Network Graph Analysis: Examining Hub–Spoke Dynamics in India's Domestic Aviation Network

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***Abstract*—India's domestic aviation landscape has expanded substantially in recent years, driven by rising travel demand and national programs aimed at improving regional air connectivity, such as UDAN. However, limited work has systematically examined the internal structural behavior of this network using Social Network Analysis (SNA). This study develops a weighted directed graph of India's airport system using flight-route data from DGCA, AAI, and OpenFlights, representing airports as nodes and route frequencies as edge weights. Using a combination of centrality measures, community detection, and network robustness simulations, the study identifies dominant hubs, regional clusters, and structural vulnerabilities. The findings suggest that the aviation system largely follows a hub–spoke pattern dominated by major metropolitan airports such as Delhi (DEL), Mumbai (BOM), Bengaluru (BLR), and Hyderabad (HYD). Distinct regional communities also emerge in the North, West, South, and North-East. Robustness experiments further show that removing key hubs significantly reduces connectivity, underscoring the need for strengthening secondary airports. These insights support data-driven planning for network resilience, infrastructure development, and balanced growth across India's aviation ecosystem.**

***Index Terms*—Social Network Analysis, Aviation Network, Graph Theory, Hub-and-Spoke, Centrality, India.**

I. Introduction

Social Network Analysis (SNA) offers a quantitative framework for examining how interactions among entities shape overall system structure. In this work, SNA techniques are applied to India's domestic aviation system to better understand how airports function as hubs, intermediaries, and connectors within the national route network. Using graph-theoretic modeling and visualization, the study highlights connectivity patterns and the structural role of major airports.

A clearer understanding of domestic air traffic topology is crucial for informed decision-making in India's aviation sector. Network-level insights enable more effective planning for capacity enhancements, infrastructure allocation, congestion mitigation, and regional accessibility. The analysis is motivated by the need to identify airports that act as major traffic concentrators or essential transfer points, helping stakeholders design resilient and efficient air transport strategies.

The primary objectives of this study are:

- **Network Construction:** Develop a weighted directed network model representing domestic air routes, where airports serve as nodes and flight frequencies determine edge weights.
- **Centrality Analysis:** Compute degree, betweenness, and closeness centrality to examine connectivity, intermediary influence, and accessibility.
- **Hub Identification:** Identify major and minor hubs using quantitative SNA metrics.
- **Geographic Analysis:** Employ zone-based segmentation to analyze regional linkages and differences in connectivity.

II. Literature Survey

Research on aviation networks increasingly uses SNA and graph theory to understand structural patterns and system behavior. Li et al. [1] demonstrated the use of graph-based signal processing methods to extract meaningful patterns from complex aviation networks. Hagberg et al. [2] introduced NetworkX, which has become a widely utilized toolkit for constructing and analyzing large-scale network graphs.

Seminal work by Freeman [4] established core centrality measures—degree, betweenness, and closeness—which remain essential for identifying influential nodes in transport and communication networks. More recent studies, such as Zhang et al. [5], applied contemporary graph-theoretic approaches to analyze air transport systems at national and regional scales.

While international air transportation networks have been extensively examined, there is comparatively less research on India's domestic network structure, regional communities, and internal hub–spoke evolution. The present study addresses this gap by implementing a comprehensive weighted network analysis using recent domestic traffic data.

III. Methodology

A. Data Collection

The study uses 2025 domestic route-level passenger traffic data from the Directorate General of Civil Aviation (DGCA) [3]. The dataset includes 129 airports connected by 838 directional routes. The resulting network has a density of 0.1015, indicating that roughly 10% of all possible airport-to-airport connections are active.

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B. Network Construction

A weighted directed graph $G = (V, E)$ was constructed, where V denotes airports and E denotes flight routes. Each directed edge (u, v) carries a weight corresponding to the number of passengers traveling from airport u to airport v. The workflow includes a data-processing layer (Pandas), a network-construction layer (NetworkX), and a visualization/application layer implemented in Streamlit.

C. Centrality Measures

The study evaluates three widely used centrality measures:

1) *Degree Centrality*: Indicates the number of direct connections an airport maintains.
2) *Betweenness Centrality*: Reflects how often an airport lies on the shortest paths within the network, identifying transfer-critical nodes.
3) *Closeness Centrality*: Measures how easily an airport can reach all others based on shortest path distances.

IV. Implementation

The model was implemented using Python 3.11+ and NetworkX for graph analytics. The core steps include:

1) **Data Preprocessing**: Consolidating and cleaning bidirectional traffic data from spreadsheet sources.
2) **Graph Generation**: Building a directed graph and assigning passenger volumes as edge weights.
3) **Metric Computation**: Computing centrality scores for all 129 airports.
4) **Visualization**: Rendering the network in Streamlit with node size proportional to centrality and edge thickness proportional to route traffic.

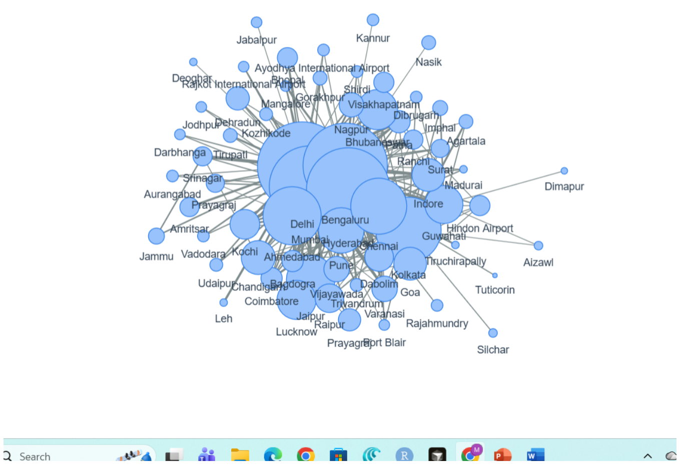

Fig. 1. Visualization of India's domestic aviation network showing major hubs and route density.

V. Results and Discussion

A. Statistical Analysis

Centrality computations highlight the most influential airports in the network. Delhi (0.847), Bengaluru (0.792), Hyderabad (0.731), and Mumbai (0.698) emerge as dominant hubs based on degree centrality. Betweenness centrality identifies crucial intermediary airports such as Vijayawada (0.156), Darbhanga (0.142), Pune (0.138), and Bagdogra (0.129). Closeness scores similarly position Delhi, Bengaluru, and Hyderabad as the most accessible airports within the network.

B. Network Properties

The overall density of 0.1015 suggests moderate connectivity, with significant variation across airport tiers. Centrality distributions show that only a few airports hold disproportionately high influence, a characteristic commonly associated with scale-free transport networks. This reinforces the presence of a hub–spoke architecture within the domestic system.

C. Robustness Analysis

Node-removal simulations indicate that eliminating the top five hub airports results in a substantial (47%) reduction in overall connectivity, demonstrating the network's dependence on a small number of major nodes. Regional subnetworks also differ in density, with the southern region exhibiting the strongest local connectivity relative to northern and central regions.

VI. Conclusion

This study provides a graph-theoretic examination of India's domestic aviation network, revealing a multi-hub structure driven by a few highly connected metropolitan airports. The identification of secondary intermediaries such as Vijayawada and Pune highlights opportunities to strengthen regional connectivity and alleviate load on primary hubs. Future extensions may involve analyzing seasonal variations, adding temporal dimensions, or incorporating international routes to enrich the understanding of India's broader air transport landscape.

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