Resilience and Efficiency of Indian Urban Bus Networks

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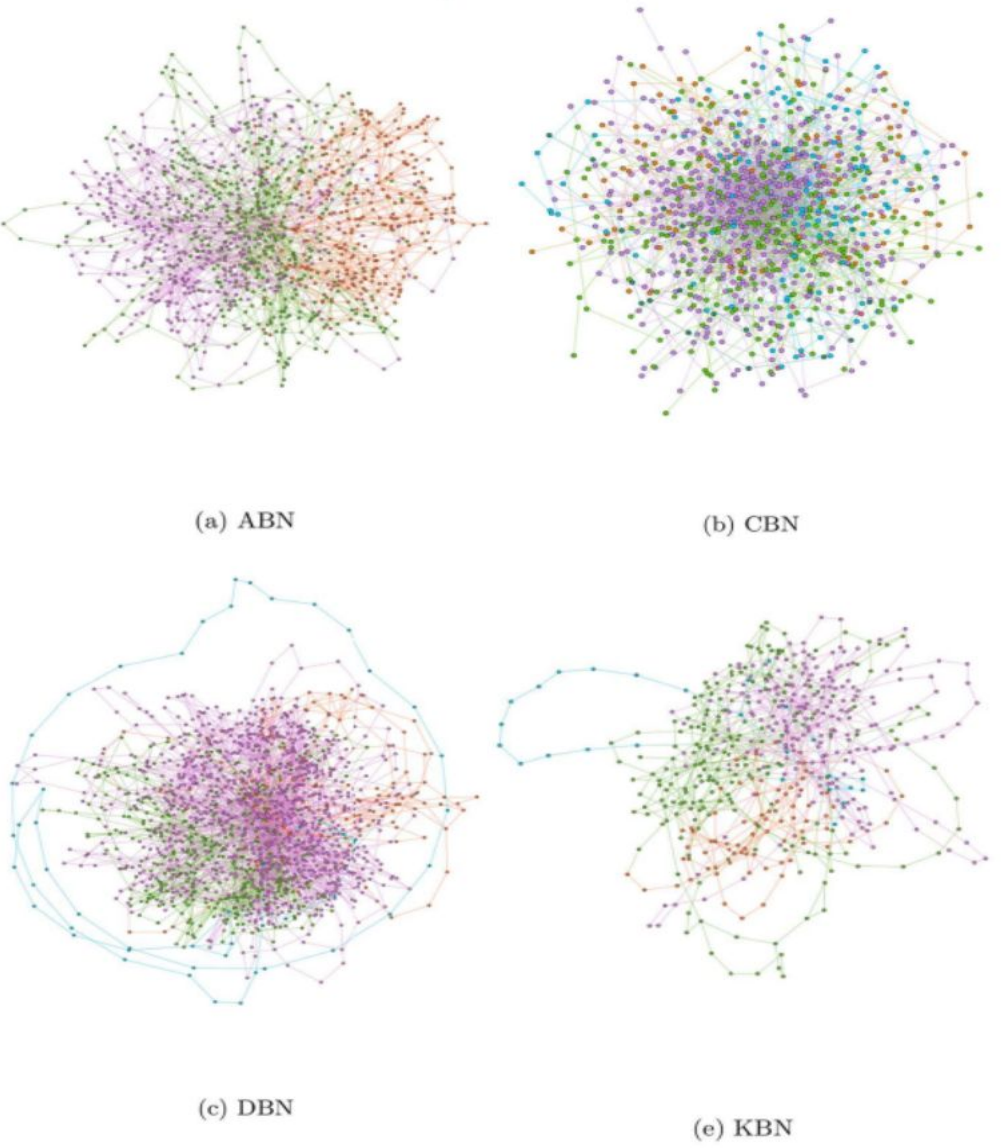
1. Introduction



Urban bus networks are critical for mobility in Indian cities. This study analyzes the bus networks of Ahmedabad, Kolkata, Delhi, and Chennai as weighted graphs to assess resilience against disruptions, passenger transfer efficiency, and connectivity compared to global standards. Insights aim to optimize urban transit systems.

2. Research Questions

- How resilient are Indian bus networks to random disruptions versus targeted removal of high-centrality stops, and which stops are most critical to network connectivity and efficiency?
- What is the distribution of minimum-hop paths between origin-destination pairs, and where do riders face the most transfers?
- How do Indian urban bus networks compare to global standards in terms of connectivity, robustness, and transfer efficiency?

3. Datasets

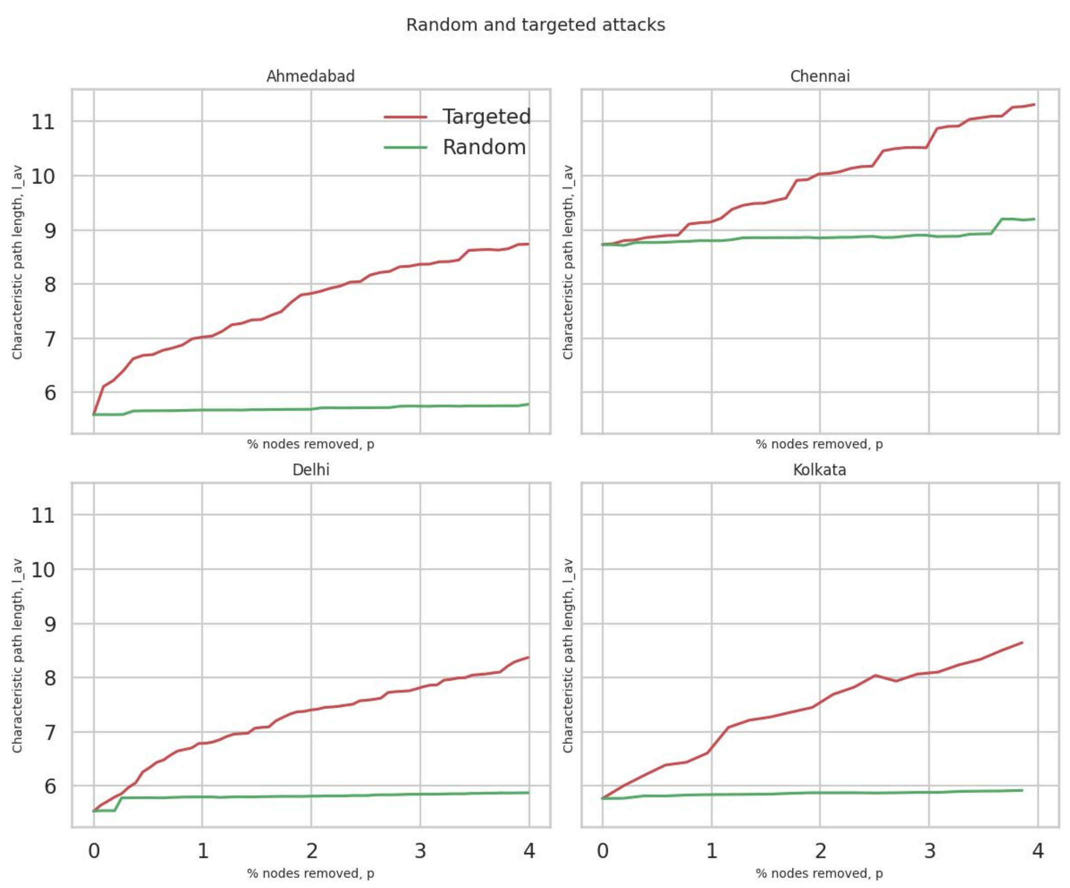
Network Parameters of Indian Bus Networks

Parameter	Ahmedabad	Kolkata	Delhi	Chennai
Number of Nodes	1103	519	1554	1009
Number of Edges	2157	878	3617	1610
Average Degree	3.91	3.38	4.66	3.19
Network Density	0.0035	0.0065	0.003	0.0032
Avg Clustering Coefficient	0.1891	0.0793	0.1833	0.0678
Avg Shortest Path Length	5.59	5.77	5.54	8.73
Max Shortest Path Length	16	16	29	27
Top Critical Stop (Betweenness)	Lal Darwaja	Howrah Station	Anand Vihar Bus Terminal	Node 1037

4. Methodology

The analysis used NetworkX and igraph libraries to assess bus network properties. Data from CSV files included nodes as bus stops and weighted edges as overlapping routes. NetworkX computed centrality (degree, betweenness) and simulated disruptions, tracking characteristic path length changes. igraph visualized critical transfer nodes and network graphs, highlighting hubs. Shortest path distributions were calculated with NetworkX, and global comparisons normalized metrics (average degree, assortativity, density, clustering, efficiency) against benchmarks, with plots generated using library tools for accuracy.

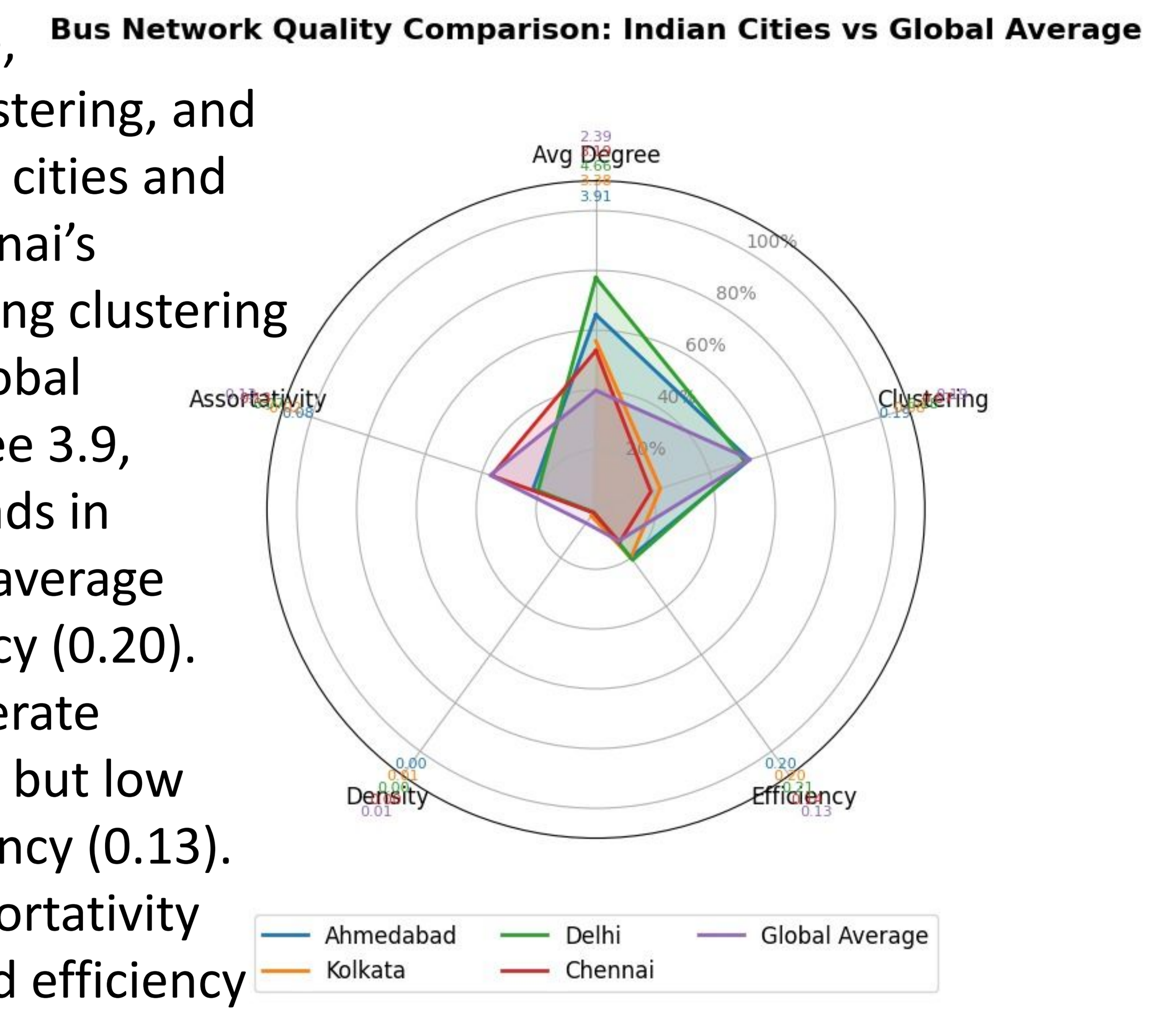
5. Results



Bus network resilience under node removal is shown by changes in characteristic path length. In Ahmedabad, targeted removal increases path length from 6 to 11 with just 4% of nodes removed, revealing high vulnerability, while random removal has little effect. Chennai shows a similar pattern, rising from 9 to 11 under targeted attacks. Delhi's path length grows from 7 to 10, indicating better resilience, and Kolkata's increases from 7 to 9, suggesting moderate fragility. Overall, targeted removal of high-centrality hubs severely disrupts connectivity, emphasizing the need to protect these critical stops.

This plot visualizes critical transfer nodes, marked in red, with average transfers per trip. In Ahmedabad, nodes like Lal Darwaja, Naroda Terminus, and Vasna Terminus form dense hubs, averaging 7.64 transfers across 1103 stops and 2592 routes, reflecting high transfer demand. Kolkata's key nodes—Karunamoyee, Ultadanga, and Howrah Station—average 8.84 transfers over 519 stops and 983 routes, indicating a centralized structure. Delhi's hubs, including Nehru Place and Badarpur, average 8.35 transfers across 1554 stops and 4285 routes, showing a more distributed network. Chennai stands out with nodes like Central and T. Nagar, averaging just 1.50 transfers over 1009 stops and 1610 routes, suggesting superior efficiency. This highlights Chennai's effective connectivity compared to the hub-reliant networks of other cities.

The histogram illustrates the distribution of minimum-hop paths (transfers + 1) across cities. Ahmedabad peaks at 3-5 hops with a density of ~0.3, indicating frequent short trips. Delhi's peak at 2-4 hops with a density of ~0.4 reflects efficient connectivity. Chennai peaks at 2-3 hops with a density of ~0.25, underscoring low transfer needs. Kolkata, however, peaks at 5-7 hops with a density of ~0.3, suggesting longer, transfer-heavy routes. These findings highlight Delhi and Chennai's advantage in offering shorter paths, while Kolkata's extended paths point to connectivity gaps needing attention.



The radar chart compares network metrics—average degree, assortativity, density, clustering, and efficiency—across Indian cities and the global average. Chennai's balanced metrics, including clustering (0.31), align closest to global standards (average degree 3.9, efficiency 0.20). Delhi leads in connectivity with a high average degree (3.9) and efficiency (0.20). Ahmedabad shows moderate connectivity (degree 3.1) but low density (0.01) and efficiency (0.13). Kolkata lags with low assortativity (0.08), density (0.01), and efficiency (0.13), indicating inefficiencies.

6. Conclusion

Indian bus networks exhibit resilience to random disruptions but are fragile under targeted attacks on critical stops. Chennai and Delhi outperform in efficiency, while Kolkata requires improved peripheral connectivity. A key recommendation is to enhance decentralized links and safeguard vital hubs to boost overall network performance.

7. References

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