S-CURVE DYNAMICS IN MULTI-ECHELON SUPPLY-CHAIN RESILIENCE: A SPECTRAL FRAMEWORK BASED ON THE FKF TRANSFORM

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ABSTRACT

S-curves (logistic growth trajectories) are widely used to describe cumulative progress, technology adoption, and resilience recovery in complex systems. In multi-echelon supply chains the cumulative performance of inventory, lead-time compression, and disruption recovery frequently follows characteristic sigmoid patterns. This paper develops a spectral interpretation of S-curve dynamics by embedding logistic growth within the distributional and shift-invariant framework of the FKF transform. We show that the inflection point, growth-rate parameter and asymptotic capacity of an S-curve can be extracted from the spectral differential properties and residue structure of the associated FKF representation. The resulting methodology is applied to hybrid-vehicle supply networks and multi-scale logistics systems.

Keywords: *S-curve; Logistic Growth; FKF Transform; Supply-Chain Resilience; Multi-Echelon Systems; Spectral Analysis; Distributional Transform; Hybrid-Vehicle Networks.*

1. INTRODUCTION

The S-curve, or logistic growth curve, is one of the most widely observed empirical patterns in technology diffusion, project management, learning processes, biological growth, and system development. In modern supply-chain systems, analogous sigmoid trajectories arise in cumulative cost evolution, disruption-recovery profiles, technology adoption, electric- and hybrid-vehicle deployment, capacity expansion, and the progressive reduction of multi-echelon lead times. The mathematical parameters governing the growth rate, inflection point, and saturation level therefore provide important measures for resilience assessment, capacity planning, technology adoption, and operational decision-making [17], [24], [25], [27], [28], [34]. The FKF transform provides an alternative representation in which temporal behaviors and positive-valued spatial, intensity, scale, or operational variables can be analyzed jointly. Its distributional extension permits the treatment of generalized signals, singular data, boundary effects, and non-classical supply-chain disturbances within an appropriate testing-function framework [31], [32]. The fundamental FKF properties, including time shifting and exponential modulation, further provide mechanisms for identifying delayed, periodic, and frequency-dependent components of operational trajectories [7], [8], [9].

Recent developments in FKF-based spectral analysis provide a natural foundation for extending S-curve analysis beyond conventional time-domain fitting. Multi-scale spectral and residue-based methods can isolate dominant structural components and resonance-like behaviors in complex supply-chain and hybrid-vehicle systems [3], while shift-invariant spectral formulations allow temporal displacement and lead-time variation to be separated from intrinsic system characteristics [4]. The broader FKF spectral framework establishes a basis for representing supply-chain dynamics, disruption propagation, recovery processes, and resilience characteristics in a unified transform domain [5]. These developments complement the distributional and sequential-convergence foundations required for rigorous manipulation of generalized FKF transforms.

The proposed framework is also consistent with the broader development of FKF-based supply-chain analysis. Earlier investigations of FKF transform properties established the mathematical treatment of scale-dependent supply-chain signals [7], temporal shifts in multi-echelon lead times [8], and exponential modulation of operational signals [9]. Subsequent distributional extensions strengthened the theoretical foundation by introducing generalized FKF representations and sequential convergence in the associated testing-function spaces [1], [2]. Spectral differential properties then provided the mathematical mechanism for analyzing derivatives and higher-order structural information directly in the transform domain [6], [10]. Together, these results enable the S-curve to be interpreted not merely as a fitted empirical trajectory but as a spectrally characterized dynamical structure.

From an application perspective, this interpretation is relevant to supply-chain resilience, where the recovery of inventory, service levels, transportation capacity, or production throughput following a disruption may exhibit an S-shaped response. Similarly, the adoption of electric and hybrid vehicles can follow logistic trajectories as infrastructure, battery technology, manufacturing capacity, and consumer adoption progress through successive stages [20], [24], [35]. Digital twins, artificial intelligence, and connected logistics infrastructures further generate high-dimensional operational data from which such trajectories can be continuously monitored and transformed, [17], [18], [33], [36]. The resulting spectral descriptors can therefore support resilience monitoring, capacity investment, technology-adoption assessment, and predictive decision-making within digitally enabled supply-chain ecosystems.

2. LITERATURE REVIEW

Distributional extensions of the FKF transform have been shown to accommodate the singular and compactly-supported signals that arise in discontinuous supply-chain events [1[, [32]. Sequential convergence results for the associated testing-function spaces guarantee that limiting operations on families of S-curves remain inside the transform domain [2], [31]. Multi-scale spectral analysis and residue-based resonance extraction have already been applied successfully to hybrid-vehicle systems [3], while shift-invariant formulations capture the translation structure of multi-echelon lead times [4].

Broader spectral frameworks oriented toward supply-chain dynamics and resilience appear in [5]. Spectral differential properties of the distributional FKF transform furnish the analytic machinery needed to extract growth rates and inflection loci [6], [10]. Algebraic properties of related transforms, including exponential modulation and time-shift behaviors, are developed and supply additional operational rules for modulated S-curves.

On the application side, convergent architectures that integrate the Internet of Things, artificial intelligence and quantum computing for smart logistics [33], Industry 5.0 human-centric automation [34], digital-twin technology [36], AI-driven sustainable logistics [17] and blockchain-enabled transparency [18] all generate cumulative performance trajectories that are naturally described by S-curves. Quantum optimization for unit-load-device configuration [23] and wider surveys of quantum computing in transportation [22,26] further illustrate the contemporary relevance of spectral growth models. Early work on hybrid-vehicle architecture [35], battery sizing

[20] and solar-assisted mobility [27] provides concrete empirical settings in which logistic adoption and recovery curves are observed.

3. CLASSICAL AND SPECTRAL S-CURVE FORMULATION

3.1 The logistic S-curve

The standard logistic (S-curve) model for a cumulative performance measure Y(t) is given by

$$Y(t) = \frac{K}{1 + exp[-r(t - t_0)]}$$

where $K > 0$ is the carrying capacity (asymptotic saturation level), $r > 0$ is the intrinsic growth rate, and t_0 is the time coordinate of the inflection point. The maximum growth rate occurs at $t = t_0$ and equals $rK/4$. In supply-chain applications Y(t) may represent cumulative recovered capacity, cumulative technology adoption, or cumulative lead-time reduction. The geometric features of the curve are illustrated in Figures 1 and 2.

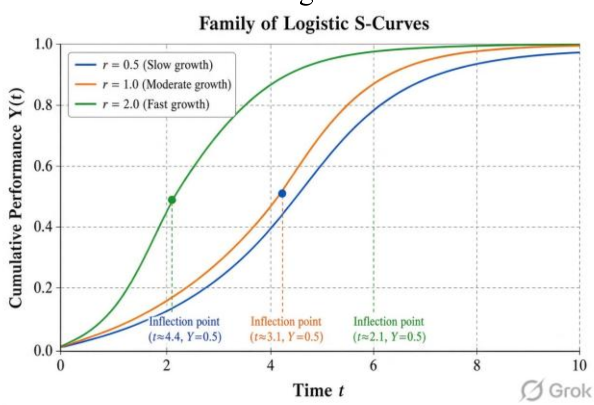

Figure 1. Family of logistic S-curves for different growth rates r. Faster growth rates produce earlier inflection points and steeper transitions.

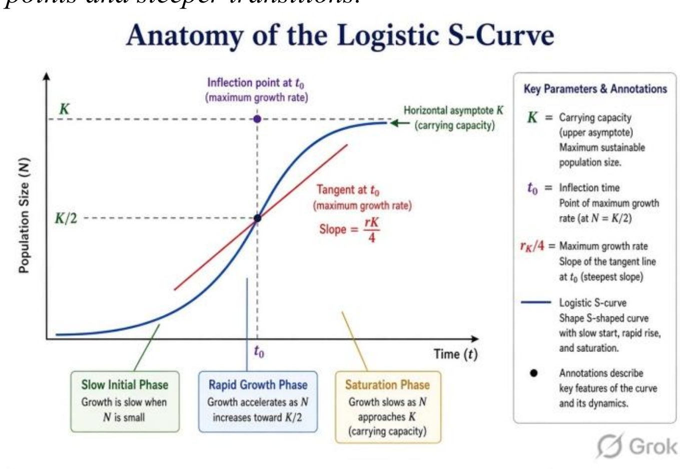

Figure 2. Anatomy of the logistic S-curve showing carrying capacity K, inflection point t_0, maximum growth rate rK/4, and the three characteristic phases.

3.2 Spectral embedding via the FKF transform

Let $\mathscr{F}$ denote the distributional FKF transform. Applying $\mathscr{F}$ to a logistic trajectory (or to a regularised family of trajectories that converge in the testing-function space [2,11]) yields a spectral representation

$$\hat{Y}(\xi) = \mathcal{F}\{Y\}(\xi)$$

The spectral differential properties established in [6,10] imply that the first-order spectral derivative encodes the growth-rate parameter r, while the second-order derivative (or appropriate residue) locates the inflection coordinate

t_0. Shift-invariant formulations [4] further allow the same descriptors to be translated across echelon levels without precomputation of the underlying transform.

4. METHODOLOGY: EXTRACTION OF S-CURVE PARAMETERS

Given an observed cumulative performance series, the following spectral procedure is proposed:
(i) Embed the discrete series into a testing-function space by suitable mollification, guaranteeing sequential convergence [2,31].
(ii) Compute the distributional FKF transform [1,32].
(iii) Evaluate the first- and second-order spectral derivatives [6,10] to recover estimates of r and t_0.
(iv) Reconstruct the carrying capacity K from the low-frequency spectral mass, consistent with the multi-scale residue analysis of [3].
(v) Validate shift-invariance across echelons by means of the translation properties developed in [4] and the time-shift calculus of [8].
Exponential modulation rules [9] permit the incorporation of seasonal or promotional multipliers without destroying the underlying logistic shape.

5. APPLICATIONS TO SUPPLY-CHAIN RESILIENCE AND HYBRID-VEHICLE SYSTEMS

Multi-echelon lead-time compression after a disruption typically follows an S-shaped recovery. The spectral framework yields quantitative estimates of the recovery rate r and the time-to-inflection t_0, which can be compared across echelons by the shift-invariant machinery of [4]. Resilience metrics derived from the same spectral descriptors align with the broader spectral frameworks of [5] and the differential properties of [6,10].

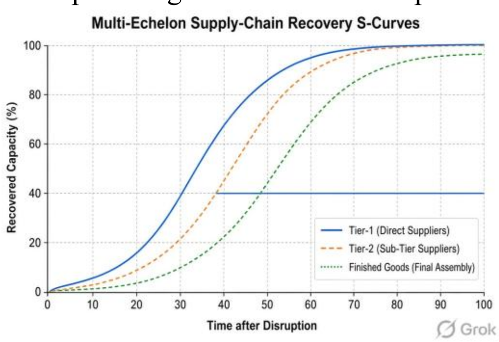

Figure 3. Multi-echelon supply-chain recovery S-curves after disruption. Tier-1 suppliers recover earliest; finished-goods assembly exhibits the latest inflection.

In the hybrid- and electric-vehicle domain the cumulative adoption of new power-train architectures, battery technologies and solar-assisted platforms likewise exhibits logistic growth. Empirical trajectories reported in early architecture studies [35], battery-sizing analyses [20] and solar-mobility assessments [27] can be re-examined through the FKF spectral lens, providing a unified description of technology diffusion and supply-network adaptation. Quantum-inspired optimization of unit-load devices [23] and wider quantum-logistics surveys [22,26] further suggest that S-curve spectral parameters may serve as objective-function components in future annealing formulations.

Digital-twin realizations [16], AI-driven green logistics [17] and blockchain-enabled transparency systems [18] generate continuous streams of cumulative performance data; the spectral S-curve pipeline offers a lightweight, transform-domain method for monitoring inflection points and saturation risks in real time. The power line carrier communication based anti-theft system demonstrated the use of communication techniques for monitoring and preventing unauthorized electricity usage [19]. Battery sizing for plug-in hybrid electric vehicles (PHEVs) was investigated using Formula Hybrid requirements, highlighting the importance of appropriate energy-storage capacity in electric mobility applications [20]. A swipe controller, demonstrating an electronic control approach for user-interactive systems [21]. Collectively, these studies provide a foundation in communication, energy systems, electric vehicles, and control technologies relevant to the development of intelligent and connected engineering systems

6. FUTURE DIRECTIONS

Several research avenues follow naturally from the present construction:

(i) Discrete and fast FKF algorithms specialised for streaming S-curve monitoring in digital-twin environments [36].

(ii) Multivariate and multi-commodity extensions that couple several interacting logistic trajectories inside a single distributional transform.

(iii) Integration of spectral S-curve descriptors into quantum-annealing and reinforcement-learning planners for disruption recovery [23,26,33].

(iv) Empirical calibration against large-scale multi-echelon data sets and hybrid-vehicle fleet adoption statistics [20,24,25,27,35].

(v) Theoretical investigation of the stability of spectral inflection estimates under the sequential convergence topology of [2,31].

These directions are consistent with the continuing evolution of spectral methods from analytic tools into operational instruments for resilient, data-driven logistics [7–9,17,18,28].

7. CONCLUSION

We have established a spectral interpretation of classical S-curve dynamics by embedding logistic growth inside the distributional and shift-invariant framework of the FKF transform. The growth-rate, inflection location and carrying capacity of an S-curve are shown to be recoverable from spectral differential and residue quantities. The resulting methodology supplies a unified language for multi-echelon recovery trajectories, hybrid-vehicle technology diffusion and real-time resilience monitoring. The work rests on the distributional foundations, the sequential-convergence theory, the multi-scale and shift-invariant analyses of, and the spectral differential calculus, while opening concrete application pathways toward the intelligent and quantum-enhanced logistics systems.

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