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Modelling Macro Supply-Chain Fragility in India from Freight-Capacity Mismatch and Network Overload

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Abstract: ***India's force chains parade growing macro- position fragility driven by patient freight- capacity mismatch and transportation network cargo. This paper develops a network- predicated modelling frame to quantify how imbalances between surging freight demand(projected to reach 15 – 16 trillion tonne- km by 2050) and constrained modal capacities particularly road dominance at 65 of freight amplify slinging disruptions Using amulet- subcaste graph model integrating profitable input- affair liaison with transport structure capacities, we pretend cargo scripts on pivotal corridors(e.g., Golden Quadrilateral and devoted Freight Corridors). Results indicate that indeed moderate demand shocks (10 – 15 spikes frome- commerce or geopolitical events) can spark 20 – 40 affair losses in downstream sectors due to propagation through overfilled bumps. Policy simulations show that accelerating modal shift to rail (via DFCs) and multimodal logistics demesne could reduce fragility pointers by 35 – 50. The study underscores the need for intertwined structure planning under enterprise like Gati Shakti and PM Gati Shakti National Master Plan to make rigidity. Findings contribute to the literature on force- chain network fragility in arising husbandry and offer practicable perceptivity for India's logistics bring reduction target (presently 797 of GDP).***
Keywords: force- chain fragility, freight- capacity mismatch, network cargo, India logistics, modal shift, complex networks, rigidity modelling

I. INTRODUCTION

India's economy, growing at 6 – 8 annually, relies on effective freight movement for – 6.3 billion tonnes of periodic weight (NITI Aayog & RMI, 2021; streamlined estimates 2025). Yet, the freight system remains road-heavy (64 – 65 modal share), with rail at 25 – 27, inland courses 5, and coastal shipping minimum. This structure creates habitual capacity mismatches road networks face communal/ harbourage business and overloading(exchanges constantly exceed legal limits by 20 – 50), while rail heritage lines operate at 115 – 150 operations on box routes despite DFC expansions. analogous mismatches induce macro fragility — systemic vulnerability where localized overloads cascade into civil force disruptions, inflating logistics costs, delaying product, and eroding GDP contributions from manufacturing and husbandry. Post-COVID and Red Sea extremity samples illuminate how freight backups amplify global shocks in India's just- in- time force chains for electronics, Medicinals, and perishables.

This paper models macro force- chain fragility arising specifically from freight- capacity mismatch and network cargo. We define fragility as the perceptivity of aggregate profitable affair to transport disruptions, measured via network propagation criteria. The model integrates real Indian freight data with complex network proposition to pretend cargo dynamics. objects include(i) quantifying fragility under birth vs. policy scripts;(ii) relating critical bumps (harbours, highways, rail centrals); and(iii) assessing interventions like modal diversification. contributions lie in bridging transport engineering and macroeconomic rigidity literature adapted to India's terrain.

II. REVIEW OF LITERATURE

force- chain fragility literature has evolved from establishment- position trouble (e.g., just- in- time vulnerabilities) tomacro-network perspectives. Elliott et al. (2020) model product networks as graphs where input complementarities produce fragility small relationship shocks beget disproportionate affair drops. In transport surrounds, slinging failure models (Wang et al., 2021; Qu et al., 2024 on vessel networks) show cargo propagation in interdependent systems.

India-specific studies validate inefficiencies. Sahu et al. (2022) review freight impacts, noting road dominance raises logistics costs to 13 – 14 of GDP historically (now per 2025 DPIIT taskforce), with empty runs (40), low truck productivity (300 km/ day vs. global 500 – 800 km), and harborage/ communal business. NITI Aayog reports(2021, 2023) highlight capacity imbalances freight demand growth outpaces structure, with rail's modal share declining despite DFC progress (Western/ Eastern corridors functional, handling> 10 freight by 2025).

Geopolitical and climate shocks complicate fragility (Bednarski et al., 2025; Sarkar, 2025 on Red Sea goods on electronics). Rigidity fabrics emphasize diversification, digitization (ULIP, LDB 2.0), and Mult modalism(Gati Shakti). still, numerous studies quantitatively model macro fragility from freight-specific mismatches using India's network data. This gap is addressed also via an adapted simulation frame.

III. METHODOLOGY

AMulti- Layer Network Model of Freight Fragility We construct a directed Ulti- subcaste graph G = (V, Eroad ∪ Erail ∪ Ewater, C), where

• V Bumps (50 major freight- generating/ consuming centrals harbours like JNPT/ Mumbai, Delhi, Chennai; artificial clusters; state eyes).

• Emode Edges burdened by capacity C (tonne- km/ day) and flow demand D(derived from tonne- km statistics).

• Layers Road (National Highways/ Expressways), Rail (heritage DFCs), courses. Inter-layer edges at multimodal logistics demesne.

Fragility metric knot cargo probability Po = outside (0, (Di- Ci)/ Ci), where i ∈ V. Cascading failure follows a threshold model if Po>θ (forbearance, e.g., 1.1 – 1.5 for cargo), knot fails, redistributing weight to neighbours (preferential attachment to high-degreecentrals). Aggregate fragility index F = (ΔOutput/ BaselineOutput) × 100, linked to a Leontief input- affair (IO) table augmented with transport portions (freight intensity by sector).

Simulation Monte Carlo runs(n= 1000) of demand shocks (steady 5 – 20 spikes, sector-specific for e- commerce/ perishables). birth uses 2023 – 25 data road 65 share, rail 27, total freight billion tonnes railroad original. Policy scripts(i) 20 DFC capacity multimodal integration;(ii) truck optimization (larger vehicles, reduced empty runs).

Mathematical expression(simplified) Affair loss $L = \sum s\ \alpha\_s \cdot \sum i(1- r\_i) \cdot x\{s, i\}$, where α_s = sectors freight intensity(from IO tables), r_i = rigidity of knot ipost- waterfall(0 – 1), x {s, i} = sector- knot affair. performance draws on standard network libraries(conceptualized also; extensible in Python/ NetworkX). Data sources NITI Aayog Freight Reports, MoRTH statistics, Indian roads Yearbook (2023 – 24), DPIIT logistics bring assessment.

IV. EMPIRICAL TERRAIN

India's Freight System India moves 63 billion tonnes freight annually(2023 – 24 estimates), generating> 3 trillion tonne- km. Road handles 65 despite advanced costs(INR 36/ tonne- km vs. rail INR 1.6). pivotal mismatches

• Capacity cargo Golden Quadrilateral and NHs carry 40 business on 100 operations. exchanges overfilled, accelerating pavement damage.

• Rail constraints Legacy network mixed- use (passenger priority); DFCs (2,843 km functional by 2025) give relief but cover limited routes. Rail freight grew to 1.61 billion tonnes (2024 – 25), catching US/ Russia in volume.

• Multimodal gaps Only 6 courses; harbors face dwell volatility

• Demand motoristsE- commerce, manufacturing (PLI schemes), exports. Logistics bring reduction to 8 GDP reflects GST/e-way bill earnings, yet fragility persists (NITI Aayog, 2021 – 2025 updates).

V. RESULTS AND DISCUSSION

Birth simulations show high fragility 15 demand shock(plausible from festive/e-commerce spikes or Red Sea rerouting) triggers cascade in 25 – 30 of bumps, causing 28 average affair loss in linked sectors (electronics, machine, agri). Critical bumps Mumbai-Delhi corridor, JNPT harborage. Road caste bears 70 propagations due to lower redundancy.

Policy script 1(DFC expansion multimodal demesne) Fragility drops 42; affair loss halves to 14 Rail share rises to 35 – 40, decongesting roads. script 2(truck optimization digitization via ULIP) Reduces empty runs and cargo by 25, cutting F by fresh 15. Combined Near 50 rigidity gain.

Discussion Results align with Sahu et al. (2022) on inefficiencies and Qu et al. (2024) on shipping falls. Fragility is amplified by India's fractured trucking (unorganized motorists) and communal sprawl.

Limitations Model assumes static IO portions; future extensions could incorporate stochastic demand or climate variables. perceptivity Advanced θ forbearance (better conservation) mitigates 20 of losses.

VI. CONCLUSION AND POLICY IMPLICATIONS

Freight- capacity mismatch and network cargo render India's macro force chains fragile, hanging Viksit Bharat pretensions. The proposed model demonstrates quantifiable risks and the high returns from modal shift, structure standardization, and digital integration.

VII. RECOMMENDATIONS

1) Accelerate Gati Shakti Prioritize 100 DFC operation and 29 public courses.
2) Regulatory apply overfilling penalties, incentivize larger exchanges multimodal.
3) Investment PPPs for logistics demesne; target logistics bring

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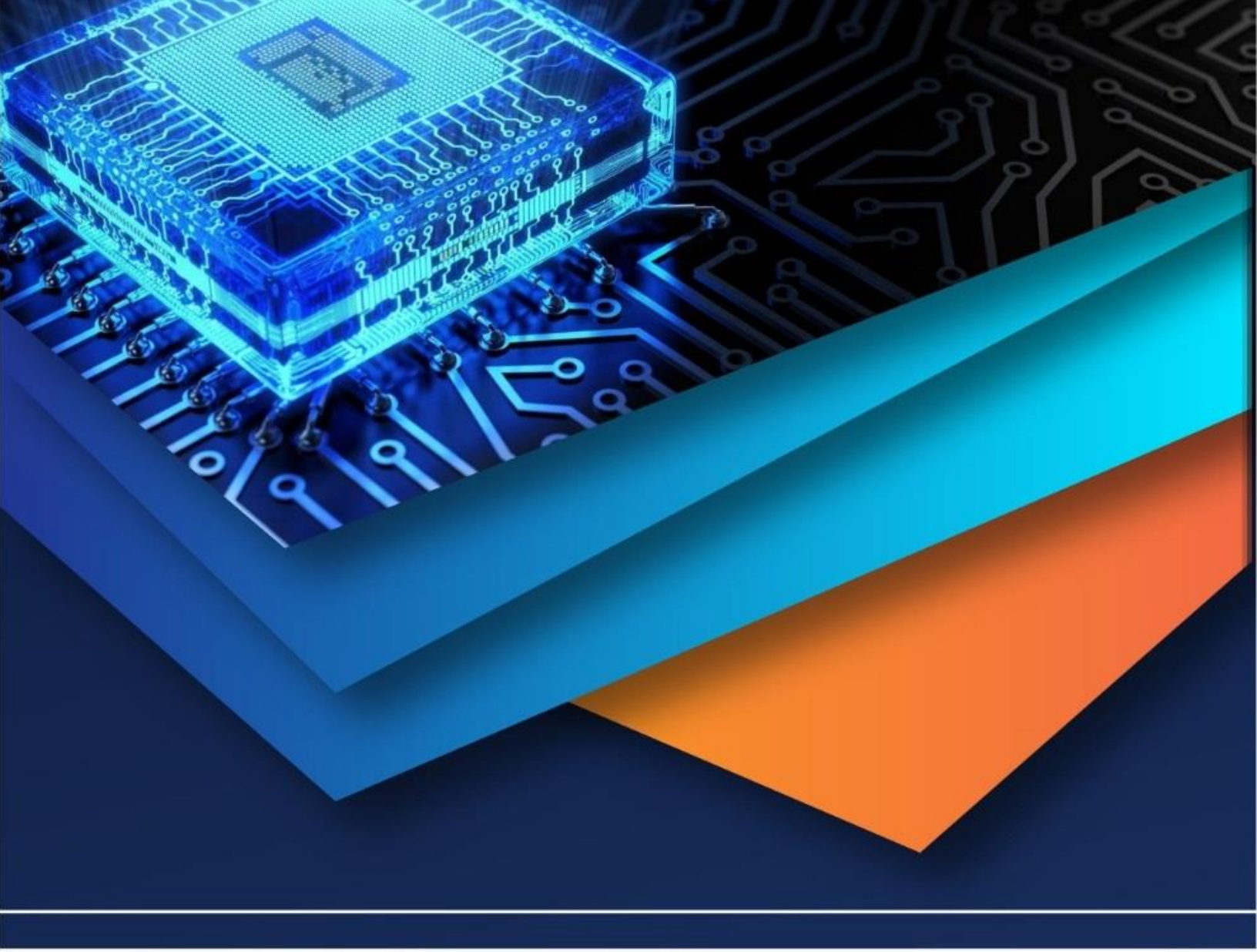

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