].

$$f_n \to f \quad \Rightarrow \quad F_{H[f_n]} \to F_{H[f]}$$

$$Res[F_H\ ](z_0\ ) \lim_{\{z\to z_0\}(z-z_0)} \quad F_H(z)$$

Residue-based extraction can therefore be interpreted as a mechanism for isolating concentrated spectral contributions associated with recurring modes or resonance-like behavior. In a resilient logistics application, these features may indicate persistent demand cycles, repeated congestion, charging oscillations, or delayed recovery signatures.

VII. ARTIFICIAL INTELLIGENCE, DIGITAL TWINS AND TRACEABLE MOBILITY

7.1 AI-assisted prediction and control

Artificial intelligence in sustainable logistics can support demand forecasting, routing, predictive maintenance, anomaly detection, and resource allocation. The supplied bibliometric review positions AI as an enabling technology for sustainable logistics and green supply-chain management [20]. For the present framework, AI should operate on physically meaningful states and constraints rather than treating the battery or logistics network as an unconstrained black box.

$$\hat{y}(t+\Delta) = g_{\theta[x(t),u(t),d(t)]}$$

$$J_AI = \sum_t \left|\left|y(t) - \hat{y}(t)\right|\right|^2 + \lambda\Omega(\theta)$$

The transform domain adds diagnostic information to the learning objective by measuring whether prediction residuals contain persistent frequency or scale components.

$$J_{total} = J_{AI} + \lambda_s \left|\left|F_{H[r]}\right|\right|^2$$

7.2 digital-twin synchronization

A digital twin provides a continuously updated representation of the physical asset or network. The supplied review of digital twins for resilient global supply chains emphasizes adaptive, data-driven representation as a resilience mechanism [22]. In the proposed architecture, the twin receives telemetry, updates state estimates, evaluates constraints, and supplies validated states to planning and optimization.

$$x_{Twin(t+\Delta t)} = \Phi\left[x_{Twin(t)}, y_{meas(t)}, u(t)\right]$$

7.3 blockchain-supported provenance

AI decisions and digital-twin updates become more useful when the origin and integrity of operational records can be established. The supplied AI–blockchain reference connects artificial intelligence and distributed traceability with transparency and resilience [21]. A simple hash-chain abstraction is

$$h_k = Hash(h_{\{k-1\}}\,|data_k|\,|timestamp_k|\ )$$

The hash-chain does not replace physical validation; it records the lineage of observations, decisions, and state updates so that a later audit can identify whether the data sequence has been altered.

VIII. RESILIENT LOGISTICS NETWORKS AND COMPLEXITY MANAGEMENT

8.1 resilience as constrained adaptation

Supply-chain resilience concerns the ability to withstand disruption while maintaining critical service and recovering toward an acceptable operating state. The supplied resilience review provides the conceptual basis for considering preparedness, response, recovery, and adaptation as connected activities [23]. Resilience is not equivalent to eliminating all disturbances; it is the capacity to preserve essential functions under uncertainty.

$$R_{res} = \int_0^T w(t)S(t)dt \ \ / \int_0^T w(t)S_{nom}(t)dt$$

Here S(t) represents normalized service performance and w(t) weights critical operating periods. The metric can be extended with energy, safety, and recovery constraints.

$$\min J = \alpha C + \beta E + \chi D + \delta T$$

$$subject\ to\ g(x,u,d) \le 0, \qquad h(x,u,d) = 0$$

8.2 internal and external complexity

Modern supply chains contain internal complexity from processes, inventories, facilities, technologies, and decision structures, and external complexity from suppliers, customers, markets, regulations, infrastructure, and disruptions. The supplied complexity study frames resilience as navigation through these interacting layers [24].

Digital transformation changes this complexity by increasing observability while also increasing data volume and dependency on interconnected systems. The systematic review supplied in the references identifies digital transformation as an important context for resilience research and agenda setting [25].

8.3 disruption classification

The hybrid framework distinguishes envelope violation, category error, and optimizer overreach. Envelope violation occurs when a predicted state exceeds a physical limit. Category error occurs when distinct event types are collapsed into a common disturbance class. Optimizer overreach occurs when an abstract optimization solution cannot be supported by the continuous physical state.

IX. QUANTUM LOGISTICS OPTIMIZATION AND QUBO REPRESENTATION

9.1 quantum optimization layer

Quantum computing in transportation and logistics is relevant to combinatorial planning problems involving routing, assignment, scheduling, packing, and configuration. The supplied review emphasizes current industrial opportunities while recognizing practical implementation constraints [19]. Quantum optimization is therefore positioned here as a decision layer above the continuous physical model.

For binary decision variables $x_i \in \{0,1\}$, a generic QUBO objective is

$$\min_{x} Q(x) = x^{T} Q x$$

Constraints can be incorporated through penalty functions. For an equality constraint A x=b, a quadratic penalty is

$$Q_{pen(x)} = \lambda \left||Ax - b|\right|^{2}$$

$$Q_{total(x)} = Q_{cost(x)} + \lambda \left||Ax - b|\right|^{2}$$

9.2 annealing for unit-load-device configuration

The supplied work on quantum annealing for unit-load-device configuration motivates binary formulations for cargo-placement and disruption-aware configuration [27]. A configuration variable may represent whether a cargo item is assigned to a candidate position, subject to capacity and compatibility constraints.

$$x_i, j \in \{0,1\}, \ \sum_{j} x_i, j = 1$$

$$\sum_{i} w_i x_i, j \le W_j$$

Quantum annealing should not be asked to decide a solution that violates the battery or vehicle physics. The continuous feasibility layer must first define allowable routes, energy budgets, charging windows, and payload conditions. The annealer then searches within or near that discrete feasible space.

9.3 integrated quantum–classical logistics

The broader quantum-logistics reference emphasizes practical opportunities for quantum methods in supply-chain management [26]. A hybrid solver can therefore use classical simulation and digital-twin evaluation to generate feasible candidates, quantum annealing to search combinatorial assignments, and classical validation to reject physically unsupported solutions.

X. INTEGRATED HYBRID TRANSFORM ARCHITECTURE

10.1 unified state representation

The preceding layers can be combined into a single architecture. Battery states define the energy envelope; mobility states define vehicle and infrastructure conditions; logistics states define demand and service requirements; transforms expose multi-scale structure; AI estimates uncertain states; digital twins synchronize the representation; blockchain preserves provenance; and quantum optimization addresses selected discrete decisions.

$$X(t) = \left[x_{b(t)}, x_{m(t)}, x_{l(t)}, x_{c(t)}\right]^{T}$$

$$\dot{X}(t) = F[X(t), U(t), D(t), \Theta(t)]$$

The hybrid transform acts on selected components or residuals rather than indiscriminately transforming every state variable. This preserves physical interpretability and avoids using spectral features where direct state constraints are more informative.

10.2 constrained decision formulation

$$\min_{\{u,x\}} J = J_{energy} + J_{service} + J_{risk} + J_{recovery}$$

$subject\ to\ x \in \mathcal{X}, u \in \mathcal{U}, \dot{x} = f(x,u,d), SOC_{min} \le SOC \le SOC_{max}$esilience objective may include energy consumption, service loss, disruption exposure, recovery time, and computational cost. A decision is accepted only if the digital twin can reproduce it within the modeled physical envelope.

10.3 transform-guided anomaly and recovery analysis

Transform coefficients can be monitored over rolling windows. A change in spectral energy can trigger an anomaly detector, while a phase or shift signature can help distinguish delayed events from genuinely new operating modes. This interpretation is consistent with the supplied time-shift and sequential-convergence references [28], [29].

$$A(t) = \left||F_{H[r_t](\omega,\kappa)}|\right|_2$$

$$A(t) > \tau_A \ \Rightarrow \ anomaly\ flag$$

The threshold τ_A should be calibrated from validated baseline data and should not be treated as universal. Physical constraints remain the final safety gate.

XI. VALIDATION, SUSTAINABILITY AND FUTURE RESEARCH

11.1 validation protocol

Validation should proceed from component models to integrated scenarios. Battery parameters should be identified from controlled tests and then evaluated under representative drive cycles. Mobility models should be checked against route and traffic observations. Logistics simulations should reproduce baseline demand and lead-time behavior before disruptions are introduced.

$$RMSE = \sqrt{\left[\left(\frac{1}{N}\right)\sum_{\{k=1\}}^{N}(y_k - \hat{y}_k)^2\right]}$$

$$MAE = \left(\frac{1}{N}\right)\sum_{\{k=1\}}^{N}|y_k - \hat{y}_k|$$

For resilience experiments, scenarios should include demand surges, transport delays, charging outages, communication failures, payload changes, and recovery actions. The complexity literature indicates that resilience must account for interacting internal and external sources rather than isolated failure events [24].

11.2 green and sustainable mobility

Sustainable mobility requires simultaneous attention to energy efficiency, renewable integration, lifecycle impacts, and service performance. AI-enabled green logistics can support forecasting and resource coordination [20], while battery technology developments emphasize management and sustainability across the vehicle lifecycle [15].

$$E_{specific} = \frac{E_{batt}}{D_{trip}}$$

$$CO_2eq = \sum_k E_k EF_k$$

The framework can compare conventional, hybrid, battery-electric, and solar-assisted architectures by normalizing energy and service measures over an equivalent logistics task. The objective is not simply minimum energy, but minimum lifecycle burden subject to service and resilience constraints.

11.3 future directions

Future research should develop rigorous distributional FKF operators for noisy mobility telemetry, establish convergence results for evolving digital-twin states, integrate parameter uncertainty into battery sizing, and formulate physics-aware quantum optimization. The quantum logistics references suggest that practical value will depend on hybrid quantum-classical workflows rather than isolated quantum computation [26], [27].

A further direction is to create benchmark datasets linking battery telemetry, route conditions, logistics events, and recovery histories. Such datasets would allow transform-domain signatures to be compared against AI embeddings and operational outcomes without losing the provenance required for reproducible resilience studies.

The framework compares conventional, hybrid, battery-electric, and solar-assisted architectures by normalizing energy, service, control, and security measures over an equivalent logistics task. The objective is therefore not merely minimum energy, but minimum lifecycle burden subject to service, resilience, and security constraints.

Communication-based protection can strengthen intelligent mobility systems by supporting monitoring and anti-theft functions through existing electrical infrastructure [12]. Likewise, swipe-based control demonstrates the value of controlled access and electronic authorization in smart operational systems [13]. These principles can be incorporated into the architecture assessment as security and control layers, ensuring that an energy-efficient system also maintains authorized operation and operational continuity.

A generalized objective is

$$J = w_E E_{\text{life}} + w_C C_{\text{control}} + w_S C_{\text{security}} + w_M C_{\text{maintenance}} + w_R C_{\text{risk}},$$

subject to

$$\eta \geq \eta_{\min},\ R_{\text{serv}} \geq R_{\min},\ P_{\text{sec}} \geq P_{\min}.$$

Thus, communication-assisted protection [12] and controlled-access mechanisms [13] complement energy and resilience measures in evaluating intelligent mobility architectures.

XII. CONCLUSION

A unified theoretical pathway from battery sizing to smart mobility and resilient logistics, the physical layer describes electrical, thermal, energy, and ageing constraints; the transform layer represents temporal and scale-dependent behavior; the estimation layer separates measured states from uncertainty; and the digital layer connects telemetry, AI, provenance, and optimization.

The central contribution is the positioning of hybrid transform calculus as an analytical bridge rather than as an isolated mathematical device. Time-shift properties, sequential convergence, multi-scale spectral structure, and residue-based extraction can support interpretation of recurring mobility and logistics patterns, while digital twins provide the physical context required for trustworthy decisions.

Battery sizing remains a feasibility problem, mobility remains a constrained cyber-physical problem, and logistics optimization remains a discrete decision problem. Their integration is therefore most robust when continuous dynamics are preserved and discrete optimization is applied only after feasibility has been established. This separation helps prevent envelope violations, event-classification errors, and optimizer overreach.

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