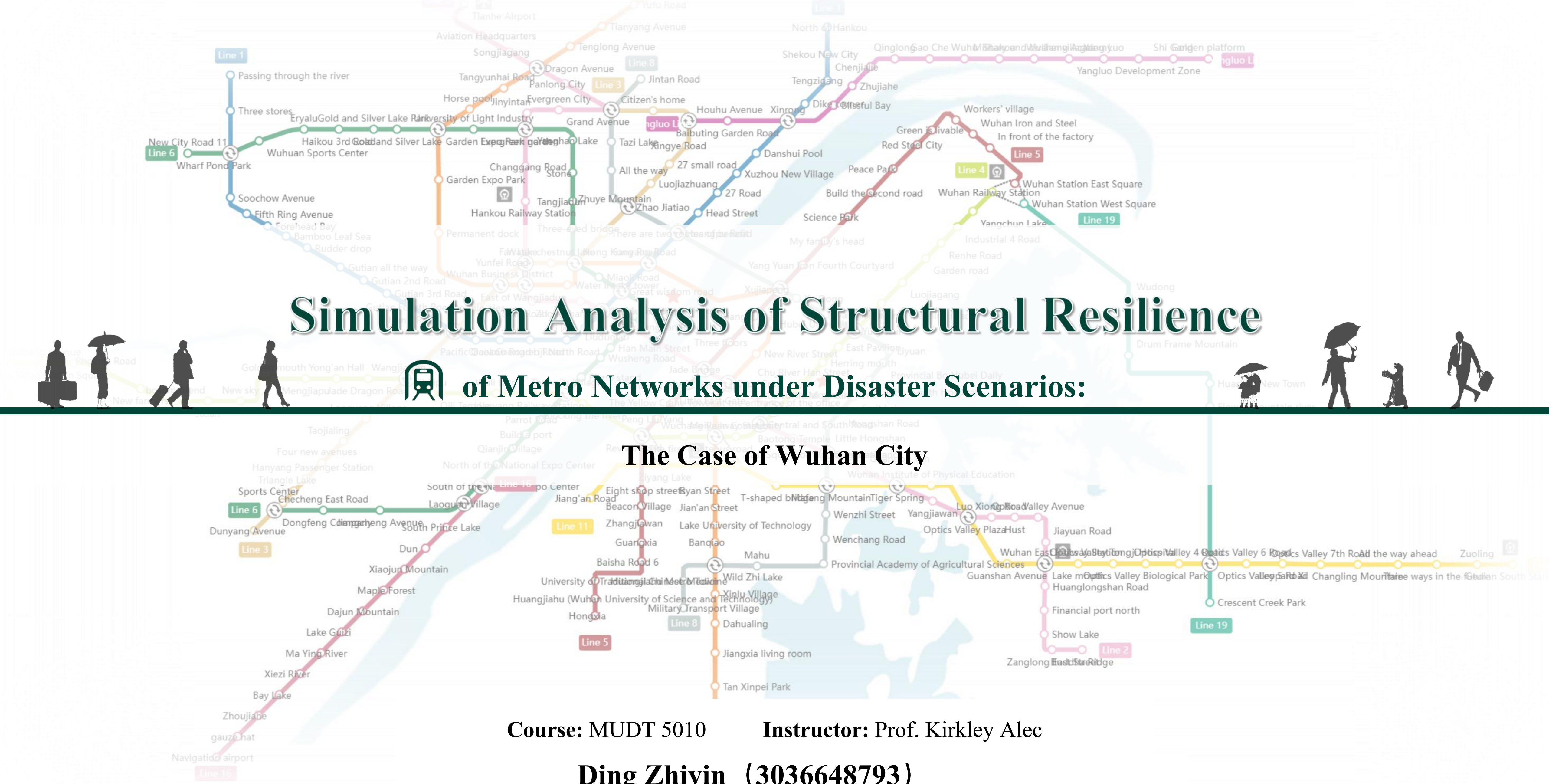


Simulation Analysis of Structural Resilience

of Metro Networks under Disaster Scenarios:

The Case of Wuhan City

Course: MUDT 5010 **Instructor:** Prof. Kirkley Alec

Ding Zhiyin（3036648793）

CONTENTS

1.1 Urbanization & Metro System Resilience

With global urbanization accelerating, metro has become **critical infrastructure** for maintaining urban **operations and commuting**.

System disruptions can cause traffic paralysis, economic losses, and hindered emergency response.

Resilience = ability to resist, absorb, recover from disruptions.

1.2 Metro network vulnerability

Metro networks are complex and highly interconnected, improving efficiency but prone to **cascading failures**.

Disasters such as floods, earthquakes, or equipment failures may trigger node breakdowns, thereby impacting the network's overall connectivity and transport capacity.

1.3 Why Wuhan?

Wuhan: located at Yangtze-Han River **confluence**, with **low-lying terrain**, **frequent floods**.

Rapid expansion, many transfer stations → efficient but fragile.

This study, based on the framework of complex network theory, constructs a **topological model** of the Wuhan metro network. By simulating two different types of disturbance scenarios—**random and targeted attacks**—compares changes in network performance indicators before and after the attacks, assesses its **structural resilience**, and identifies key nodes.

Title: Wuhan Metro, Hubei Province's First Rail Transit Line
Source: https://www.daobowh.com/article/7801.html

2.1 Literature Review - Complex Network Theory in Metro Systems

I Theoretical Foundation: From Graph Theory to Complex Systems

The metro system is abstracted as a Graph, where stations are Nodes and track sections are Edges, establishing the mathematical basis for structural analysis.(Latora & Marchiori, 2002)

II Topological Characteristics Revealing Systemic Properties

Studies find that many metro networks exhibit "small-world" (shorter average paths) and "scale-free" (existence of hub nodes) properties. This leads to their co-existing robustness against random failures and vulnerability to targeted attacks on key nodes.(Derrible & Kennedy, 2010)

III Centrality Metrics: Core Tools for Identifying Critical Nodes

Indicator	Meaning	Sources
Degree Centrality	Identifies hubs with numerous connections (e.g., transfer stations).	Yang et al., 2015
Betweenness Centrality	Identifies key stations acting as bridges in the network.	Freeman, 1977; Qi et al., 2022
Closeness Centrality	Identifies the most centrally accessible stations to all other parts	Ma et al., 2022

IV Research Gap and Limitations

Conceptual Ambiguity in Application

Although many studies use the term "resilience", their analyses often fail to strictly distinguish between structural resilience (topological attributes) and functional resilience (passenger load). (Pagani & Mosquera, 2018)

Insufficient Understanding of Rapidly Evolving Networks

Most research is based on structurally stable, mature networks (e.g., London, New York),There is a lack of targeted research on the networks of large Chinese cities like Wuhan, which are undergoing rapid expansion and have continuously evolving topological structures.

Oversimplified Topological Models

Most studies use highly simplified topological models, ignoring the real impact of spatial geospatial constraints (such as the impact of river separation on actual connectivity) on network structural resilience.

2.2 Literature Review - Attack Simulation & Resilience Assessment

Ⅰ Attack Simulation: A Standard Experimental Method for Assessing Resilience

Observing the degradation process of network performance by simulating the failure of nodes or edges.(Albert et al., 2000)

Ⅱ Random Attack vs. Targeted Attack

Attack Strategy	Meaning	Applicable Scenario	Sources
Random Attack	Random node failure	Small-scale sporadic failures	Albert et al., 2000
Targeted Attack	Prioritize removal of high-centrality nodes	Terrorism/Key hub failure scenarios	Albert et al., 2000; Holme et al., 2002

Ⅲ Random Attack vs. Targeted Attack

Quantification Metric	Primary Role	Specific Interpretation	References
Global Efficiency	Measures network travel efficiency	Reflects the decline in accessibility and operational efficiency, indicating increased travel delays and detours.	Latora & Marchiori, 2001
Largest Connected Component (LCC)	Measures network connectivity integrity	Assesses the degree of system fragmentation	Albert et al., 2000
Area Under the Curve (AUC)	Provides a single resilience score	Comprehensively characterizes the entire resilience degradation process	Wang et al., 2016; Ma et al., 2022

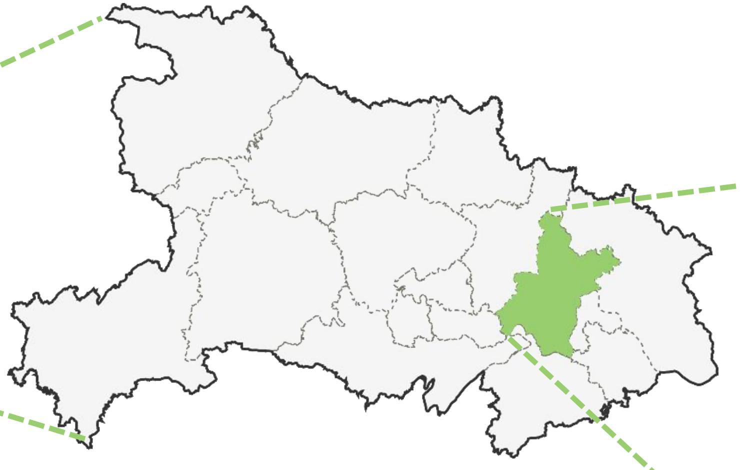
Ⅳ Research Gap and Limitation

Insufficient Differentiation and Integration of Vulnerability Mechanisms

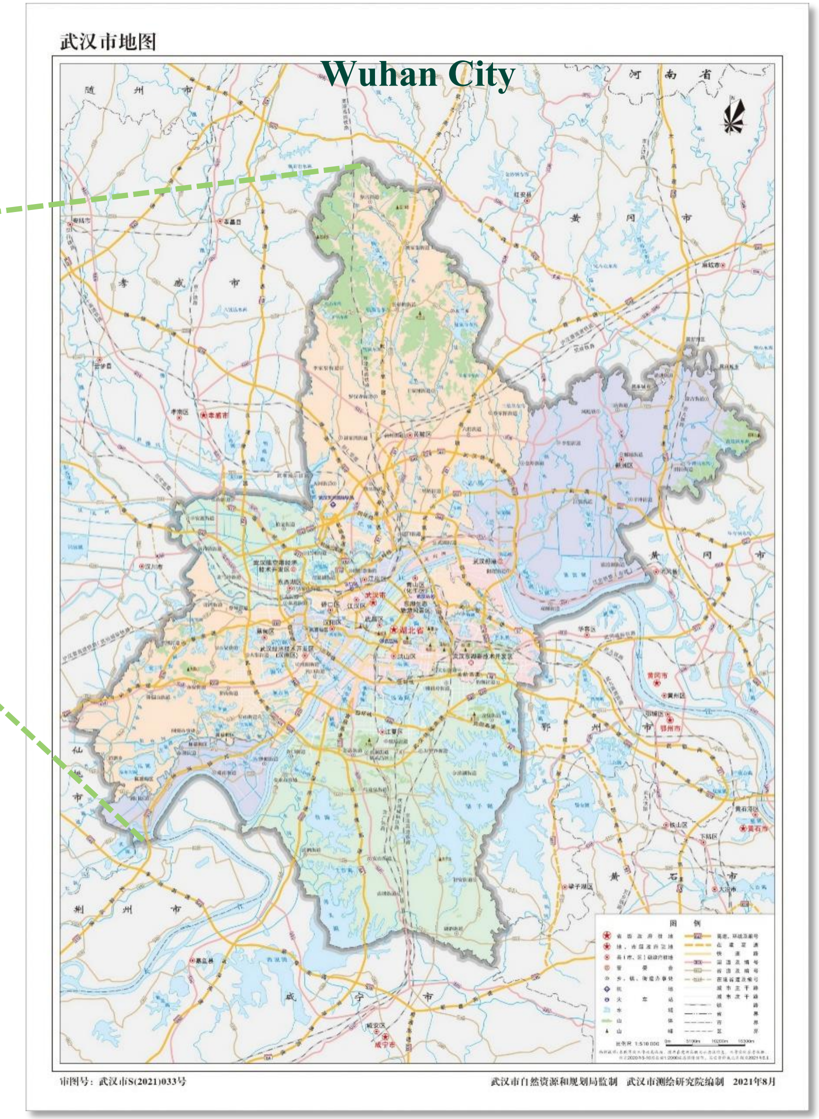
Existing research lacks clear differentiation and integration of the structural vulnerability mechanisms revealed by different attack strategies. There is a lack of focused attention on the super vulnerability of "dual-core" nodes possessing both high betweenness and high degree centrality.

3.1 Study Area

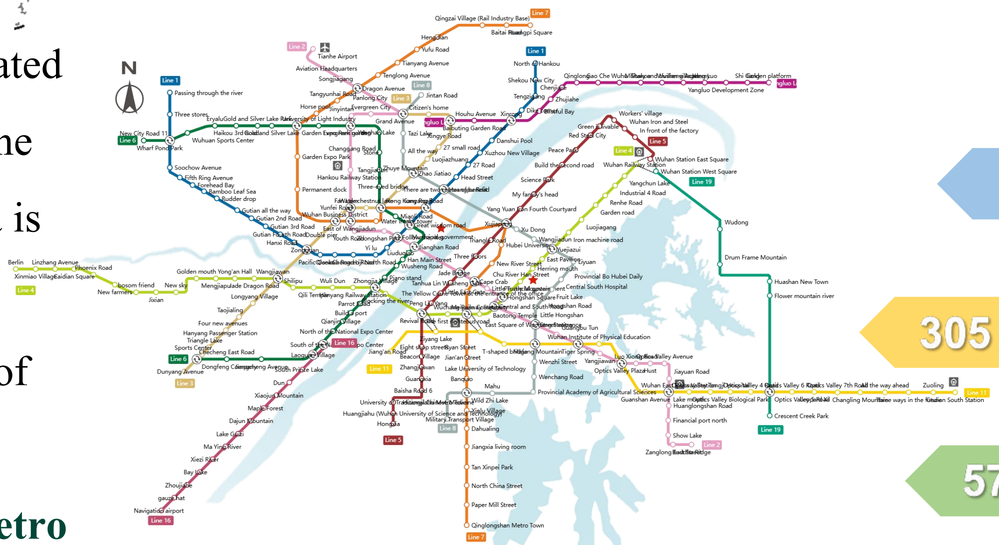
China · Hubei Province



Hubei Province · Wuhan City



This project is located in China Hubei. The specific study area is **Wuhan city**, the provincial capital of Hubei Province, focusing on the **metro network**.



Wuhan Metro Network Map
Source: https://h5.whrtmpay.com/whrtMap/#/

15 lines

305 stations

574.46 km

(By 2024)

Map of Wuhan City
Source: Wuhan Municipal Bureau of Natural Resources and Planning

3.2 Research Framework

Step 1: Data Preparation

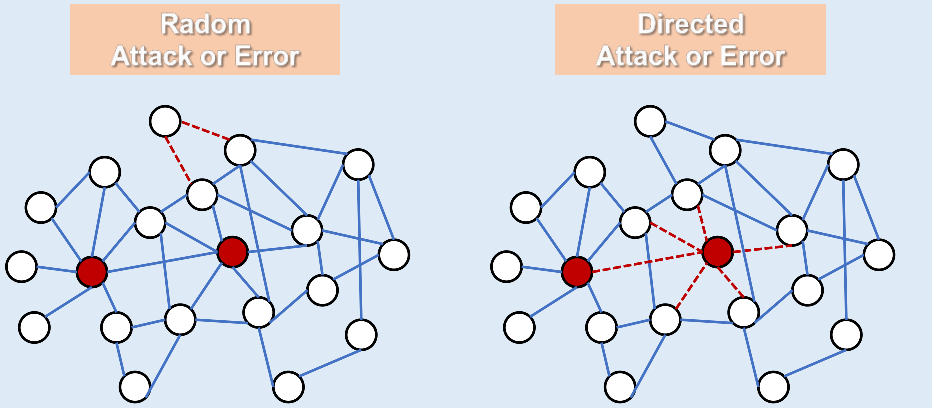
- Wuhan Metro. shp File
- Wuhan Metro. graphml File

Step 2: Network Modelling & Topological Analysis

- Network Visualization
- Centrality Calculation
- Topological Metrics Calculation
- Minimum Spanning Tree Analysis

Step 3: Attack Simulation & Resilience Evaluation

- Identify 5 Key Nodes (Based on Betweenness Centrality)
- Simulate Attack Strategies
- Track Performance
- Record Node Removal Order
- Random Attack
- Degree-based Attack
- Betweenness-based Attack



Source: Drawn by the author

- Global Efficiency
- Relative Size of LCC

Step 4: Result Visualization

- Plot Resilience Curves
- Quantify Resilience (AUC)
- Identify Critical Nodes (Achilles' Heel)

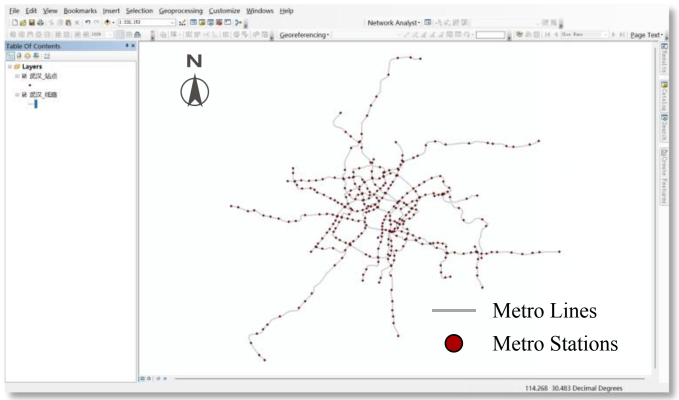
Step 5: Conclusions & Recommendations

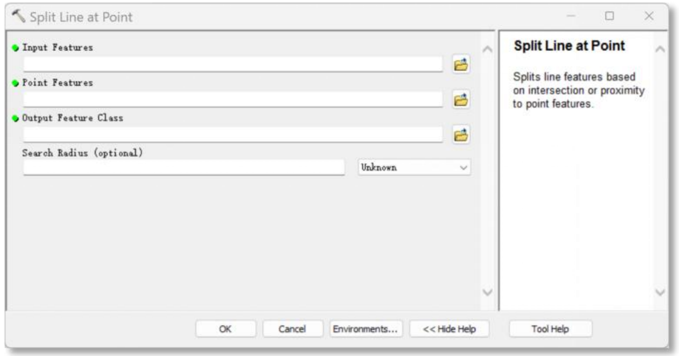
- Network Vulnerability Analysis
- Planning Suggestions for Resilience Enhancement
- Future Work

3.3 Data Preparation & Network Construction

Step 1 — **Raw Data Source**
(Split 15 Lines at stations)

✓ **Metro Lines. shp + Metro Stations. shp**



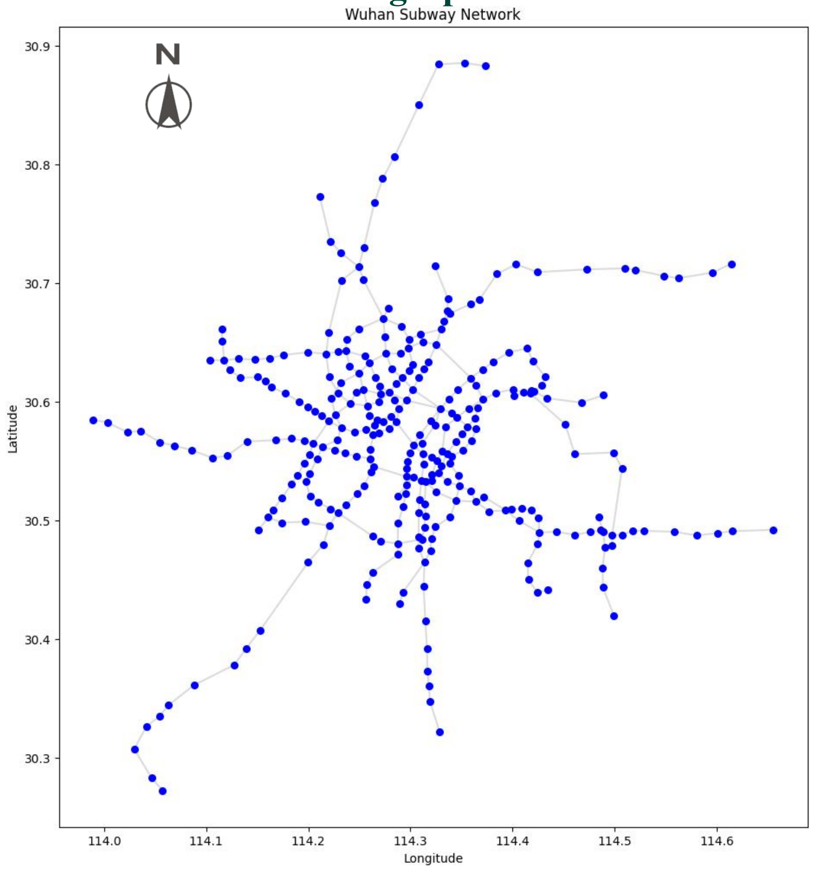


Data Source: https://blog.csdn.net/gitblog_09701/article/details/142951618

Step 2 — **Analyzable data**
(Generate graphml file to analyze)

```python
import geopandas as gpd
import networkx as nx
from shapely.geometry import Point, LineString

# Read data
stations = gpd.read_file("station.shp")
lines = gpd.read_file("line.shp")

print("Number of stations: ", len(stations))
print("Number of lines: ", len(lines))
print("stations columns: ", stations.columns.tolist())
print("lines columns: ", lines.columns.tolist())

# ------------------------------
# Step 1. Create an empty graph
# ------------------------------
G = nx.Graph()

# ------------------------------
# Step 2. Add Nodes (Subway Stations)
# ------------------------------
for idx, row in stations.iterrows():
    geom = row.geometry
    if isinstance(geom, Point):
        G.add_node(
            row.get("name", f"station_{idx}"),
            x=geom.x,
            y=geom.y,
            **{col: row[col] for col in stations.columns if col != "geometry"},
        )

# ------------------------------
# Step 3. Add Edges (Subway Lines)
# ------------------------------
for idx, row in lines.iterrows():
    geom = row.geometry
    if isinstance(geom, LineString):
        # Extract the start and end points
        start_point = Point(geom.coords[0])
        end_point = Point(geom.coords[-1])

        # Find the station node closest to both the starting point and the destination.
        start_station = None
        end_station = None
        min_start_dist = 1e9
        min_end_dist = 1e9

        for node, data in G.nodes(data=True):
            node_geom = Point(data["x"], data["y"])
            d1 = node_geom.distance(start_point)
            d2 = node_geom.distance(end_point)
            if d1 < min_start_dist:
                min_start_dist = d1
                start_station = node
            if d2 < min_end_dist:
                min_end_dist = d2
                end_station = node

        # Add edges
        if start_station and end_station:
            G.add_edge(
                start_station,
                end_station,
                length=geom.length,
                **{col: row[col] for col in lines.columns if col != "geometry"},
            )

# ------------------------------
# Step 3a. Scale edge lengths
# ------------------------------
scale_factor = 100000
for u, v, data in G.edges(data=True):
    if 'length' in data:
        data['length'] *= scale_factor

# ------------------------------
# Step 4. save as GraphML
# ------------------------------
nx.write_graphml(G, "Wuhan Metro.graphml")
print("✅ File successfully generated: Wuhan Metro.graphml")
```

✓ **Wuhan Metro. graphml file**



Source: Drawn by the author in Colab

3.4 Research Methodology —— Topological Network Analysis

➢ **Purpose: To understand the static structural characteristics of the network and identify critical hubs**

■ Basic Metrics:

① Number of Nodes & Edges

② Average Degree

③ Average Shortest Path Length

④ Global Efficiency

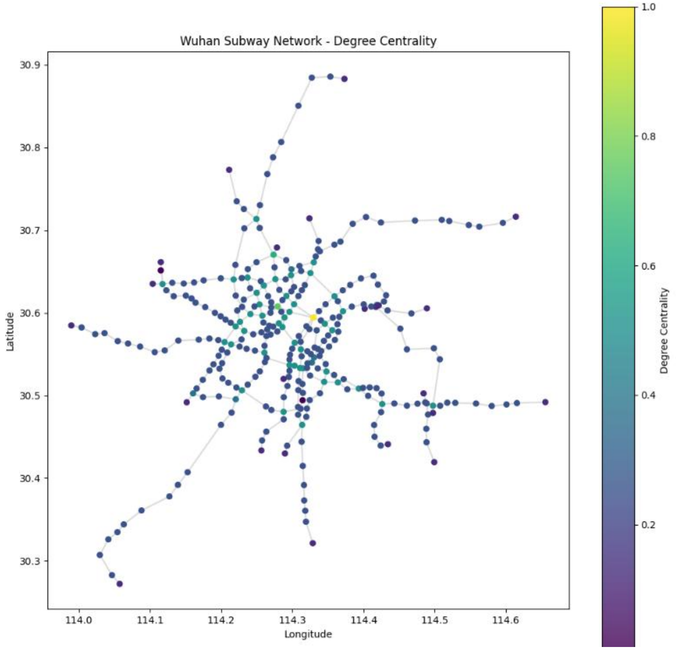
⑤ Clustering Coefficient

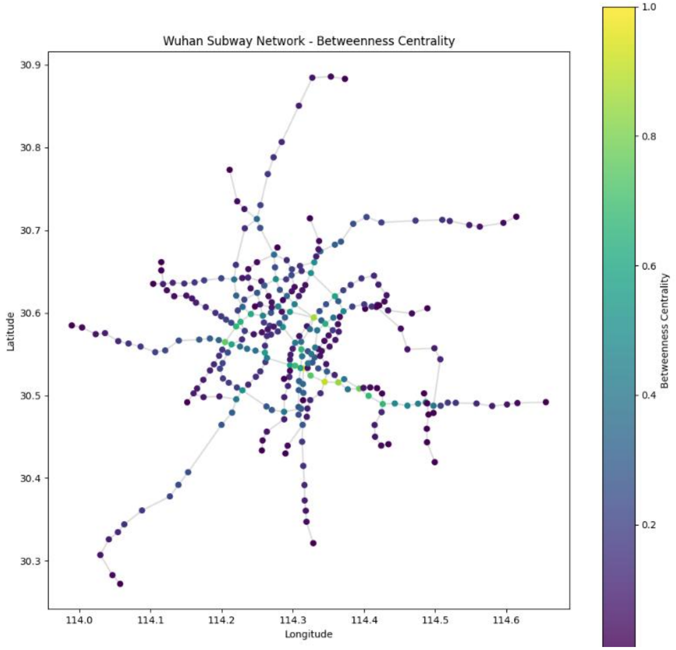
■ Centrality Metrics:

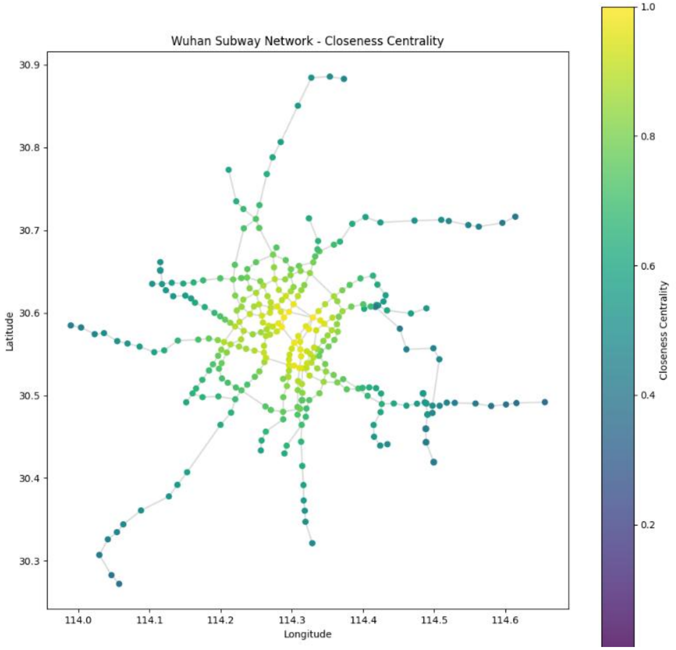
① **Degree Centrality:** Identify the most connected hub stations.

② **Betweenness Centrality:** Identify the most critical "bridge" stations in the network.

③ **Closeness Centrality:** Identify the stations that are most accessible to all other stations.

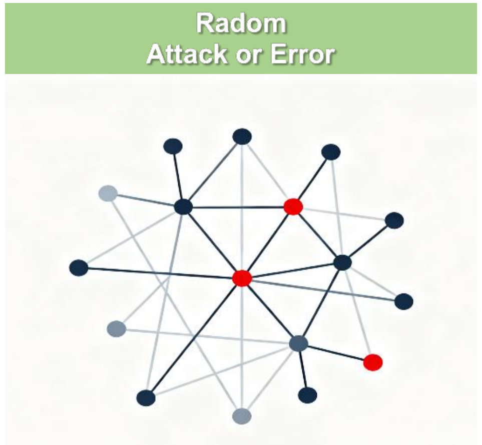






3.5 Research Methodology —— Random Attack vs. Deliberate attack

■ Random Attack



Source: Online resources

- **Objective:**

To stimulate the randomness of station failures during urban disasters or accidental outages.

- **Simulation Process:**

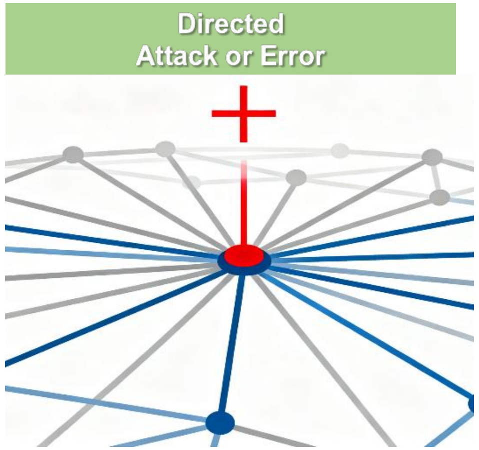
Continuously select and remove a node randomly from the network to simulate the fault accumulation process of traffic stations in real disaster scenarios.

- **Key Features:**

I. Impact is typically localized and non-catastrophic.

II. The network is highly tolerant of random attacks, and the overall structure remains stable.

■ Deliberate Attack



Source: Online resources

- **Objective:**

To simulate worst-case scenarios where key nodes are preferentially destructed.

- **Simulation Process:**

Involves the strategic removal of the most influential nodes based on their topological characteristics.

- **Two deliberate attack strategies**

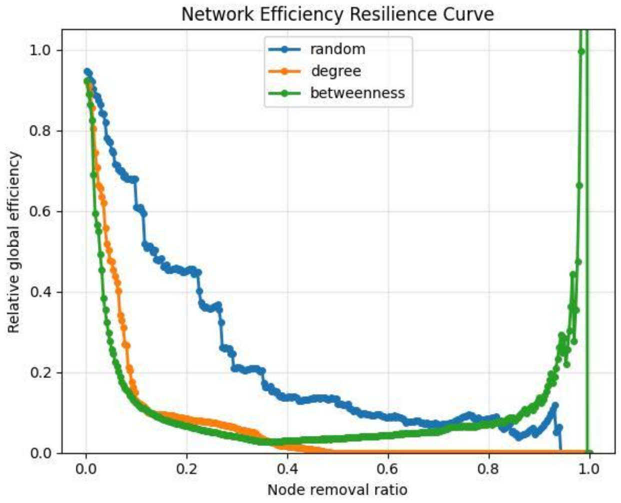
Degree-based Attack	Prioritizes attacking "local hubs" with the highest number of direct connections.
Betweenness-based Attack	Prioritizes attacking "bridge" nodes that lie on the shortest paths.

3.4 Research Methodology —— Attack Simulation & Performance Monitoring

➢ **Core: Simulate different disaster scenarios and dynamically monitor network performance**

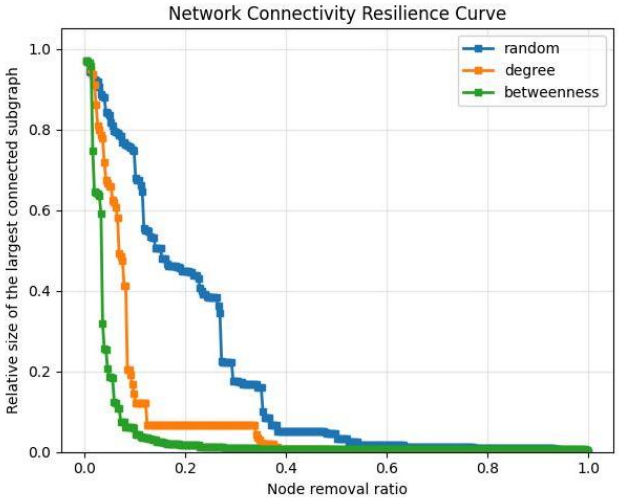
■ Define Attack Strategies:

- **Random Attack:** Simulates random failures (e.g., random equipment failures).
- **Degree-based Attack:** Simulates attacks on hubs (e.g., targeting the busiest transfer stations).
- **Betweenness-based Attack:** Simulates attacks on the most critical "bridges" (e.g., attacking a key station connecting two major parts of the city).



■ Define Performance Metrics:

- **Global Efficiency:** Measures the overall travel efficiency of the network.
- **Relative Size of the Largest Connected Component (LCC):** Measures the connectivity integrity of the network.



4.1 Network Modelling & Topological Analysis

I Closeness Centrality

- The metro station with the highest closeness centrality is: **Xujiapeng** with a value of 0.0968.

Xujiapeng - Metro station

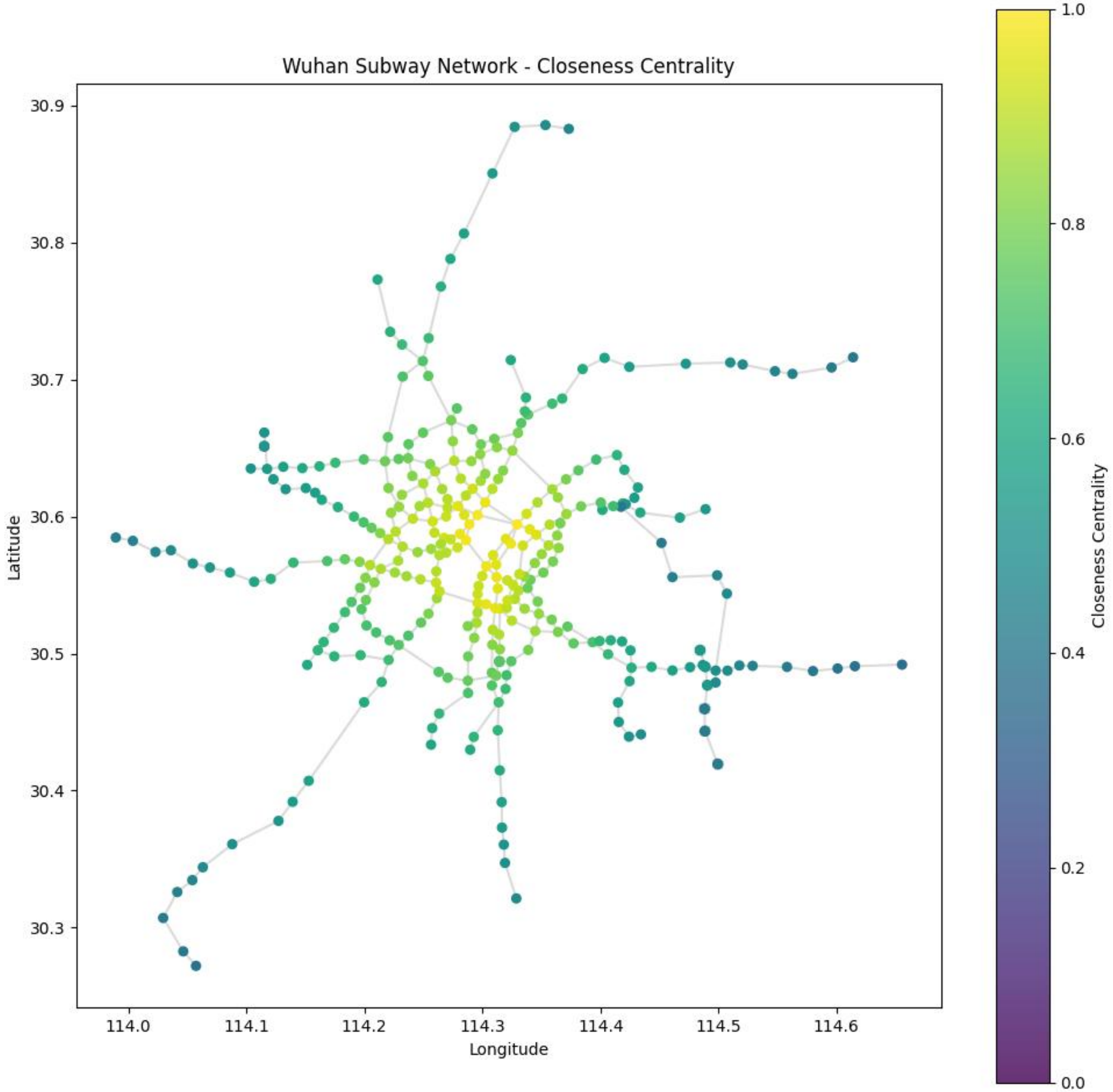
By subway: Metro line 5 Metro Line 7 Metro Line 8

Entrance and Exit Arrangements
Source: Baidu Map

Map of Xujiapeng Station
Source: Baidu Map

- **Core Agglomeration:** High-value areas of closeness centrality are highly concentrated in the city center, forming a distinct core ring. This indicates that stations within this area have the highest network accessibility, with the shortest average distance to all other stations.

- **Layered Attenuation:** The centrality value shows a clear, layered decrease from the core to the peripheral lines. The farther a station is from the city center, the darker its color and the lower its closeness centrality, signifying lower overall network accessibility.



Source: Drawn by the author in Colab

4.1 Network Modelling & Topological Analysis

Ⅱ Betweenness Centrality

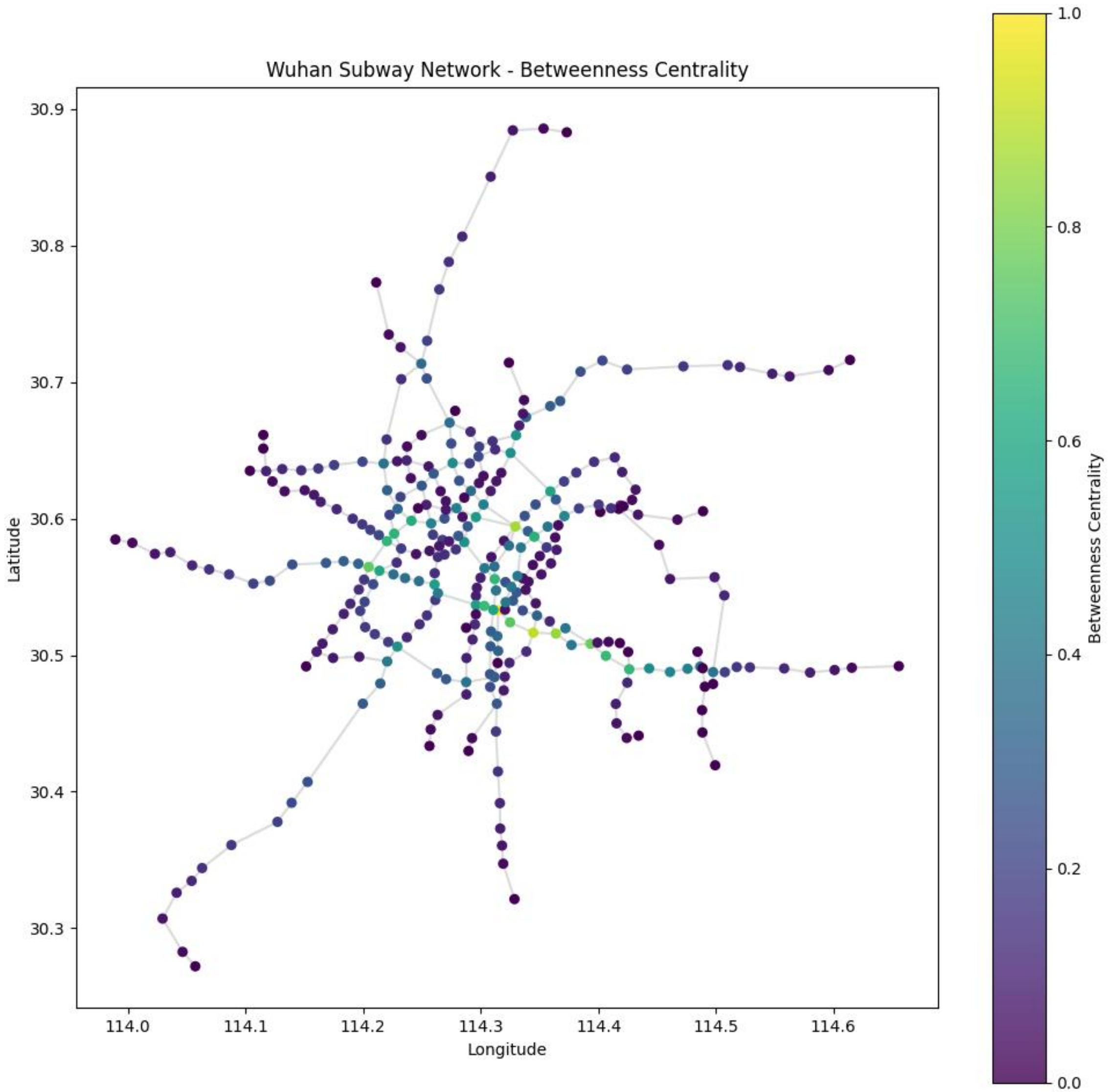
- The metro station with the highest betweenness centrality is: **East Square of Wuchang Station**.

Virtual Transfer Diagram
Source: Zhihu

Map of East Square of Wuchang Station
Source: Baidu Map

- **Critical Bridge Feature:** High-value stations in betweenness centrality act as critical "bridges" that connect different regions of the network and handle cross-line passenger flow. These stations are core interchanges that lie on the highest number of shortest paths.

- **Path Dependency:** Stations with fewer interchange lines but a critical geographical location can also have high betweenness centrality. Conversely, a major transfer station might have a relatively lower betweenness centrality if it is not on an essential path.



Source: Drawn by the author in Colab

4.1 Network Modelling & Topological Analysis

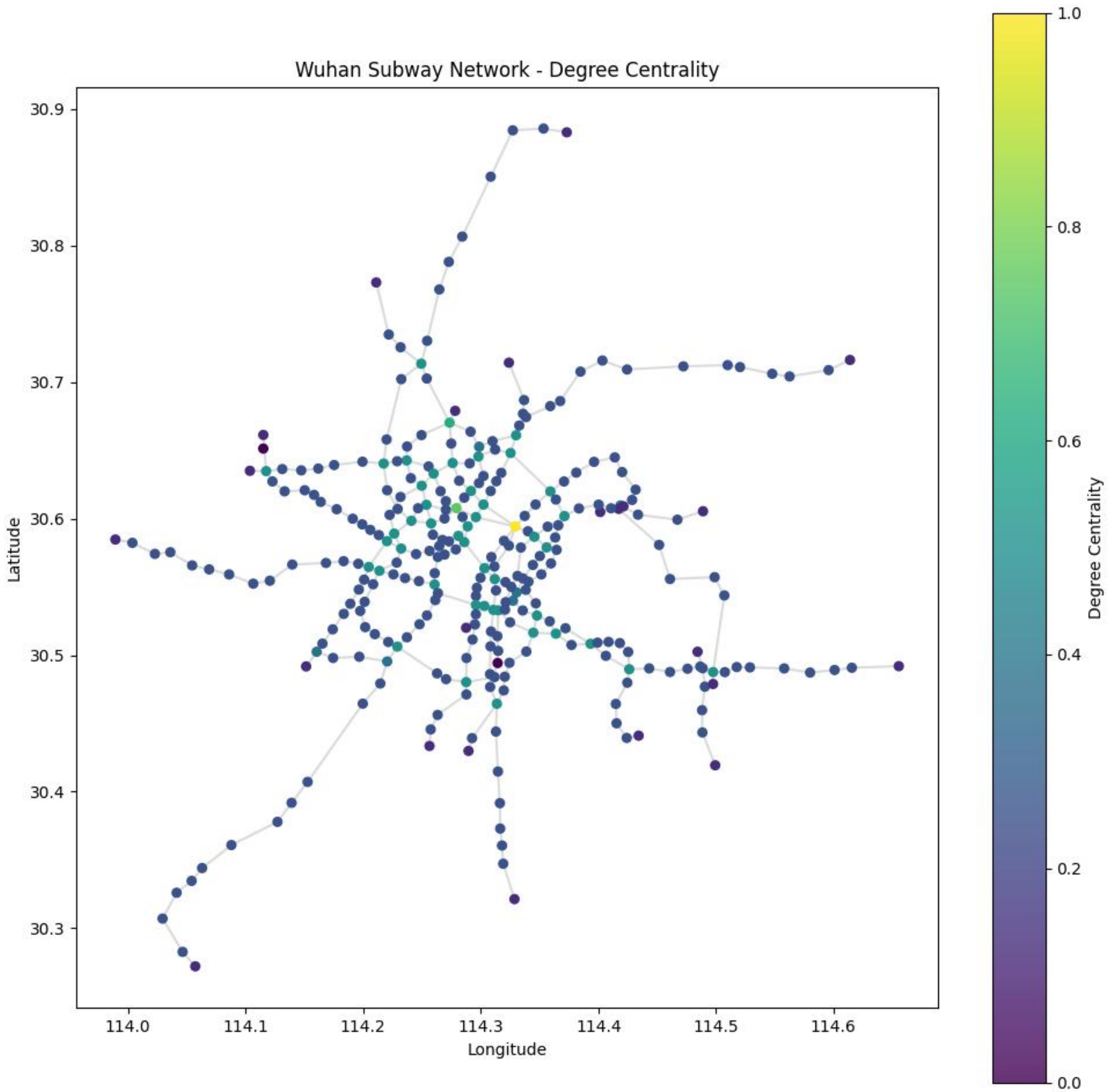
Ⅲ Degree Centrality

- The metro station with the highest degree centrality is also: **Xujiapeng**.

Entrance and Exit Arrangements
Source: Baidu Map

Map of Xujiapeng Station
Source: Baidu Map

- **Hub Identification:** High-value stations in degree centrality (brightly colored) are exclusively the network's transfer stations. The more lines a station serves, the higher its degree centrality. Therefore, this map clearly identifies the key interchange hubs in the network.
- **Prevalence of Low Values:** The vast majority of stations in the network (non-transfer stations) have very low degree centrality (dark blue). This is because they are only directly connected to two adjacent stations on their respective lines, playing a more singular role in the network's structure.



Source: Drawn by the author in Colab

4.1 Network Modelling & Topological Analysis

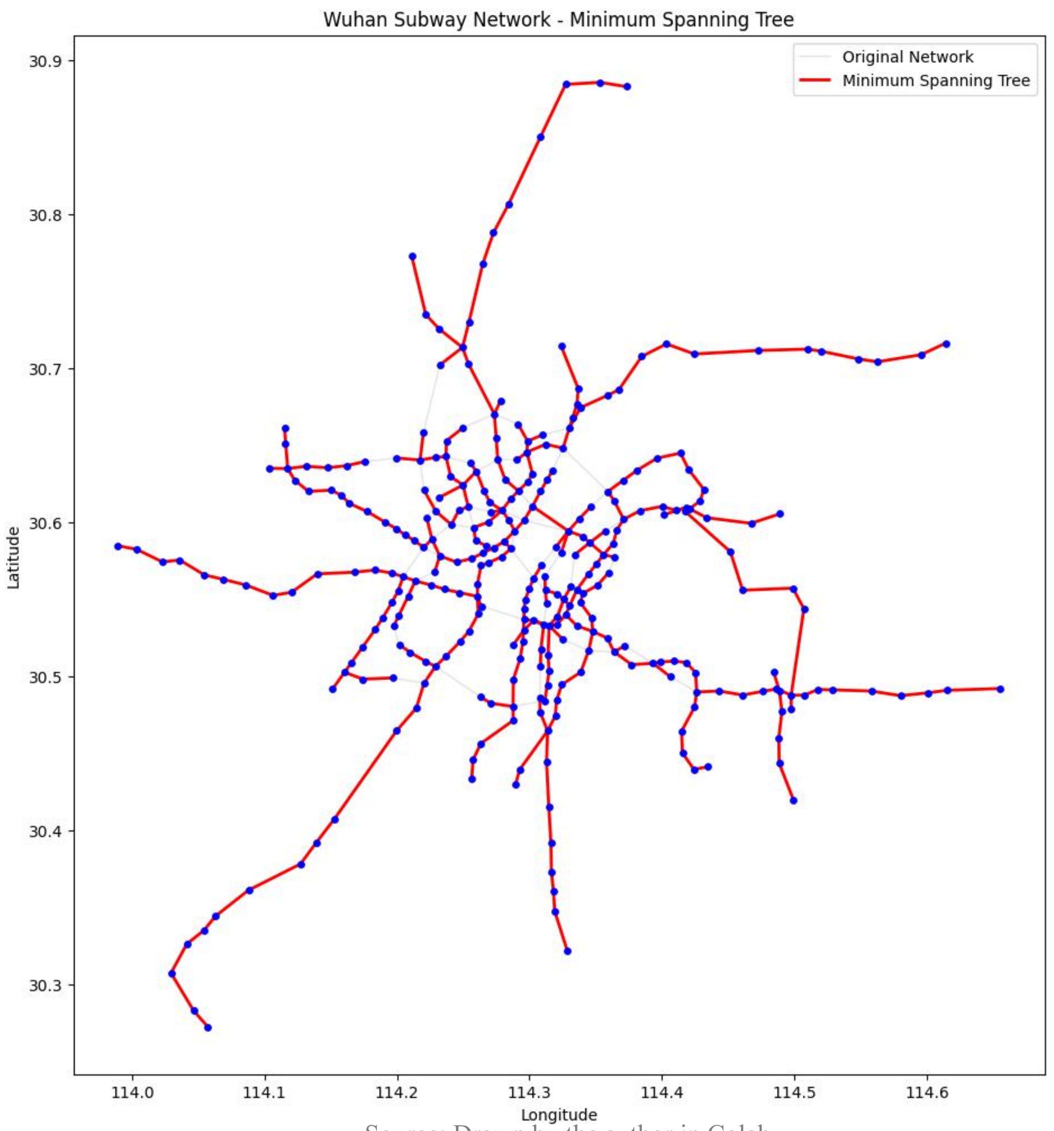
Ⅳ Minimum Spanning Tree

- **Reveals the Core Backbone and Topological Structure:**

The Minimum Spanning Tree (red lines) illustrates the most economical and fundamental backbone required to connect all metro stations in Wuhan.
It removes all loops and redundant connections, retaining only the essential shortest paths needed to maintain full network connectivity. Its shape clearly outlines the "centralized core with axial radiation" topology of the network: a densely connected central area with several main corridors extending outwards.

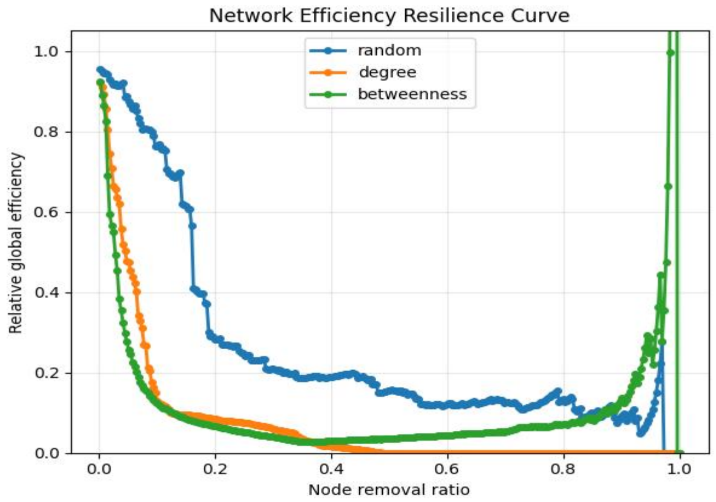
- **Quantifies Network Redundancy and Resilience:**

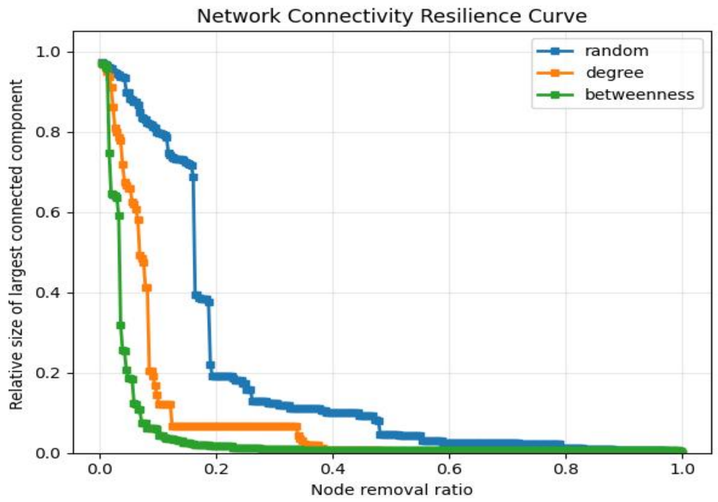
The difference between the original network (faint grey lines) and the MST (bold red lines) visually represents the network's redundancy. The connections that exist in the original network but are absent from the MST (especially in the city center) are the redundant links that provide alternative routes and shorten travel times. This high level of redundancy is crucial for the resilience and efficiency of a modern metro system, ensuring that passengers have alternative paths even if a section is disrupted.



Source: Drawn by the author in Colab

4.2 Resilience Curve Analysis





X-axis: Node removal ratio

Y-axis (Left): Relative global efficiency

Y-axis (Right): Relative size of larger connected component

Source: Drawn by the author in Colab

- **Random Attack (Blue Curve):** The curve exhibits a gradual and slow decline. Even with 40% of nodes removed, global efficiency and connectivity remain at a high level. Therefore, Wuhan Metro network demonstrates high robustness against random, coincidental failures.

- **Betweenness-based Attack (Green Curve):** The curve shows the steepest descent. Removing just 10% of nodes causes global efficiency and connectivity to plummet below 0.20 as the network rapidly fragments into isolated components.

- **Degree-based attack (Orange Curve):** The efficiency and connectivity decay of the degree attack is obviously faster than that of random attack, but slightly slower than the betweenness-based attack .

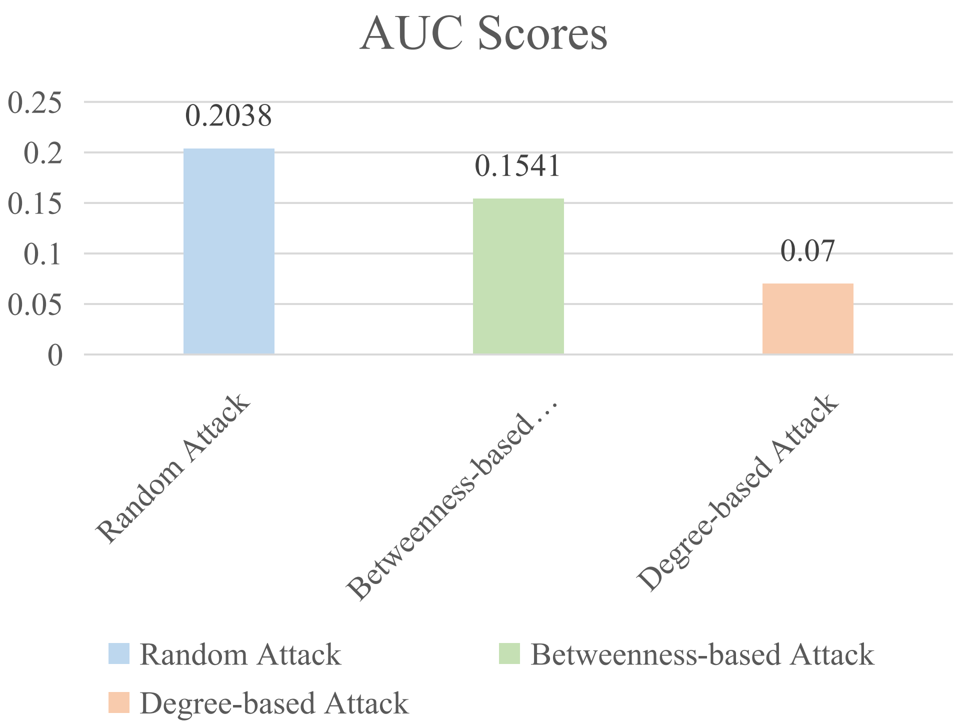
4.3 Quantitative Resilience Assessment: AUC Analysis

Ⅰ What is AUC(Area Under Curve):

AUC is to quantify the overall resilience of the network under different attack strategies by calculating the total area below the toughness curve. The larger the AUC value, the stronger the network resilience.

Ⅱ AUC Results

Attack Strategies	AUC Score	Resilience Assessment
Random Attack	0.2038	Highest(Most Resilient)
Betweenness-based Attack	0.1541	Medium
Degree-based Attack	0.0700	Lowest(Most Fragile)



Source: Drawn by the author

4.4 Key Nodes Impact Analysis Under Targeted Attacks

- **Degree Attack Core Node – Xujiapeng**
- **Betweenness Attack Core Node – East Square of Wuchang Railway Station**

Table: Top 5 Key Nodes

Node	Betweenness Centrality	Degree Centrality	Efficiency Drop After Removal
East Square of Wuchang Railway Station	**0.2245**	0.0132	7.59%
Mafangshan	0.2043	0.0132	5.38%
Xujiapeng	0.1947	**0.0263**	3.57%
Huquan	0.1897	0.0132	2.00%
Optics Valley Square	0.1739	0.0132	2.91%

Source: Drawn by the author

Figure: Wuhan Metro Network Map
Source: Drawn by the author

5.1 Conclusions

Ⅰ The Wuhan metro network exhibits typical "scale-free & small-world" dual resilience characteristics.

- It shows high robustness against random attacks, maintaining strong performance even with 40% of nodes removed;
- However, it demonstrates significant vulnerability to targeted attacks (especially on high-betweenness nodes), where failure of key nodes triggers sharp systemic performance drops.

Ⅱ Two types of critical nodes were identified: "Hub-type" and "Bridge-type", with distinct failure impacts.

- Xujiapeng (high degree) serves as a connection hub; its failure disrupts local connectivity.
- East Square of Wuchang Station (high betweenness) acts as a cross-region bridge; its failure causes a significant drop in global efficiency.

Ⅲ The resilience simulation provides a quantitative tool for structural vulnerability diagnosis and disaster prevention planning.

- Combining the AUC index and resilience curves allows systematic assessment of network resilience under different attack scenarios.
- The research findings provide a scientific basis for redundancy design, emergency scheduling, and protection of critical nodes in the Wuhan Metro.

5.2 Limitation and Future Work

Ⅰ **This study has the following limitations, which provide directions for future research:**

- **Static and Non-Load-Based Analysis:**

Due to the lack of passenger flow data, there is insufficient analysis of spatio-temporal resilience.

- **Data Timeliness and Network Dynamics:**

This study is based on the 2024 network data. The Wuhan metro network is still expanding rapidly, so the conclusions require regular updates.

Ⅱ **Based on the above limitations, future work can be deepened in the following aspects:**

- **Simulation Analysis of Spatiotemporal Resilience:**

Using machine learning techniques such as ARIMA models, we want to forecast **the gradual recovery of passenger flow** in the Wuhan subway network after the disaster, providing practical recommendations for transportation disaster prevention planning.

- **Investigating the Collaborative Resilience of Multi-Modal Transportation Networks:**

Extend the research scope from the metro network to a **Multi-Modal Transport Network** including buses, ferries, and shared bikes. Analyze how other transport modes can provide alternative paths when metro stations fail, thereby enhancing the resilience of the entire urban transport system. Investigating the Collaborative Resilience of Multi-Modal Transportation Networks.

06 References

[1] Albert, R., Jeong, H. and Barabási, A.-L. (2000). Error and attack tolerance of complex networks. Nature, 406(6794), pp.378–382.

[2] Crucitti, P., Latora, V., Marchiori, M. and Rapisarda, A. (2004). Error and attack tolerance of complex networks. Physica A: Statistical Mechanics and its Applications, 340(1-3), pp.388–394.

[3] Francis, R. and Bekera, B. (2014). A metric and frameworks for resilience analysis of engineered and infrastructure systems. Reliability Engineering & System Safety, [online] 121, pp.90–103.

[4] Freeman, L.C. (1977). A Set of Measures of Centrality Based on Betweenness. Sociometry, 40(1), p.35.

[5] Holme, P., Kim, B.J., Yoon, C.N. and Han, S.K. (2002). Attack vulnerability of complex networks. Physical Review E, 65(5).

[6] Hu, J., Wen, W., Zhai, C. and Pei, S. (2024), "A Comprehensive Review of Resilience of Urban Metro Systems: A Perspective from Earthquake Engineering", Tunnelling and Underground Space Technology, Vol. 152, Art. 105920.

[7] Latora, V. and Marchiori, M. (2002). Is the Boston subway a small-world network? Physica A: Statistical Mechanics and its Applications, 314(1-4), pp.109–113.

[8] Li, K., Xiahou, X., Wu, Z., Shi, P., Tang, L. and Li, Q. (2024), "Influencing Factor Identification and Simulation for Urban Metro System Operation Processes-A Resilience Enhancement Perspective", Systems (Basel), Vol. 12, No. 2, p. 43.

[9] Ma, Z., Yang, X., Wu, J., Chen, A., Wei, Y. and Gao, Z. (2022). Measuring the resilience of an urban rail transit network: A multi-dimensional evaluation model. Transport Policy, 129, pp.38–50.

[10] Meng, Y. (2024), “Vulnerability Comparisons of Various Complex Urban Metro Networks Under Multiple Failure Scenarios”, Sustainability, Vol. 16, No. 21, 9603.

[11] Pagani, A., Mosquera, G., Alturki, A., Johnson, S., Jarvis, S., Wilson, A., Guo, W. and Varga, L. (2019). Resilience or robustness: identifying topological vulnerabilities in rail networks. Royal Society Open Science, 6(2), p.181301.

[12] Qi, Q., Meng, Y., Zhao, X. and Liu, J. (2022). Resilience Assessment of an Urban Metro Complex Network: A Case Study of the Zhengzhou Metro. Sustainability, 14(18), p.11555.

[13] Sun, H., Li, M., Jiang, H., Ruan, X. and Shou, W. (2022), “Inundation Resilience Analysis of Metro-Network from a Complex System Perspective Using the Grid Hydrodynamic Model and FBWM Approach: A Case Study of Wuhan”, Remote Sensing (Basel, Switzerland), Vol. 14, No. 14, 3451.

[14] Wang, Y. and Tian, C. (2021), “Measure Vulnerability of Metro Network Under Cascading Failure”, IEEE Access, Vol. 9, pp. 683-692.

[15] Xu, Z. and Chopra, S.S. (2023). Interconnectedness enhances network resilience of multimodal public transportation systems for Safe-to-Fail urban mobility. Nature Communications, [online] 14(1), p.4291.

[16] Yang, Y., Liu, Y., Zhou, M., Li, F. and Sun, C. (2015). Robustness assessment of urban rail transit based on complex network theory: A case study of the Beijing Subway. Safety Science, 79, pp.149–162.

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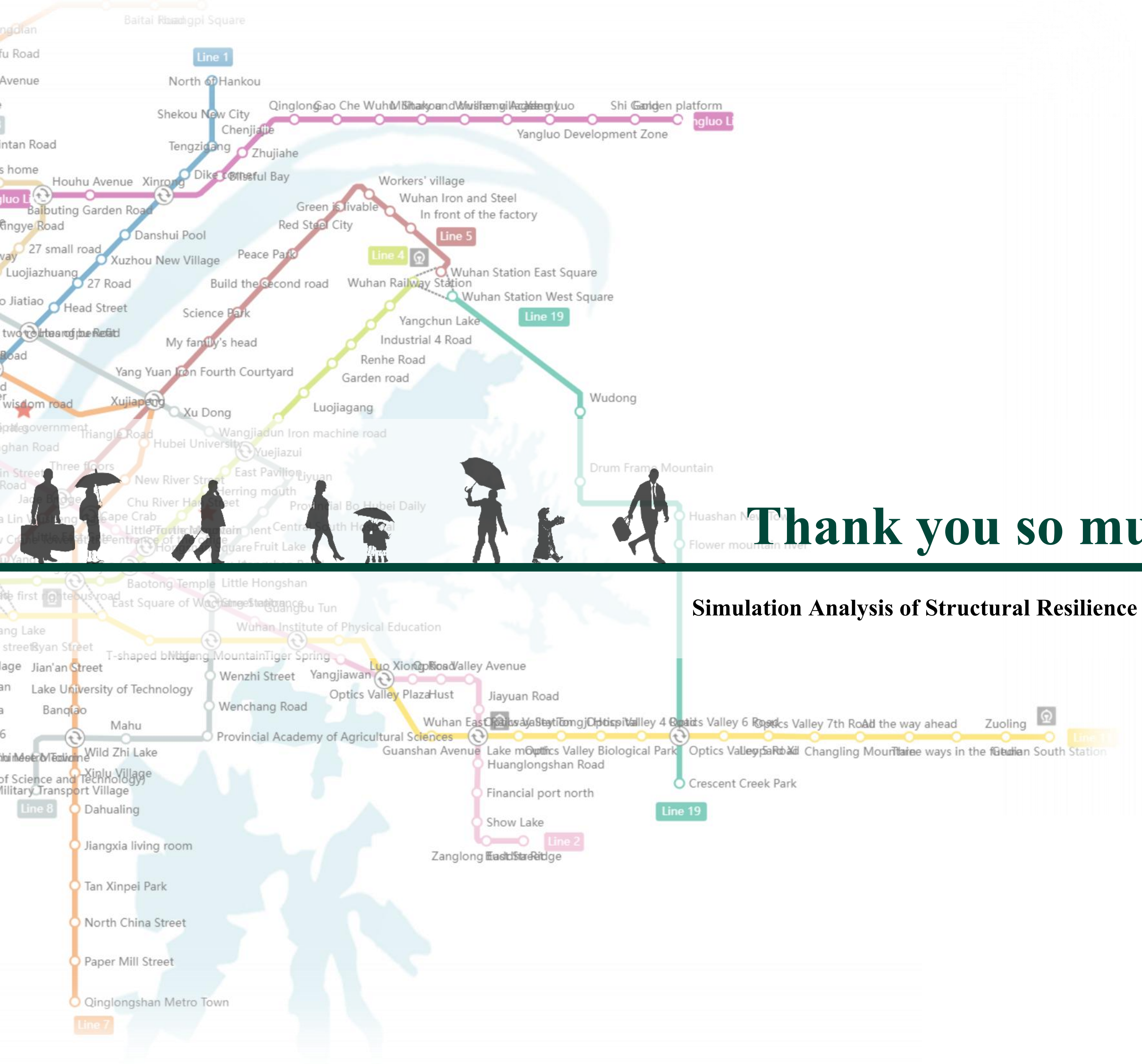

Thank you so much for watching and listening!

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