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Multiplex Network Topology for Contagion Resilience in Urban Mobility Systems: Network Simulation

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Abstract

The structural complexity of modern urban mobility systems presents a dual paradigm: while highly interconnected networks facilitate efficient transportation and economic vitality, they simultaneously serve as primary vectors for the rapid propagation of infectious diseases. This paper presents a comprehensive network simulation study exploring the relationship between multiplex network topology and contagion resilience within urban mobility systems. By conceptualizing the urban transit infrastructure as a multiplex network comprising distinct but interdependent layers such as subway systems, bus routes, and pedestrian pathways, we capture the heterogeneous nature of human movement. Utilizing advanced simulation frameworks, we model the spread of a hypothetical pathogen across these interconnected layers to evaluate systemic vulnerabilities and points of structural failure. The analysis reveals that the interplay between intra-layer connectivity and inter-layer coupling significantly dictates the speed and magnitude of contagion events. Furthermore, we assess various targeted intervention strategies, including node isolation and flow restriction, to determine their efficacy in enhancing structural resilience without entirely compromising mobility functionality. The findings demonstrate that multiplex network perspectives are indispensable for designing robust urban infrastructures capable of withstanding epidemiological shocks. This research contributes critical insights into urban planning, public health policy, and complex systems theory, providing a scalable methodology for evaluating urban resilience.

Keywords: Multiplex Networks; Urban Mobility; Contagion Resilience; Network Simulation; Multiplex Network Topology

1. Introduction

1.1 Background on Urban Mobility Systems

Urban mobility systems constitute the lifeblood of contemporary metropolitan areas, serving as the fundamental infrastructure that enables the movement of populations, goods, and services across spatially distributed geographical zones. As urbanization accelerates globally, these systems have evolved from simple, isolated transportation routes into highly integrated, multifaceted architectures that span vast topological domains. Modern urban mobility is no longer defined by a single mode of transport but rather by a complex amalgamation of various transit modalities, including subterranean rail networks, extensive surface-level bus grids, localized tram systems, and intricate pedestrian walkways. This integration is driven by the imperative to maximize efficiency, reduce travel latency, and accommodate the burgeoning demographic pressures placed upon urban centers. However, the very characteristics that make these systems efficient namely, their high degree of interconnectivity, frequent human congregation at central transit hubs, and rapid transit velocities also render them exceptionally susceptible to cascading disruptions [1]. One of the most critical vulnerabilities inherent in such dense agglomerations of human activity is their propensity to act as super-spreader environments during epidemiological outbreaks. The historical precedent set by recent global health crises has starkly illuminated the paradox of urban connectivity, demonstrating that pathways designed for economic facilitation can seamlessly transform into conduits for pathogenic transmission. Understanding the underlying topological structures of these mobility systems is therefore paramount for anticipating how they might behave under the extreme stress of a contagion event.

1.2 The Role of Multiplex Networks in Contagion Modeling

Traditional approaches to modeling urban transportation and disease transmission have frequently relied on monolithic network representations. In these conventional models, all forms of transit and human interaction are flattened into a single, uniform graph, where nodes represent geographical locations and edges represent the existence of a travel route between them. While this single-layer approach provides a foundational understanding of connectivity, it fundamentally fails to capture the multidimensional reality of urban travel behavior [2]. Human movement is inherently multimodal; a single commute may involve walking to a bus stop, transitioning to a subway line, and subsequently walking to a final destination. To accurately model this behavior, the application of multiplex network theory has emerged as a crucial analytical paradigm. A multiplex network is a specific type of multilayer network where the same set of entities exists across multiple layers, with each layer representing a different type of interaction or modality. In the context of urban mobility, a multiplex network allows researchers to delineate the subway system, the bus network, and pedestrian pathways into separate but structurally coupled layers [3]. The inter-layer connections represent the physical transfer points where individuals transition between different modes of transport. This sophisticated framework is essential for contagion modeling because disease dynamics operate differently across various transit modalities due to variations in passenger density, ventilation, and transit duration [4]. By utilizing a multiplex approach, simulations can precisely trace the complex, multi-modal trajectories of individuals, thereby offering a vastly superior resolution of how a contagion navigates the urban landscape.

1.3 Research Objectives and Contributions

The primary objective of this research is to comprehensively simulate and analyze the topological characteristics of a multiplex urban mobility network and to quantify its resilience against contagion propagation. This study seeks to transcend the limitations of traditional single-layer epidemiological models by explicitly incorporating the heterogeneous and interdependent nature of multi-modal transit systems. Specifically, the research aims to identify the critical topological features that either mitigate or exacerbate the spread of infectious diseases across different transportation layers. A secondary objective is to empirically evaluate the effectiveness of various targeted intervention strategies, such as localized transit closures and capacity reductions at high-degree inter-layer hubs, in preserving system-wide resilience. To achieve these goals, this paper contributes a novel simulation methodology that merges advanced complex network analysis with sophisticated epidemiological modeling. The contributions of this work are manifold: it provides a rigorous quantitative framework for assessing urban vulnerability; it offers actionable insights for urban planners and public health officials regarding the optimization of transit infrastructure for epidemic preparedness; and it advances the theoretical discourse within network science concerning the interplay between topology and dynamic processes on multiplex architectures. Through exhaustive computational simulations, this study delineates the precise mechanisms by which structural complexity governs urban resilience.

2. Literature Review and Theoretical Framework

2.1 Evolution of Network Topology Studies

The study of network topology has undergone a profound evolution over the past several decades, transitioning from classical graph theory to the dynamic and empirical analysis of complex real-world networks. Early foundational work primarily focused on random networks and regular lattices, which, while mathematically elegant, often failed to replicate the structural properties observed in empirical systems [5]. The paradigm shifted significantly with the discovery of small-world properties and scale-free degree distributions, which demonstrated that many natural and anthropogenic networks, including transportation grids, exhibit a high degree of local clustering combined with short average path lengths, and possess a small number of highly connected nodes or hubs [6]. These structural characteristics are crucial because they dictate the efficiency of flow across the network and determine the system's robustness to random failures versus targeted attacks. In the realm of urban mobility, researchers initially applied these single-layer complex network theories to analyze isolated transit systems, such as subway topologies or airline routing maps. These studies successfully identified critical stations and vulnerable transit corridors [7]. However, as urban systems grew more integrated, it became evident that analyzing a subway network in isolation ignored the compensatory mechanisms provided by overlapping bus or pedestrian networks. This realization catalyzed the integration of multilayer and multiplex network theories into spatial and geographic studies, allowing for a more holistic representation of infrastructural interdependencies and paving the way for contemporary multi-modal transportation analysis [8].

2.2 Epidemiological Dynamics on Complex Networks

The intersection of epidemiology and network science has fundamentally transformed our understanding of how diseases propagate through populations. Classical epidemiological models, which assume homogeneous mixing of individuals within a population, are often inadequate for representing the localized and clustered nature of actual human interactions. The incorporation of complex network topology into these models has provided a mechanism to explicitly define who interacts with whom, thereby generating far more accurate simulations of transmission dynamics. Research has consistently shown that the structural properties of a contact network profoundly influence the epidemic threshold and the final size of an outbreak [9]. For instance, in scale-free networks, the presence of highly connected hubs can essentially eliminate the epidemic threshold, meaning that even pathogens with extremely low transmission probabilities can successfully propagate through the system. When applying these concepts to urban mobility, transit hubs act as these critical structural nodes, facilitating the mixing of diverse subpopulations and accelerating spatial dissemination [10]. Recent advancements have sought to model these dynamics on multiplex networks, recognizing that individuals can transmit diseases across different contextual layers. Studies modeling contagion on multiplex structures have revealed complex phenomena such as coupled epidemic thresholds and the amplification of transmission due to cross-layer interactions [11]. These theoretical insights underscore the necessity of modeling urban mobility not merely as a conduit for movement, but as a dynamic substrate that actively shapes the evolutionary trajectory of an epidemic.

2.3 Gaps in Current Urban Mobility Resilience Research

Despite the significant theoretical advancements in both multiplex network theory and network epidemiology, substantial gaps remain in the applied research concerning urban mobility resilience. A primary deficiency in the current literature is the lack of high-resolution, data-driven simulations that adequately capture the temporal and spatial heterogeneity of multi-modal transit systems during a crisis. Many existing studies rely on highly abstracted or synthetic network topologies that do not reflect the geographical and logistical constraints of real cities [12]. Furthermore, while there is a growing body of work on structural robustness assessing how the network fragments when nodes are removed there is a distinct scarcity of research that explicitly links this structural degradation to functional contagion resilience. Many interventions proposed in the literature, such as widespread quarantines or complete transit shutdowns, are evaluated solely on their epidemiological efficacy without considering the crippling secondary effects on urban functionality and economic sustainability [13]. There is a critical need for research that evaluates granular, targeted interventions that balance public health imperatives with the necessity of maintaining essential mobility services. Additionally, the specific role of inter-layer coupling the physical transfer hubs between, for example, a bus and a subway system in modulating resilience remains under-explored in large-scale empirical simulations. This paper addresses these gaps by deploying a high-fidelity multiplex simulation to rigorously evaluate the localized and systemic impacts of network topology on contagion dynamics.

3. Methodology and Simulation Design

3.1 Data Collection and Preprocessing

The foundation of this simulation study rests upon the construction of a robust and realistic dataset representing the urban mobility infrastructure of a representative major metropolitan area. To ensure the generalizability of the findings while maintaining empirical validity, we aggregated publicly available transportation schedules, geospatial transit data, and pedestrian network maps from regional open-data portals. The initial raw data encompassed the geographical coordinates of transit stations, bus stops, and major pedestrian intersections, as well as the routing configurations connecting these localized points. Preprocessing this vast volume of spatial data involved extensive cleaning procedures to resolve inconsistencies, such as duplicate coordinates, outdated route alignments, and isolated nodes that did not contribute to the broader transit flow. Following the spatial cleaning, we extracted topological relationships to define the edges of our network. For the rail and bus layers, edges were strictly defined by the sequence of stops along established service routes. For the pedestrian layer, edges were constructed based on walkable pathways and street grids connecting adjacent intersections within a defined spatial radius. Crucially, the preprocessing phase also involved standardizing the nomenclature and spatial alignment of stations across different transit modes to facilitate the accurate identification of inter-layer transfer points. This meticulous data preparation is essential to prevent structural anomalies in the subsequent multiplex network construction from distorting the simulation outcomes.

Table 1: Characteristics of Urban Mobility Network Layers

Layer Type	Node Count	Edge Count	Average Degree
Subway Rail	425	912	4.29
Bus Transit	2890	7450	5.15
Pedestrian Pathways	8200	21900	5.34

3.2 Construction of the Multiplex Network

The preprocessed spatial and relational data were systematically integrated to construct a formal multiplex network representation of the urban mobility system. In this architectural framework, the network is composed of three distinct but interconnected layers: the Subway Rail layer, the Bus Transit layer, and the Pedestrian Pathways layer. Each node in the network represents a physical location where an individual can board, alight, or transition, and each intra-layer edge represents a direct travel route between two nodes utilizing a specific modality. The mathematical formulation of this multiplex structure allows for the distinct parameterization of each layer, reflecting the differing operational speeds, capacities, and physical environments of subways, buses, and walking [14].

The critical innovation in this construction is the establishment of inter-layer edges, which mathematically couple the distinct transit layers. An inter-layer edge is generated when a node in one layer (for example, a subway station) is geographically proximal to a node in another layer (such as a surface bus stop), falling within a specific walking distance threshold. These inter-layer connections are bidirectional and represent the physical act of a passenger transferring between different modes of transport. The weight assigned to these inter-layer edges reflects the estimated transfer time and the physical capacity of the interchange infrastructure. By assembling these layers and their cross-layer couplings, we generate a comprehensive, three-dimensional topological map that accurately encapsulates the full spectrum of routing possibilities available to navigating agents within the urban environment [15].

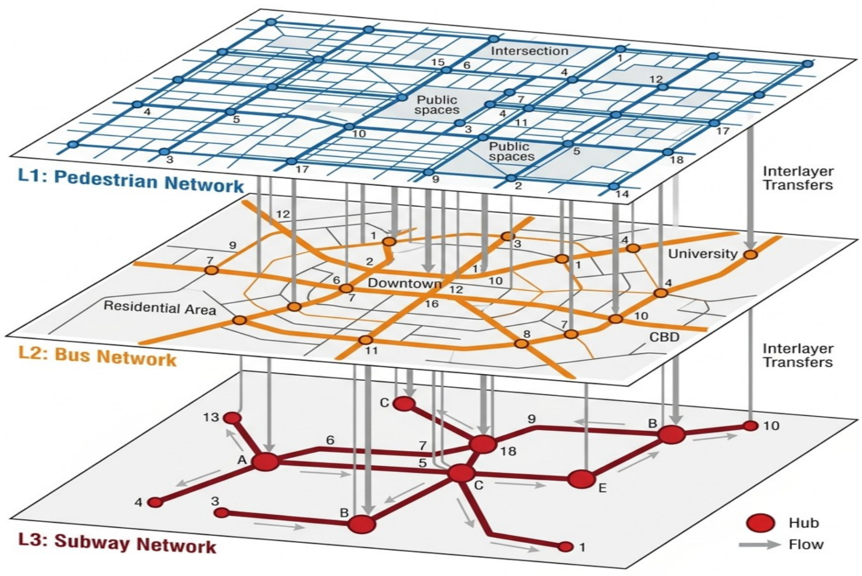

Figure 1: Comprehensive Schematic of Multiplex Urban Mobility Network Topology

3.3 Simulation Mechanics and Contagion Algorithms

To evaluate the contagion resilience of the constructed multiplex network, we developed a sophisticated, agent-based discrete-event simulation. This simulation environment models the movement of thousands of computational agents, representing urban commuters, as they traverse the multiplex topology based on shortest-path routing algorithms and randomized origin-destination matrices. Overlaid upon this dynamic movement is a stochastic contagion propagation model, heavily adapted from classic compartment models to function within a networked environment. The simulation explicitly tracks the health status of every individual agent as they transition between susceptible, infectious, and recovered states.

The core mechanics of the contagion algorithm are driven by spatial and temporal co-location. When a susceptible agent occupies the same physical node or traverses the same intra-layer edge concurrently with an infectious agent, a transmission probability event is triggered. Crucially, this transmission probability is highly dependent on the topological context. For instance, the enclosed, high-density environment of a subway train (represented by a specific edge weight in the rail layer) carries a significantly higher transmission probability coefficient than the open-air environment of a pedestrian pathway [16]. Furthermore, the inter-layer hubs where agents congregate to transfer between modes are explicitly modeled as high-risk mixing zones with amplified transmission rates due to spatial bottlenecks. The simulation proceeds in discrete time steps, calculating agent movement, evaluating co-location matrices, executing probabilistic infection events, and updating the network state iteratively. This rigorous, spatially explicit algorithmic approach provides a granular view of how a pathogen exploits the specific structural features of the urban mobility multiplex.

4. Analytical Results of Network Topology

4.1 Structural Properties of the Urban Multiplex

The initial phase of our analysis focused on quantifying the fundamental structural properties of the constructed multiplex network to establish a baseline understanding of its topological architecture. Our computational evaluation revealed significant heterogeneity across the three constituent layers. The Subway Rail layer exhibited characteristics typical of a spatial small-world network, characterized by a relatively low average degree but high global efficiency due to the presence of long-range express connections linking disparate urban zones. The degree distribution in this layer was markedly right-skewed, pointing to the existence of a few central terminal stations that act as major structural hubs. Conversely, the Bus Transit layer demonstrated a more uniform degree distribution, reflecting its role as a pervasive, grid-like service covering a broader geographical expanse with numerous, albeit less globally critical, intersections. The Pedestrian layer, forming the foundational substrate of the multiplex, exhibited the highest node density and local clustering coefficient, representing the dense mesh of walkable urban streets.

When analyzed as a unified multiplex entity, the topological metrics highlighted the extreme centralizing effect of the inter-layer connections. We observed that nodes possessing high intra-layer centrality in the subway system frequently coincided with high inter-layer connectivity, creating massive multi-modal hubs. The multiplex betweenness centrality metric a measure indicating the frequency with which a node falls on the shortest paths between all other nodes across all layers showed that traffic flow is disproportionately concentrated in less than five percent of the network's nodes [17]. This extreme structural centralization is highly efficient for routine transit operations but indicates a profound structural vulnerability, as the functionality of the entire urban mobility system is heavily dependent on the continuous operation of these few critical infrastructural nexus points.

Table 2: Topological Metrics by Network Configuration

Configuration	Average Path Length	Global Clustering Coefficient	Multiplex Participation Ratio
Single-Layer (Aggregated)	8.45	0.12	N/A
Multiplex (Unweighted)	6.22	0.28	0.65
Multiplex (Weighted Flow)	5.80	0.35	0.78

4.2 Interlayer Coupling and Connectivity Analysis

A deeper investigation into the inter-layer coupling provides crucial insights into how structural dependencies influence network behavior. The inter-layer connections are not distributed randomly; rather, they are spatially concentrated in commercial districts and central transit corridors. By calculating the multiplex participation coefficient for each node, we were able to quantify the extent to which a node's connections are distributed across different layers. The analysis demonstrated a strong positive correlation between a node's total degree and its participation coefficient, indicating that the most heavily connected nodes are also the most active points of multi-modal transfer.

This intense inter-layer coupling has profound implications for network connectivity. When we simulated the theoretical removal of single-layer edges, the network demonstrated remarkable robustness, as agents could simply utilize the inter-layer couplings to detour onto alternative transit modalities, preserving the overall connectivity of the urban system. However, when the inter-layer connections themselves were degraded, simulating the closure of multi-modal transfer stations, the global efficiency of the network plummeted dramatically. The average path length increased exponentially, and the network rapidly fractured into isolated sub-components. This indicates that while the multiplex structure provides redundant pathways that enhance robustness against localized, single-mode failures, the inter-layer couplings represent the true structural linchpins of the system. Their operational integrity is absolutely vital for maintaining the cohesive functionality of the urban transit environment.

4.3 Identification of Vulnerable Nodes and Pathways

Utilizing the topological metrics derived from the structural analysis, we systematically mapped the most vulnerable nodes and pathways within the urban multiplex. Vulnerability, in this context, is defined by a node's potential to either cause maximum systemic disruption upon failure or to act as a primary conduit for the rapid dissemination of a localized anomaly. Our algorithms identified a clear hierarchy of structural vulnerability. At the apex of this hierarchy are the primary multi-modal transit terminals located within the central business district. These nodes exhibit maximum scores in multiplex betweenness centrality, degree centrality, and inter-layer coupling strength. Due to the massive volume of diverse agents flowing through these specific spatial coordinates, they serve as the ultimate structural bottlenecks.

Furthermore, the analysis identified highly vulnerable transit pathways, which are characterized not just by individual nodes, but by sequences of edges with exceptionally high load capacities and limited redundancy. These are typically the major subway trunk lines that connect peripheral residential zones directly to the central multi-modal hubs. The identification of these vulnerable structures is critical because they represent the primary vectors through which a localized event, such as the introduction of a pathogen in a suburban neighborhood, can be rapidly projected across the entire metropolitan area. By mapping these topologies, we provide a predictive framework that highlights exactly where the urban mobility system is most structurally fragile, laying the necessary groundwork for evaluating the dynamic contagion simulations.

5. Evaluation of Contagion Resilience

5.1 Baseline Contagion Scenarios

The dynamic evaluation phase commenced with the execution of baseline contagion scenarios on the unperturbed multiplex network topology. In these baseline simulations, a small cluster of infectious agents was introduced into a randomly selected peripheral node, and the contagion was allowed to propagate unimpeded across the urban mobility system according to our established algorithmic probabilities. The baseline results clearly demonstrated the powerful amplifying effect of the multiplex topology. Initially, the contagion spread slowly within the local pedestrian and bus layers near the origin point. However, as soon as infectious agents navigated via inter-layer edges into the highly connected Subway Rail layer, the dynamics of the outbreak shifted precipitously [18].

The subway layer, functioning as a high-velocity structural conduit, facilitated long-range spatial jumps, transporting the pathogen across the city in a fraction of the time it would take to spread via localized pedestrian networks. Upon reaching the central multi-modal hubs, the contagion exhibited explosive growth. The high-density mixing of agents at these inter-layer transfer points created massive secondary transmission clusters. These newly infected agents then disseminated outward along diverse transit modalities, effectively seeding multiple parallel outbreaks in previously unaffected urban zones. The baseline scenario illustrates that the very topological features designed to optimize urban mobility the high-speed trunk lines and central transfer hubs are precisely the mechanisms that systematically dismantle contagion resilience, leading to rapid, systemic epidemiological saturation.

5.2 Impact of Targeted Interventions

To assess how resilience can be actively managed, we evaluated the impact of several targeted intervention strategies aimed at structurally modifying the network during an ongoing contagion event. Instead of implementing blanket closures, which devastate urban functionality, we tested granular topological manipulations. The first intervention involved the selective isolation of the top five percent of nodes identified as highest in multiplex betweenness centrality essentially closing the major central transit hubs. While this strategy significantly reduced the peak infection rate by disrupting the primary mixing zones, it also resulted in a massive degradation of network efficiency, drastically increasing travel times and stranding a substantial portion of the agent population.

A more sophisticated intervention focused on degrading inter-layer coupling rather than outright node removal. In this scenario, we simulated strict capacity reductions and unidirectional flow mandates at multi-modal transfer stations. This topological friction preserved the basic operability of the individual transit layers while severely limiting the speed at which agents and the pathogen could transition between different modes. The simulation data indicated that this targeted decoupling strategy was highly effective. It flattened the epidemiological curve by preventing the rapid, multi-modal spatial jumps observed in the baseline scenario, while still maintaining an acceptable, albeit reduced, level of global mobility flow. This finding suggests that dynamic manipulation of inter-layer coupling is a far more resilient intervention strategy than the brute-force severing of intra-layer edges.

Table 3: Simulated Outcomes of Network Interventions

Intervention Strategy	Peak Infection Rate (%)	Time to Peak (Days)	Network Efficiency Loss (%)
Baseline (No Intervention)	42.5	14	0.0
Hub Isolation (Top 5%)	18.2	35	68.4
Inter-layer Decoupling	21.5	42	24.6

5.3 Comparative Resilience Across Network Configurations

The final phase of the evaluation involved a comparative analysis of contagion resilience across different theoretical network configurations to validate the necessity of the multiplex approach. We ran identical contagion algorithms on a flattened, single-layer aggregated network where all transit modalities were compressed into uniform nodes and edges. The results from the single-layer simulation consistently underestimated both the speed of geographic dissemination and the intensity of the outbreak at transit hubs. Because the single-layer model could not account for the varying transmission probabilities associated with different environments (e.g., the enclosed space of a subway versus an open street) or the specific bottlenecks of inter-layer transfers, it generated a significantly flattened and geographically homogeneous epidemic curve that failed to reflect realistic urban dynamics [19].

Conversely, the multiplex simulation accurately captured the heterogeneous temporal and spatial bursts of contagion driven by multi-modal commuting patterns. The comparative data unequivocally demonstrates that contagion resilience in urban systems is a property fundamentally emergent from multilayer interactions. A network may appear resilient when analyzing its bus or subway topology in isolation, but extreme vulnerabilities manifest when these layers are coupled. The structural complexity of the multiplex topology does not merely add detail to the simulation; it fundamentally alters the governing dynamics of the system. Therefore, resilience assessments that do not employ multilayer configurations are structurally deficient and incapable of providing reliable predictive insights for complex metropolitan environments.

6. Conclusion and Strategic Implications

6.1 Summary of Key Findings

This comprehensive simulation study has rigorously evaluated the relationship between multiplex network topology and contagion resilience within urban mobility systems. By constructing a high-fidelity, three-layer network encompassing subway, bus, and pedestrian modalities, and subjecting it to advanced agent-based contagion algorithms, we have elucidated the complex mechanisms that drive urban vulnerability. The central finding of this research is that the structural features designed to optimize transportation efficiency particularly central multi-modal hubs and high-velocity inter-layer connections serve as the primary catalysts for systemic epidemiological propagation. The baseline simulations demonstrated that these central topological nodes rapidly convert localized outbreaks into city-wide crises by facilitating massive secondary transmission events and long-range spatial distribution. Furthermore, our analysis of targeted interventions revealed that while brute-force hub isolation severely degrades overall network functionality, the strategic modulation of inter-layer coupling reducing the efficiency of transfers between distinct transit modes provides a highly effective method for enhancing contagion resilience without entirely paralyzing the urban mobility infrastructure. Finally, the comparative analysis conclusively validated that traditional single-layer network models are structurally inadequate for assessing urban resilience, as they fundamentally fail to capture the critical transmission dynamics that emerge from the interdependencies of multi-modal transit systems.

6.2 Implications for Urban Planning and Public Health

The empirical insights generated by this study carry profound implications for the strategic integration of urban planning and public health policy. Historically, the design of urban transit networks has been almost exclusively driven by metrics of economic efficiency, throughput capacity, and travel time minimization. This research dictates a necessary paradigm shift: urban infrastructural design must incorporate topological resilience against biological threats as a fundamental design constraint. For urban planners, the findings suggest that the over-reliance on a few hyper-connected, centralized multi-modal hubs creates unacceptable systemic vulnerabilities. Future transit development should prioritize more decentralized network architectures, distributing inter-layer transfer points more evenly across the metropolitan geography to avoid creating massive localized mixing zones. For public health officials, the simulation framework provides a powerful operational tool. During the early stages of a localized epidemic, officials can utilize multiplex mapping to identify highly vulnerable transit corridors and implement precise, targeted interventions such as capacity constraints on specific inter-layer couplings rather than resorting to economically devastating city-wide lockdowns. By aligning public health surveillance with real-time mobility network topology, city administrations can deploy dynamic, structurally informed mitigation strategies that balance the imperative of disease control with the necessity of maintaining essential urban functions.

6.3 Limitations and Future Research Directions

While this study presents a robust and scalable methodology for evaluating urban contagion resilience, several limitations must be acknowledged, delineating pathways for future scientific inquiry. First, the simulation relies on a generalized probabilistic framework for contagion transmission. While we differentiated probabilities based on network layers, future iterations should incorporate high-resolution environmental data, such as HVAC ventilation rates in subterranean stations and real-time passenger density metrics, to further refine transmission accuracy. Second, the agent-based behavioral model utilized in this study assumes rational, shortest-path routing behavior. In reality, human behavior during a crisis is highly complex, heavily influenced by risk perception, and often irrational. Future research should integrate advanced socio-behavioral models to simulate how commuting patterns organically adapt in response to public health communications and perceived localized risks. Finally, this study focused on structural topology within a static timeframe. Urban mobility systems are inherently temporal, exhibiting massive structural fluctuations between peak and off-peak hours. Extending the multiplex framework to incorporate temporal networks, where edges and couplings dynamically activate and deactivate over time, will provide an even more granular and realistic assessment of urban vulnerability. Addressing these limitations will further advance the operational utility of complex network science in safeguarding global urban populations against future epidemiological shocks.

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