Understanding the Terminal Area Traffic Flow Characteristics Using Flight Record Data

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Abstract
Terminal area (TMA) is a significant component of the air transportation and air traffic management system. TMA consists of the airport and the transitional airspace between airports and air traffic control sectors and plays a non-trivial role in determining throughput and operational efficiency. Flights in TMA fly through defined courses, distances, and altitudes between specified navigation aids, expressed as standard terminal arrival routes and standard instrument departures. TMA operations are intrinsically complex, and a deeper understanding of TMA operational behaviour and performance is essential to provide timely solutions for schedule and slot allocations, flow, and congestion management. This paper proposes a flight record driven descriptive framework for simplified analysis and characterization of air traffic flows in TMA. This framework aims to perform a cross-sectional descriptive analysis of four key flow performance metrics and proposes a three-step methodology to extract these parameters from flight records. The framework is easy to comprehend, and results can contribute to developing new strategies and decision support tools for TMA traffic management.

Keywords
Terminal area (TMA) traffic · Flow characterization · Terminal area complexity · Flight records

Introduction
The global air passenger demand reached the 4.34 billion mark and is expected to triple in the next 20 years [1]. The forecasted air passenger demand in India is poised to reach 500 million by 2037 [2]. India is expected to become the third-largest market for air passengers after the US and China despite the temporary setbacks due to the current unprecedented situation of COVID-19 [3]. This rapid growth in domestic and global air travel demand raises critical challenges for the existing and future air traffic management (ATM) system. The future ATM will face an additional burden on the current and prospective airspace and airport capacity [4]. The terminal area (TMA)
is a significant component of the air transportation and ATM system and plays a non-trivial role in determining throughput and operational efficiency [5].

TMA represents the airport and the transitional airspace between airports and air traffic control sectors and is characterized by spatial and time-related interactions between aircraft operating in given airspace for a given time [6]. Several factors influence the TMA operations: number, length, and duration of arrival/departure trajectories, traffic volume, runway system capacity, aircraft fleet type, final approach spacing of aircraft, and spatial and temporal distribution of traffic and operation rules [5, 6]. TMA comprises arrival trajectories converging and departure trajectories diverging at specified navigation aids. The aircraft in TMA fly through well-defined courses and altitudes between these navigation aids, characterized by the standard terminal arrival routes (STARs) and standard instrument departures (SIDs) [6]. Therefore, TMA operations are intrinsically complex and depend on traffic demand, procedural, meteorological, technical, administrative, and other policies. A deeper understanding of TMA operational behaviour and performance is essential to provide timely solutions for schedule and slot allocations, flow, and congestion management [5]. The air traffic flow characterization using suitable flight trajectory data analytics frameworks can contribute to this understanding [5, 7].

Although several studies exist that apply specific machine learning methods, big data analysis, and statistical techniques on the raw flight track data [5, 7, 8] to better assess and understand operational efficiency, improve the predictive power of the system, and create enhanced decision support tools. A simplified approach for easy understanding and characterization of TMA flows using more accessible data types, such as flight records, remains a major gap in the literature. To address this research gap, the paper (i) identifies the key parameters that can be used for simplified analysis and characterization of air traffic flows in TMA, and (ii) develop a framework to extract the parameters from the well-documented flight records. The aim is to answer the following research questions:

1. What are the possible key parameters that can provide a simplified understanding of the TMA traffic flows?
2. How do we extract these parameters from easily accessible data sources?
3. What role can the TMA flow characterization play in developing effective decision-making frameworks, planning, and policy measures?

Literature Review and Background

Initial attempts to measure how difficult the air traffic behaviour is, i.e., its complexity, started with the introduction of Dynamic Density (number of aircraft in airspace) and other complex factors such as the number of potential interactions [8]. The complexity measures were primarily studied as contributing factors to controller workload [9]. The emergence of new complexity measures based on traffic structure and airspace geometry found wide applications in sector load balancing, traffic distribution during congestion, network design, slot scheduling, flow management etc. [6, 10, 11]. However, the majority of these measures focused on enroute traffic rather than TMA traffic, even though TMA has a much more complex structure [6, 12]. The development of parameters to analyze TMA traffic behaviour started with introducing static and dynamic metrics that were a function of quantity and quality of conflicts between observed flight trajectories [6, 13, 14]. These parameters are a function of multiple variables that vary based on aircraft fleet, airspace geometry, and structure [6], making them difficult to comprehend.

The emergence of new and improved technologies, machine learning, and data mining techniques created opportunities to gain more insights into flight trajectory patterns [5, 15]. Studies focused on innovative aspects to examine TMA traffic behaviour. They include flight track taxonomy based on segment identification [16], track decomposition and clustering [16]; monitoring TMA using a density-based clustering of flight trajectories [5, 17]; identification of nominal and abnormal spatial traffic patterns using hierarchical and spectral clustering [18]; grid-based trajectory clustering algorithm to identify flows and critical sections [19]; density-based clustering algorithm to identify dominant routing structures [20]; visual inspection of trajectory data for qualitative evaluation of airspace design and potential flow conflicts [21]; capacity impacts analysis associated with TMA interactions [22], etc. Although these methods have general applicability, widespread adaptations for the intended application at resource-constrained airports are a possible limitation [7].

The search for more comprehensible metrics to understand flow characteristics led to the introduction of trajectory-derived flow counts, track distance, and track time [23]. Track distance and time are defined by the distance and time traversed by an aircraft based on the relative position of SID/STAR with the runway. Track distance and track time give a direct measure of operational efficiency, TMA complexity, runway productivity, and schedule efficiency [23–25]. Congested TMA and inefficient operations lead to higher track distance and track time and large variance in track distance and track time [23]. Increased variance in track distance and track time is directly correlated with lost runway productivity [23]. Factors such as type of flight, flight direction, and fleet type also affect track distance and track time variance. Therefore, it is possible that we can understand TMA behaviour simply through a descriptive study about the track distance and track time...
corresponding to different types of operations, rather than employing high computation and complex methods. A similar effort was made to study the flow characteristics at Chicago Midway International Airport [23]. However, the study only considered arrival flows and used flight track data. The availability of different high fidelity flight data sources such as flight records can be used as a substitute since track data are high-dimensional data that requires huge storage. Track data most often need to be bought from secondary clients or require the installation of costly equipment like Automatic Dependent Surveillance-Broadcast (ADS-B). On the other hand, flight records are readily available and of smaller dimension.

In summary, the choice of using track distance and time metrics for a descriptive analysis of arrival/departure flows using flight records seems appropriate to address the discussed research questions and literature gaps.

**Data Description**

Chennai airport provides a good representation of a typically congested air network hub. It serves as a primary center for the Chennai flight information region and handles over 22 million passengers and 178 thousand aircraft movements per year. Chennai has four operational runways, RWY 07-25 and RWY 12-30. There are a total of 13 routes that merge at defined transition points, meant for arrivals. Similarly, 20 routes diverge from designated transition points, meant for departures. A total of 80 navigation aids constitutes the SID and STAR points in Chennai TMA. As per the Total Airspace and Airport Modeler (TAAM) report [26], RWY 07 is the busiest runway with an operational capacity of 31 movements/hour. The major contributing factor to runway operational delay has been attributed to arrivals. Arrival delays are primarily a result of runway occupancy time for arrival, whereas departure delays are caused due to increased idle queue time [26].

The flight records, also known as Flight Data Processing System (FDPS) data, are the output of radar track data processed by the Advanced Air Traffic Services (ATS) FDPS at Chennai. This structure enables improved situational awareness, supporting the application of uniform level of separation standards & procedures, dynamic sectoring, and reduced horizontal separation. The system provides, from other things, a CSV file containing the following information of flights operating in the FIR every day: Aircraft Call sign, type, the direction of flight, departure airport, Arrival airport, departure time, arrival time, distance travelled, wake category, Special Service Request (SSR) code, Waypoint name/coordinates, time and flight level at every waypoint over which the aircraft fly, aircraft registration, etc. Every given position of an aircraft in the CSV file, which is tracked by more than one radar, is the fused position of the aircraft, as computed by the ATS-FDPS, from radar position data from individual radars. For this study, we have only considered the flight record collected from a single day (January 1, 2020) of TMA operations.

**Methodological Framework**

**Step 1: SID and STAR Track Assignment**

As discussed in the previous section, the FDPS data only provide the set of all enroute waypoints for each arrival and departure at Chennai airport. It records information on the set of SID points tracked by the departing aircraft and the set of STAR points tracked by the arriving aircraft. Moreover, the FDPS data do not contain any information on the runway assigned to any particular arrival or departure. Figures 1 and 2 can be used as an illustration to understand this concept. Figure 1 illustrates the STAR points tracked by aircraft arriving at Runway 30 from two routes, W25 and W116.

It can be seen that the transition points for Route W25 and W116 are TEBAM and TANGO, respectively. Therefore, the set of STAR track points that will be covered by an aircraft while arriving at Runway 30 via route W115 are TEBAM-BACOM-ACUBU-MM507-MM501-MM509. Similarly, the set of STAR track points that will be covered by an aircraft while arriving at Runway 30 via route W25 are TANGO-RESMA-BACOM-ACUBU-MM507-MM501-MM509. Figure 2 illustrates the set of SID points tracked by aircraft departing from Runway 7 and going towards route A465.

The SID transition point, in this case, is DABAR. The figure suggests that the set of SID track points covered by an aircraft while departing from Runway 7 to route A465 are MM604-RADAB-DAMAD-LOCOSO-DABAR. As in the case of any major airports, the primary challenge for Chennai is that multiple runways and multiple routes are connecting those runways. Hence, it is apparent that to identify the runway assigned to a particular arrival or departure; we need to identify the set of STAR/SID track points in the set of all enroute waypoints for each arrival and departure. Airport Authority of India provides the SID and STAR charts for major airports in India. The SID/STAR charts are converted to quantifiable units by decoding all the track points for different route-runway pairs in a common database. The process to identify this set of STAR/SID track points for each arrival/departure trajectory can be summarised using the following steps:

1. **Step 1: SID and STAR Track Assignment**
2. **Step 2: Data Preprocessing**
3. **Step 3: Data Analysis**
4. **Step 4: Result Interpretation**
Fig. 1  STAR Chart for Runway 30 (Route W25 and W116)

Fig. 2  SID Chart for Runway 7 (Route A4655)
Arrivals
Let \( W_i^{\text{arrival}} \) be the set of all enroute waypoints for the \( i \)th arrival
Sort the elements in \( W_i^{\text{arrival}} \) based on the increasing order of the arrival time

Let \( R_k \) be the set of all STAR track points that joins the transition point \( j \) to runway \( k \)
Scan \( W_i^{\text{arrival}} \) to identify the first element that matches any one of the elements in \( R_k \).
Let the identified element be \( W_i^{\text{arrival}} \)
Scan \( W_i^{\text{arrival}} \) and create a set of waypoints that contains only elements starting from \( W_i^{\text{arrival}} \) till the last waypoint
Let this new set be called \( W_i^{\text{STAR}} \). Clearly, \( W_i^{\text{STAR}} \subset W_i^{\text{arrival}} \)
Departures
Let \( W_i^{\text{departure}} \) be the set of all enroute waypoints for the \( i \)th departure
Sort the elements in \( W_i^{\text{departure}} \) based on the decreasing order of the departing time

Let \( D_k \) be the set of all SID track points that join the runway \( k \) to the transition point \( j \)
Scan \( W_i^{\text{departure}} \) to identify the last element that matches any one of the elements in \( D_k \).
Let the identified element be \( W_i^{\text{departure}} \)
Scan \( W_i^{\text{departure}} \) and create a set of waypoints that contains only elements starting from the first waypoint till \( W_i^{\text{departure}} \)
Let this new set be called \( W_i^{\text{SID}} \). Clearly, \( W_i^{\text{SID}} \subset W_i^{\text{departure}} \)

Therefore, the outputs from step 1 are the set of STAR (\( W_i^{\text{STAR}} \)) or SID (\( W_i^{\text{SID}} \)) track points traversed by each arrival or departure in the flight record. In the flight records, erroneous entries are primarily in the form of waypoint names along certain departure/arrival trajectories. There are instances when some of the names of the enroute waypoints do not conform to conventional waypoint names but indicate the aircraft’s latitude and longitude, recorded by radar (e.g., 1300N08015E). In such cases, the following steps were taken to obtain clean data:
1. Check if the location of that waypoint signifies an existing waypoint. If so, assign the existing name.
2. If the location of that waypoint matches does not match with an existing waypoint, remove the waypoint.

Step 2: Runway Allocation

The next step in the framework is to allocate the runway for each arrival and departure. This step is achieved through the following steps:

Runway allocation to Arrivals
For each \( W_i^{\text{STAR}} \)
Calculate its similarity with each \( R_k \)
Assign the \( k \)th Runway to \( i \)th arrival based on the highest similarity
Runway allocation to Departures
For each \( W_i^{\text{departure}} \)
Calculate its similarity with each \( D_k \)
Assign the \( k \)th Runway to \( i \)th departure based on the highest similarity

The output from step 2 are the runways facilitating any particular arrival or departure.

Step 3: Flow Characterization

The first two steps add the following new information to the dataset:
- Set of STAR/SID waypoints tracked by each arriving/departing aircraft at Chennai airport.
- The runway allocated to each arriving/departing aircraft at Chennai airport.

Apart from that, we also have the following flight information for each arriving/departing aircraft:
- Travel direction of the aircraft (Eastbound/Westbound flights).
- Aircraft wake type (Heavy /Medium weight flights).
- Travel type (Domestic/International flights).

The final set of performance metrics calculated for each flow are flight distance, flight time, track distance, and track time. As the name suggests, the flight distance and flight time is the total distance (in km) and total time (in minutes) taken by the aircraft to travel from its origin to destination. The track distance (in km) and track time (in minutes) for arrivals are the total distance and time from the transition point on the STAR to the runway threshold. Similarly, the track distance (in km) and track time (in minutes) for departures are the total distance and time from the runway threshold to the SID transition point. Flight distance and flight time were considered to understand the influence of long-distance and short-distance flights. There exists a correlation between delays and flight distance/duration for many different airports in the world [27]. Therefore, the inclusion of flight distance and time will increase the granularity of flight types. The flow characterization is conducted through a cross-sectional descriptive analysis (minimum, maximum, median, mean and standard deviation) of the flow metrics based on the different categories of flight information.

Results and Discussion

Chennai Airport Inventory

The Chennai airspace is a circular area of 25 NM radius centered around the waypoint MMV (125915N, 0800918E). Chennai airspace is classified as Class D airspace with a vertical limit of 5000 feet and transition altitude of 400 feet. The airport is facilitated with Instrument Landing System
(ILS) Category I with provisions available for Low visibility Procedures. RWY 07 & RWY 25 can accommodate departures even in Runway Visual Range (RVR) less than 800 m and 550 m, respectively. RWY 12 & RWY 30 can accommodate departures with RVR up to 200 and 300 m, respectively. Runway centreline lights and transmissometers are available for RWY 07-25. The runway centerline marking, edge, and end lights are available for all the runways. The overall airport layout is shown in Fig. 3. The airport has a total of 104 parking stands, all with concrete surfaces. Most of the aprons are designed for narrow-body aircraft, and few can accommodate wide-body aircraft. All aircraft stands are either Power-in or Pushback type. There are 24 taxiways (TWY) with concrete/asphalt surfaces. The average width of taxiways is 24 m with a minimum and maximum width of 22.5 and 31 m. TWY M is a 411 m long primary taxiway and connects main RWY 25 at 30° and main RWY 07 at 150°. TWY C1 and M are the preferred options to vacate RWY 07 and RWY 25, respectively. All taxiways are marked with designation, centerline, and holding positions. Chennai airport consists of 4 runways, RWY 12, 30, 07, and 25. The surface type, true bearing, Take-off run available (TORA), Take-off distance available (TODA), Accelerate stop distance available (ASDA), and Landing distance available (LDA) for each runway are provided in Table 1. The hourly arrival, departure, and total movements of the airport are shown in Fig. 4. The hourly arrival and departure

![Chennai airport layout](image)

**Table 1** Chennai airport runway specifications

| RWY | Surface type | True bearing (degrees) | TORA (m) | TODA (m) | ASDA (m) | LDA (m) |
|-----|--------------|------------------------|----------|----------|----------|---------|
| 12  | Concrete/Asphalt | 117.65               | 2890     | 2890     | 2890     | 2110    |
| 30  | Concrete/Asphalt | 297.65               | 2680     | 2680     | 2680     | 2680    |
| 07  | Concrete/Asphalt | 69.05                | 3661     | 3814     | 3711     | 3661    |
| 25  | Concrete/Asphalt | 249.05               | 3661     | 3721     | 3721     | 3661    |
movements on all the runways are provided in Figs. 5 and 6, respectively.

**Arrival Flow Characteristics**

Daily arrival flow counts are given in Table 2. The table suggests that Runway 07 handles more than 70% of the daily arrivals. Runway 30, 25, and 12 follows RWY07 in terms of daily arrival counts. More than 90% of the aircraft belong to the medium weight (wake) category among the arrivals. The low traffic in Runway 12-30 is attributed to the fact that these are subsidiary runways and are only used when Runway 07-25 is under maintenance. The majority of the arrivals are east-directional. The observation satisfies the geographic location of Chennai, which lies in the southwestern region of India. International arrivals are higher as compared to domestic arrivals. This observation can be attributed to the day for which the data are processed (new year). The overall observation indicates that Runway 07 has a higher propensity for congestion and delay as it handles most of the incoming traffic. Therefore, it needs greater attention to maintain runway and airspace productivity.

Table 3 provides the overall descriptive statistics of the four flow performance metrics corresponding to arrivals in each runway. The statistics suggest that RWY 07-25 serves long-distance flights as compared to Runway 12-30. This can be attributed to the higher operational efficiency of RWY 07-25. They have higher LDA resulting in a higher
degree of safety during arrivals. Hence, even though RWY 07 handles a substantial proportion of daily arrivals, they still handle long-distance flights. These observations are further substantiated based on track distance and track time observations. Aircrafts arriving at Runway 12-30 need to traverse higher track distance and track time. On the contrary, Runway 07-25 shows a lower track distance and time. Lower track distance results in lesser fuel consumption during landing hence justifies the higher counts in Table 2. However, it should be noted that lower track distance might be one of the reasons for higher flow count but not the only reason. As discussed earlier, RWY 12-30 are smaller as compare to RWY 07-25 and cannot handle heavy fights. Moreover, factors such as wind also affect the flow pattern. All these factors lead to the higher flow in RWY 07. The presence of higher standard deviation in flow metrics for arrivals in Runway 07-25 indicates increased delays, possibly resulting from the high incoming traffic.

More detailed cross-sectional descriptive analyses of arrivals are provided in Tables 4 and 5. The tables are divided based on flow directions (East-directional and West-directional). The flow metrics are further categorized based on flight wake and travel type. Tables 4 and 5 further justifies the discussion made above. A closer look indicates that Runway 07 and 25 show a higher deviation in track distance and track time for international arrivals than domestic arrivals. It indicates a higher delay for international flights during the approach on that day. The metrics for domestic arrivals are comparable; however, Runway 07 still has the least track distance and track time. The observations are further justified by observing the STAR charts of Chennai airport, as Runway 07 offers a straight course with minimal turns. For west-directional arrivals, track time is higher across all runways because of the merging and turning process before

![Fig. 6 Hourly departure movement on all the runways](image-url)

| Runway | Travel type | Domestic | International | Total count |
|--------|-------------|----------|---------------|-------------|
|        | Wake        | Heavy    | Medium        | Heavy       | Medium      |          |
|        | Direction   |          |               |             |             |          |
| 07     | E           | 0        | 46            | 10          | 74          | 130       |
|        | W           | 0        | 7             | 8           | 34          | 49        |
| 12     | E           | 0        | 3             | 0           | 2           | 5         |
|        | W           | 0        | 3             | 0           | 0           | 3         |
| 25     | E           | 0        | 13            | 0           | 6           | 19        |
|        | W           | 0        | 3             | 0           | 2           | 5         |
| 30     | E           | 0        | 26            | 0           | 3           | 29        |
|        | W           | 0        | 0             | 0           | 1           | 1         |
approaching the airport. Moreover, heavy planes traverse higher track distances across all runways. Although the inferences from Tables 4 and 5 are limited due to the small sample size in some of the categories, they provide a clear introspection into the flow characteristics of the arrivals corresponding to each runway. The overall observation substantiates the conclusion made in the Chennai airport TAAM report [26].

**Departure Flow Characteristics**

Daily departure flow counts are given in Table 6. Similar to arrivals, Runway 07-25 handles more than 80% of the daily arrivals. They are followed by Runway 30 and 25. More than 90% of the aircraft belong to the medium weight (wake) category among the departures. As discussed in the previous section, the low traffic in Runway 12-30 is attributed to the fact that these are subsidiary runways and are only used when Runway 07-25 is under maintenance. Contrary to arrivals, the majority of the departures are west-directional, owing to the geographic positioning of Chennai airport. The difference between International and Domestic departures is not substantial. Since Runway 07-25 handles most of the outgoing traffic, they have a higher tendency to face congestion and delays. Therefore, it needs greater attention to maintain runway and airspace productivity.

Table 7 provides the overall descriptive statistics of the four flow performance metrics corresponding to departures in each runway. Like arrivals, RWY 07-25 serves long-distance flights compared to Runway 12-30. This again can be attributed to the higher operational efficiency of RWY 07-25. They have higher TORA and TDA, leading to a higher degree of safety during departure. Hence, even though RWY 07 handles a substantial proportion of daily departures, they still handle long-distance flights. These observations are further substantiated based on track distance and track time observations. Runway 07-25 shows a lower track distance and time. It justifies the inferences made from overall flow counts. Lower track distance results in lesser fuel consumption during landing hence justifies the higher counts in Table 6. However, it should be noted that lower track distance might be one of the reasons for higher flow count but not the only reason. Again, RWY 12-30 are small and cannot handle heavy fights. Moreover, factors such as wind also affect the flow pattern. All these factors lead to a higher flow in RWY 07. The presence of higher standard deviation in flow metrics for departures in Runway 07-25 indicates increased delays, possibly resulting from the high outgoing traffic.

Detailed cross-sectional descriptive analyses for daily departures are provided in Tables 8 and 9. The tables are divided based on flow directions (East-directional and West-directional). Flow metrics are further categorized based on

| Table 3  | Arrival flow metric statistics for each runway |
|----------|-----------------------------------------------|
| Runway   | 07   | 12 | 25 | 30 |
|          | (N = 179) | (N = 8) | (N = 24) | (N = 30) |
| Flight distance (km) | | | | |
| Min      | 29.632 | 400.032 | 400.032 | 270.392 |
| Median   | 811.176 | 689.87 | 535.228 | 472.26 |
| Max      | 2114.984 | 825.992 | 1440.856 | 829.696 |
| Mean (Std Deviation) | 813.45 ± 364.71 | 670.42 ± 129.69 | 678.84 ± 254.54 | 500.35 ± 161.29 |
| Flight time (minutes) | | | | |
| Min      | 11 | 51 | 43 | 25 |
| Median   | 86 | 78 | 61.5 | 46.5 |
| Max      | 569 | 190 | 201 | 83 |
| Mean (Std Deviation) | 111.23 ± 77.86 | 91.75 ± 45.89 | 77.62 ± 37.74 | 48.73 ± 13.89 |
| Track distance (km) | | | | |
| Min      | 4.074 | 7.960 | 4.013 | 6.092 |
| Median   | 8.060 | 8.848 | 7.960 | 8.060 |
| Max      | 35.203 | 35.203 | 32.370 | 18.264 |
| Mean (Std Deviation) | 12.87 ± 8.73 | 15.21 ± 12.36 | 10.05 ± 7.95 | 7.65 ± 2.19 |
| Track time (minutes) | | | | |
| Min      | 1 | 11 | 8 | 5 |
| Median   | 22 | 19 | 30.5 | 15 |
| Max      | 52 | 25 | 50 | 29 |
| Mean (Std Deviation) | 22.08 ± 8.97 | 18.62 ± 4.37 | 28.04 ± 12.22 | 15.60 ± 5.93 |

N number of samples
### Table 4
Arrival flow metric statistics for east-directional flows

| Runway | Travel type | Flight distance (km) | Flight time (minutes) | Track distance (km) | Track time (minutes) |
|--------|-------------|----------------------|-----------------------|--------------------|----------------------|
|        |             | Min                  | Median                | Min                | Median               |
| 07     | Domestic    | 270.392 (N=0)        | 614.864 (N=0)         | 456.72 ± 147.8     | 11                  |
|        |             | 588.936 (N=46)       | 700.056 (N=0)         | 771.36 ± 81.01     | 53                  |
|        |             | 400.032 (N=10)       | 817.658 (N=0)         | 801.59 ± 89.49     | 88                  |
|        | International | 742.652 (N=0)         | 825.992 (N=0)         | 784.32 ± 58.93     | 65                  |
|        |             | 10 (N=3)             | 825.07 ± 22.49        | 159.0 ± 43.84      | 95.0 ± 24.16        |
| 12     | Domestic    | 746.356 (N=0)        | 768.58 (N=0)          | 694.50 ± 77.01     | 17                  |
|        |             | 833.4 (N=0)          | 825.992 (N=0)         | 784.32 ± 58.93     | 32                  |
|        |             | 1037.12 (N=46)       | 863.032 (N=0)         | 159.0 ± 43.84      | 95.0 ± 24.16        |
| 25     | Domestic    | 460.9 ± 133.10       | 460.9 ± 133.10        | 14.5 ± 7.39        | 16                  |
|        |             |                      |                       | 14.5 ± 7.39        | 16                  |
|        | International |                      |                       | 14.5 ± 7.39        | 16                  |

| Runway | Travel type | Flight distance (km) | Flight time (minutes) | Track distance (km) | Track time (minutes) |
|--------|-------------|----------------------|-----------------------|--------------------|----------------------|
| 30     | Domestic    | 270.392 (N=0)        | 614.864 (N=0)         | 456.72 ± 147.8     | 11                  |
|        |             | 588.936 (N=46)       | 700.056 (N=0)         | 771.36 ± 81.01     | 53                  |
|        |             | 400.032 (N=10)       | 817.658 (N=0)         | 801.59 ± 89.49     | 88                  |
|        | International | 742.652 (N=0)         | 825.992 (N=0)         | 784.32 ± 58.93     | 65                  |
|        |             | 10 (N=3)             | 825.07 ± 22.49        | 159.0 ± 43.84      | 95.0 ± 24.16        |
|        |             |                      |                       | 159.0 ± 43.84      | 95.0 ± 24.16        |
|        |             |                      |                       | 159.0 ± 43.84      | 95.0 ± 24.16        |

| Runway | Travel type | Flight distance (km) | Flight time (minutes) | Track distance (km) | Track time (minutes) |
|--------|-------------|----------------------|-----------------------|--------------------|----------------------|
| 07     | Domestic    | 270.392 (N=0)        | 614.864 (N=0)         | 456.72 ± 147.8     | 11                  |
|        |             | 588.936 (N=46)       | 700.056 (N=0)         | 771.36 ± 81.01     | 53                  |
|        |             | 400.032 (N=10)       | 817.658 (N=0)         | 801.59 ± 89.49     | 88                  |
| 12     | Domestic    | 746.356 (N=0)        | 768.58 (N=0)          | 694.50 ± 77.01     | 17                  |
|        |             | 833.4 (N=0)          | 825.992 (N=0)         | 784.32 ± 58.93     | 32                  |
|        |             | 1037.12 (N=46)       | 863.032 (N=0)         | 159.0 ± 43.84      | 95.0 ± 24.16        |
| 25     | Domestic    | 460.9 ± 133.10       | 460.9 ± 133.10        | 14.5 ± 7.39        | 16                  |
|        |             |                      |                       | 14.5 ± 7.39        | 16                  |
|        | International |                      |                       | 14.5 ± 7.39        | 16                  |
Table 4 (continued)

| Runway | 30 |
|---------|----|
| Travel type | Domestic | International |
| Wake | Heavy ($N = 0$) | Medium ($N = 26$) | Heavy ($N = 0$) | Medium ($N = 3$) |
| Flight time (minutes) | | | | |
| Min | – | 25 | – | 41 |
| Median | – | 45.5 | – | 57 |
| Max | – | 83 | – | 66 |
| Mean (Std Deviation) | – | 47.62 ± 14.15 | – | 54.67 ± 12.66 |
| Track distance (km) | | | | |
| Min | – | 6.092 | – | 8.06 |
| Median | – | 7.46 | – | 8.06 |
| Max | – | 18.264 | – | 8.060 |
| Mean (Std Deviation) | – | 7.59 ± 2.36 | – | 8.06 ± 0.00 |
| Track time (minutes) | | | | |
| Min | – | 6 | – | 5 |
| Median | – | 15 | – | 14 |
| Max | – | 29 | – | 14 |
| Mean (Std Deviation) | – | 15.96 ± 5.96 | – | 11.33 ± 5.51 |

$N$ no. of samples
Table 5  Arrival flow metric statistics for west-directional flows

| Runway | 07 | 12 | 25 |
|---------|----|----|----|
| Travel type | Domestic | International | Domestic | International | Domestic | International |
| Wake | Heavy (N=0) | Medium (N=46) | Heavy (N=10) | Medium (N=74) | Heavy (N=0) | Medium (N=3) | Heavy (N=0) | Medium (N=2) | Heavy (N=0) | Medium (N=13) | Heavy (N=0) | Medium (N=6) |
| Flight distance (km) | | | | | | | | | | | | |
| Min | 713.02 | 883.404 | 29.632 | 400.032 | 400.032 | 883.404 | | | | | |
| Median | 1376.03 | 1617.72 | 891.738 | 631.532 | 503.744 | 1060.27 | 631.532 | 503.744 | 1060.27 | 631.532 | 503.744 | 1060.27 |
| Max | 1442.70 | 1816.81 | 2114.98 | 679.684 | 1440.85 | 1237.13 | 503.744 | 1060.27 | 631.532 | 503.744 | 1060.27 | 631.532 |
| Mean (Std Deviation) | 1,162.7 ± 323.03 | 1,396.6 ± 418.7 | 1,125.1 ± 474.6 | 570.4 ± 149.5 | 781.5 ± 573.3 | 1,060.27 ± 250.1 | 570.4 ± 149.5 | 781.5 ± 573.3 | 1,060.27 ± 250.1 | 570.4 ± 149.5 | 781.5 ± 573.3 | 1,060.27 ± 250.1 |
| Flight time (minutes) | | | | | | | | | | | | |
| Min | 117 | 307.5 | 132.5 | 70 | 83 | 161.5 | 70 | 83 | 161.5 | 70 | 83 | 161.5 |
| Median | 117 | 307.5 | 132.5 | 70 | 83 | 161.5 | 70 | 83 | 161.5 | 70 | 83 | 161.5 |
| Max | 132 | 569 | 237 | 81 | 130 | 201 | 81 | 130 | 201 | 81 | 130 | 201 |
| Mean (Std Deviation) | 105.29 ± 30.49 | 322.75 ± 123.69 | 146.5 ± 62.38 | 69.67 ± 11.5 | 92.00 ± 34.39 | 161.5 ± 55.86 | 69.67 ± 11.5 | 92.00 ± 34.39 | 161.5 ± 55.86 | 69.67 ± 11.5 | 92.00 ± 34.39 | 161.5 ± 55.86 |
| Track distance (km) | | | | | | | | | | | | |
| Min | 7.96 | 4.07 | 4.07 | 7.96 | 7.96 | 4.71 | 7.96 | 7.96 | 4.71 | 7.96 | 7.96 | 4.71 |
| Median | 9.73 | 7.96 | 7.96 | 7.96 | 7.96 | 4.71 | 7.96 | 7.96 | 4.71 | 7.96 | 7.96 | 4.71 |
| Max | 32.37 | 32.37 | 32.37 | 32.37 | 32.37 | 4.71 | 32.37 | 32.37 | 4.71 | 32.37 | 32.37 | 4.71 |
| Mean (Std Deviation) | 15.44 ± 11.59 | 16.14 ± 13.53 | 7.85 ± 4.76 | 7.96 ± 0.00 | 16.10 ± 14.09 | 4.71 ± 0.00 | 7.96 ± 0.00 | 16.10 ± 14.09 | 4.71 ± 0.00 | 7.96 ± 0.00 | 16.10 ± 14.09 | 4.71 ± 0.00 |
| Track time (minutes) | | | | | | | | | | | | |
| Min | 14 | 17 | 5 | 15 | 16 | 8 | 15 | 16 | 8 | 15 | 16 | 8 |
| Median | 26 | 27.5 | 19 | 20 | 19 | 8.5 | 20 | 19 | 8.5 | 20 | 19 | 8.5 |
| Max | 51 | 52 | 40 | 21 | 50 | 9 | 21 | 50 | 9 | 21 | 50 | 9 |
| Mean (Std Deviation) | 30.00 ± 14.92 | 30.50 ± 13.70 | 20.29 ± 6.98 | 18.67 ± 3.21 | 28.33 ± 18.82 | 8.50 ± 0.71 | 18.67 ± 3.21 | 28.33 ± 18.82 | 8.50 ± 0.71 | 18.67 ± 3.21 | 28.33 ± 18.82 | 8.50 ± 0.71 |

Runway 30

| Travel type | Domestic | International |
|-------------|----------|---------------|
| Wake | Heavy (N=0) | Medium (N=26) | Heavy (N=0) | Medium (N=3) |
| Flight distance (km) | | | | | | | | | | | | |
| Min | - | - | - | 829.696 | | 829.696 | | 829.696 | | 829.696 | | 829.696 | |
| Median | - | - | - | 829.696 | | 829.696 | | 829.696 | | 829.696 | | 829.696 | |
| Max | - | - | - | 829.696 | | 829.696 | | 829.696 | | 829.696 | | 829.696 | |
| Mean (Std Deviation) | - | - | - | 829.696 ± 0 | | 829.696 ± 0 | | 829.696 ± 0 | | 829.696 ± 0 | | 829.696 ± 0 | |
| Flight time (minutes) | | | | | | | | | | | | |
| Min | - | - | - | 60 | | 60 | | 60 | | 60 | | 60 | |
flight wake and travel type. Tables 8 and 9 extend the inferences made from Tables 6 and 7. A closer look into the results shows that Runway 07-25 incurs a lower variance in track distance and track time for international departures than domestic departures. It indicates a higher delay for outgoing domestic flights on that day. The metrics for domestic departures are least for Runway 07 and highest for Runway 25. The observations further justified by observing the SID charts of Chennai airport, as Runway 07 offers a straight course with minimal turns. The track distance and track time are comparable for both east and west-directional flows. Heavy aircraft tend to traverse higher track distances across all runways. Like arrivals, the inferences about departures are limited due to inadequate sample size in some of the categories. However, results provide a clear introspection into the flow characteristics of the departures corresponding to each runway. The overall observation substantiates the inferences provided in the Chennai airport TAAM report [26].

**Temporal Variation of Flow Characteristics**

Analyzing the temporal variation of flow metric statistics can be instrumental in understanding the peak and off-peak hours operations. Figure 4 suggests the following peak hours. The morning peak for arrival and departure is 0200–0400 UTC and 0000–0200 UTC, respectively. The evening peak for arrival and departure is 1400–1600 UTC and 1200–1400 UTC, respectively. Based on the peaks, a day’s arrivals and departures can be categorized into three time periods: morning, evening, and off-peak. Due to reduced sample sizes for each period and space restrictions, we did not include the statistics separately for east and west-directional flows. The flow count and flow metrics for morning peak arrivals are provided in Tables 10 and 11.

The flow count and flow metrics for evening peak arrivals are provided in Tables 12 and 13.

The flow count and flow metrics for off-peak arrivals are provided in Tables 14 and 15.

Tables 10, 11, 12, 13, 14 and 15 suggest that RWY 07-25 still handles most of the arrival traffic during the peak and off-peak periods. The standard deviation of flow metrics is higher for arrivals in the evening peak period rather than the morning peak. This indicates that flights during evening peak are more susceptible to delay. During the morning peak, RWY 07-25 is more susceptible to delay due to a higher standard deviation in track metrics. The variation among track metrics (minimum, median, maximum, mean, and standard deviation) is also more uniform in the case of the morning peak. In comparison to morning peaks, evening peaks show higher track-metrics fluctuations. They also serve longer distance flights as compared to morning peaks. This justifies the higher propensity of

| Runway | Travel type | Wake | Median | Track distance (km) | Median | Track time (minutes) | Median | Mean (Std Deviation) |
|--------|-------------|------|--------|---------------------|--------|----------------------|--------|---------------------|
| 30     | Domestic    | Heavy | 60     | 7.96               | 7.96   | 19                   | 19     | 19 ± 0              |
| 30     | Domestic    | Medium| 60 ± 0 | 7.96 ± 0           | 7.96 ± 0| 19 ± 0               | 19 ± 0 |                    |

Table 5 (continued)
congestion-induced delay during the evening peak. The deviations are comparable when comparing the arrival flow metrics of peak and off-peak periods. However, the minimum, median, maximum, and mean are higher for the peak period. This suggests that higher trajectory complexity during the peak period. The standard deviation is higher in off-peak. This can be explained by the higher flow count during the off-peak. Interestingly, in all three different time periods, RWY 07-25 offers the least track distance and track time. The results also indicate that long-distance arrivals are mostly handled during the off-peak period, and peak periods accommodate short-haul flights.

The flow count and flow metrics for morning peak departures are provided in Tables 16 and 17.

The flow count and flow metrics for evening peak departures are provided in Tables 18 and 19.

The flow count and flow metrics for evening peak departures are provided in Tables 20 and 21.

Tables 16–21 suggest that RWY 07-25 handles the majority of the departures, irrespective of the time period. The standard

### Table 6 Flow count of departures

| Runway | Travel type | Domestic | International | Total count |
|--------|-------------|----------|---------------|-------------|
|        |             | Wake     |               |             |
|        |             | Heavy    | Medium        | Heavy       | Medium     |             |
| 07     | E           | 0        | 7             | 5           | 7          | 19          | 164         |
|        | W           | 0        | 60            | 9           | 76         | 145         |             |
| 12     | E           | 0        | 0             | 0           | 1          | 1           | 21          |
|        | W           | 0        | 13            | 1           | 6          | 20          |             |
| 25     | E           | 0        | 1             | 0           | 8          | 9           | 31          |
|        | W           | 0        | 16            | 0           | 6          | 22          |             |
| 30     | E           | 0        | 5             | 1           | 21         | 27          | 27          |
|        | W           | 0        | 0             | 0           | 0          | 0           |             |

### Table 7 Departure flow metric statistics for each runway

| Runway | 07 (N = 164) | 12 (N = 21) | 25 (N = 31) | 30 (N = 27) |
|--------|--------------|-------------|-------------|-------------|
| Flight distance (km) |               |             |             |             |
| Min    | 153.716      | 438.924     | 100.008     | 503.744     |
| Median | 757.468      | 564.86      | 616.716     | 716.724     |
| Max    | 1868.668     | 1676.06     | 1737.176    | 811.176     |
| Mean (Std Deviation) | 732.16 ± 344.23 | 629.94 ± 272.45 | 671.44 ± 412.42 | 688.74 ± 64.31 |
| Flight time (minutes) |             |             |             |             |
| Min    | 35           | 43          | 39          | 53          |
| Median | 106          | 74          | 106         | 110         |
| Max    | 480          | 224         | 720         | 660         |
| Mean (Std Deviation) | 120.63 ± 81.05 | 83.38 ± 39.14 | 149.03 ± 161.16 | 124.56 ± 110.92 |
| Track distance (km) |               |             |             |             |
| Min    | 1.513        | 1.513       | 5.294       | 6.084       |
| Median | 9.752        | 9.752       | 16.555      | 30.763      |
| Max    | 40.479       | 34.552      | 141.478     | 30.763      |
| Mean (Std Deviation) | 10.48 ± 6.91 | 12.44 ± 10.81 | 20.96 ± 24.39 | 29.85 ± 4.75 |
| Track time (minutes) |             |             |             |             |
| Min    | 3            | 1           | 2           | 5           |
| Median | 8            | 13          | 24          | 15          |
| Max    | 60           | 36          | 55          | 44          |
| Mean (Std Deviation) | 11.88 ± 8.89 | 16.57 ± 12.16 | 23.45 ± 12.64 | 17.00 ± 9.32 |

* N number of samples
## Table 8  Departure flow metric statistics for east-directional flows

| Runway | 07 | 12 | 25 |
|--------|----|----|----|
| Travel type | Domestic | International | Domestic | International | Domestic | International |
| Wake | | |
| | Heavy | Medium | Heavy | Medium | Heavy | Medium | Heavy | Medium | Heavy | Medium |
| | (N=0) | (N=46) | (N=10) | (N=74) | (N=0) | (N=3) | (N=0) | (N=2) | (N=0) | (N=6) |
| Flight distance (km) | | | | | | | | | | |
| Min | – | 396.328 | 1101.9 | 1687.17 | – | – | – | 1676.06 | – | 1376.03 | – | 716.72 |
| Median | – | 1377.88 | 1559.38 | 1701.98 | – | – | – | 1676.06 | – | 1376.03 | – | 738.02 |
| Max | – | 1381.59 | 1679.76 | 1868.67 | – | – | – | 1676.06 | – | 1376.03 | – | 1737.17 |
| Mean (Std Deviation) | – | 978.6 ± 502.4 | 1,458.6 ± 224 | 1,767.87 ± 90.44 | – | – | – | 1,676.06 ± 0 | – | 1376.04 ± 0 | – | 1,080.41 ± 486.91 |
| Flight time (minutes) | | | | | | | | | | |
| Min | – | 58 | 205 | 220 | – | – | – | 224 | – | 103 | – | 110 |
| Median | – | 101 | 235 | 224 | – | – | – | 224 | – | 103 | – | 117.5 |
| Max | – | 113 | 290 | 240 | – | – | – | 224 | – | 103 | – | 235 |
| Mean (Std Deviation) | – | 91.29 ± 22.22 | 250.40 ± 36.89 | 228.86 ± 7.63 | – | – | – | 224 ± 0 | – | 103 ± 0 | – | 153.62 ± 56.88 |
| Track distance (km) | | | | | | | | | | |
| Min | – | 4.96 | 4.96 | 4.96 | – | – | – | 4.96 | – | 32.37 | – | 5.29 |
| Median | – | 6.25 | 6.25 | 6.25 | – | – | – | 4.96 | – | 32.37 | – | 19.30 |
| Max | – | 37.36 | 32.37 | 32.37 | – | – | – | 4.96 | – | 32.37 | – | 141.47 |
| Mean (Std Deviation) | – | 10.42 ± 11.89 | 16.44 ± 14.55 | 9.43 ± 10.14 | – | – | – | 4.96 ± 0 | – | 32.37 ± 0 | – | 33.01 ± 45.56 |
| Track time (minutes) | | | | | | | | | | |
| Min | – | 6 | 6 | 5 | – | – | – | 14 | – | 27 | – | 4 |
| Median | – | 7 | 8 | 8 | – | – | – | 14 | – | 27 | – | 28 |
| Max | – | 60 | 27 | 28 | – | – | – | 14 | – | 27 | – | 34 |
| Mean (Std Deviation) | – | 14.57 ± 20.05 | 15.20 ± 10.80 | 10.29 ± 7.89 | – | – | – | 14.00 ± 0 | – | 27.00 ± 0 | – | 21.50 ± 12.11 |

| Runway | 30 |
|--------|----|
| Travel type | Domestic | International |
| Wake | | |
| | Heavy | Medium | Heavy | Medium |
| | (N=0) | (N=26) | (N=0) | (N=3) |
| Flight distance (km) | | | | | | | | | | |
| Min | – | 620.42 | 727.83 | 503.74 |
| Median | – | 620.42 | 727.84 | 727.84 |
| Max | – | 635.24 | 727.84 | 811.17 |
| Mean (Std Deviation) | – | 624.86 ± 6.63 | 727.84 ± 0 | 702.08 ± 63.91 |
| Travel type | Wake | Domestic |  | International |  |
|-------------|------|----------|  |               |  |
| Runway      | 30   |  |  |               |  |
| Flight time (minutes) |  |  |  |               |  |
| Min         | –    | 53       | 660 | 90             |  |
| Median      | –    | 58       | 660 | 110            |  |
| Max         | –    | 79       | 660 | 205            |  |
| Mean (Std Deviation) | –    | 62.60 ± 10.55 | 660 ± 0 | 113.81 ± 23.55 |  |
| Track distance (km) |  |  |  |               |  |
| Min         | –    | 30.76    | 30.76 | 6.08          |  |
| Median      | –    | 30.76    | 30.76 | 30.76         |  |
| Max         | –    | 32.37    | 30.76 | 30.76         |  |
| Mean (Std Deviation) | –    | 30.76 ± 0.00 | 30.76 ± 0 | 29.59 ± 5.39 |  |
| Track time (minutes) |  |  |  |               |  |
| Min         | –    | 8        | 15  | 5              |  |
| Median      | –    | 15       | 15  | 14             |  |
| Max         | –    | 26       | 15  | 44             |  |
| Mean (Std Deviation) | –    | 17.20 ± 7.60 | 15.00 ± 0 | 17.05 ± 10.06 |  |

* N no. of samples
| Runway | 07 | 12 | 25 |
|--------|----|----|----|
| Travel type | Domestic | International | Domestic | International | Domestic | International |
| Wake | Heavy | Medium | Heavy | Medium | Heavy | Medium | Heavy | Medium |
| | (N=0) | (N=46) | (N=0) | (N=74) | (N=0) | (N=3) | (N=0) | (N=6) |
| Flight distance (km) | | | | | | | | |
| Min | – | 283.35 | – | 438.92 | – | 100.01 | – | 105.56 |
| Median | – | 507.45 | – | 492.63 | – | 426.88 | – | 631.53 |
| Max | – | 775.98 | – | 638.94 | – | 748.21 | – | 783.39 |
| Mean (Std Deviation) | – | 465.3 ± 135.7 | – | 508.02 ± 69.19 | – | 468.56 ± 181.8 | – | 549.74 ± 270.21 |
| Flight time (minutes) | | | | | | | | |
| Min | – | 35 | – | 43 | – | 39 | NA | 95 |
| Median | – | 52 | – | 65 | – | 76 | NA | 122.5 |
| Max | – | 118 | – | 95 | – | 240 | NA | 720 |
| Mean (Std Deviation) | – | 56.45 ± 19.00 | – | 66.54 ± 15.69 | – | 87.62 ± 48.41 | NA | 314.33 ± 314.57 |
| Track distance (km) | | | | | | | | |
| Min | – | 7.85 | – | 10.81 | – | 16.55 | NA | 21.63 |
| Median | – | 7.85 | – | 10.81 | – | 16.55 | NA | 21.63 |
| Max | – | 27.17 | – | 34.55 | – | 27.17 | NA | 27.17 |
| Mean (Std Deviation) | – | 10.29 ± 5.98 | – | 15.46 ± 11.43 | – | 15.56 ± 8.45 | NA | 17.38 ± 9.02 |
| Track time (minutes) | | | | | | | | |
| Min | – | 4 | – | 1 | – | 3 | NA | 2 |
| Median | – | 14 | – | 16 | – | 24 | NA | 21 |
| Max | – | 51 | – | 36 | – | 55 | NA | 29 |
| Mean (Std Deviation) | – | 14.48 ± 9.55 | – | 19.00 ± 13.84 | – | 26.88 ± 13.30 | NA | 16.33 ± 10.80 |
| Runway | 30 |
|--------|----|
| Travel type | Domestic | Medium | International |
| Wake | Heavy ($N=0$) | Medium ($N=26$) | Heavy ($N=0$) | Medium ($N=3$) |
| Flight time (minutes) | | | | |
| Min | – | – | – | – |
| Median | – | – | – | – |
| Max | – | – | – | – |
| Mean (Std Deviation) | – | – | – | – |
| Track distance (km) | | | | |
| Min | – | – | – | – |
| Median | – | – | – | – |
| Max | – | – | – | – |
| Mean (Std Deviation) | – | – | – | – |
| Track time (minutes) | | | | |
| Min | – | – | – | – |
| Median | – | – | – | – |
| Max | – | – | – | – |
| Mean (Std Deviation) | – | – | – | – |

$N$ no. of samples
The deviation of flow metrics is higher for departures in the morning peak period rather than the evening peak. This indicates that flights departing during the morning peak are more susceptible to delay. Moreover, morning peaks are more congested. This is attributed to the availability of affordable ticket prices for early morning departures. The flight distance and flight time are comparable between morning and evening peaks. Interestingly, the track-metrics fluctuations (minimum, median, maximum, mean, and standard deviation) are uniform across morning and evening departure peaks. Such a case was not observed in arrivals. The deviations of departure flow metrics are not comparable between the time periods. While the minimum, median, maximum, mean, and standard deviation are higher for the off-peak period. The higher numbers can be explained by the higher count during the off-peak. Like arrivals, long-distance departures are mostly handled during the off-peak period, and peak periods accommodate short-haul flights. In addition, RWY 07-25 offers the least track distance and track time for both arrivals and departures in all three different periods. The overall results reveal that flow metrics vary during different peak periods, and, therefore, the resulting complexity will also vary.

**Research Implications and Limitations**

The flight record based descriptive analysis framework demonstrated at the TMA scale for Chennai airport can be adopted to other TMAs for a better understanding of the

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| Runway | Travel type | Domestic | International | Total count |
|--------|-------------|----------|---------------|-------------|
|        | Wake        | Heavy    | Medium        | Heavy       | Medium   |
|        | Direction   |          |               |             |          |
| 7      | E           | 0        | 3             | 2           | 10        | 15        | 19        |
|        | W           | 0        | 1             | 1           | 2         | 4         | 4         |
| 25     | E           | 0        | 3             | 0           | 1         | 4         | 4         |
|        | W           | 0        | 0             | 0           | 0         | 0         | 0         |
| 30     | E           | 0        | 6             | 0           | 0         | 6         | 6         |
|        | W           | 0        | 0             | 0           | 0         | 0         | 0         |

**Table 10** Flow count of morning peak-arrivals

| Runway | 7 (N = 19) | 12 (N = 0) | 25 (N = 4) | 30 (N = 6) |
|--------|------------|------------|------------|------------|
| Flight distance (km) | | | | |
| Min    | 270.392    | NA         | 405.588    | 270.392    |
| Median | 824.14     | NA         | 536.154    | 403.736    |
| Max    | 1594.572   | NA         | 863.032    | 748.208    |
| Mean (Std Deviation) | 827.75 ± 288.92 | NA | 585.23 ± 195.16 | 436.76 ± 180.23 |
| Flight time (minutes) | | | | |
| Min    | 30         | NA         | 43         | 33         |
| Median | 97         | NA         | 56.5       | 46         |
| Max    | 423        | NA         | 65         | 71         |
| Mean (Std Deviation) | 129.26 ± 89.11 | NA | 55.25 ± 9.54 | 49.67 ± 14.85 |
| Track distance (km) | | | | |
| Min    | 4.074      | NA         | 6.878      | 6.092      |
| Median | 7.960      | NA         | 7.960      | 6.485      |
| Max    | 22.493     | NA         | 7.960      | 18.264     |
| Mean (Std Deviation) | 12.31 ± 7.22 | NA | 7.69 ± 0.54 | 8.58 ± 4.81 |
| Track time (minutes) | | | | |
| Min    | 9          | NA         | 12         | 9          |
| Median | 24         | NA         | 27.5       | 24.5       |
| Max    | 46         | NA         | 43         | 29         |
| Mean (Std Deviation) | 26.32 ± 8.39 | NA | 27.50 ± 13.72 | 21.17 ± 7.55 |

* N number of samples
Table 12  Flow count of evening peak-arrival

| Runway | Travel type | Domestic | International | Total count |
|--------|-------------|----------|---------------|-------------|
|        |             | Heavy | Medium | Heavy | Medium |              |              |
|        | Wake |        |        |        |        |              |              |
|        | Direction |        |        |        |        |              |              |
| 7      | E     | 0     | 6      | 1     | 8      | 15            | 19            |
|        | W     | 0     | 0      | 0     | 4      | 4             | 4             |
| 25     | E     | 0     | 2      | 0     | 2      | 4             | 5             |
|        | W     | 0     | 1      | 0     | 0      | 1             | 1             |
| 30     | E     | 0     | 5      | 0     | 1      | 6             | 6             |
|        | W     | 0     | 0      | 0     | 0      | 0             | 0             |

Table 13  Evening peak-arrival flow metric statistics for each runway

| Runway | Flight distance (km) | Flight time (minutes) | Track distance (km) | Track time (minutes) |
|--------|-----------------------|-----------------------|---------------------|----------------------|
|        | Min: 270.392 (N = 19) | Min: 19 (N = 19)     | Min: 4.709 (N = 19) | Min: 14 (N = 19)     |
|        | Median: 803.768       | Median: 89           | Median: 8.060       | Median: 21           |
|        | Max: 894.516 (N = 0)  | Max: 202             | Max: 35.203 (N = 0) | Max: 41              |
|        | Mean (Std Deviation): 715.94 ± 196.13 | Mean (Std Deviation): 97.00 ± 51.83 | Mean (Std Deviation): 13.34 ± 8.40 | Mean (Std Deviation): 23.11 ± 7.65 |

| Runway | Min: 503.744 (N = 0) | Min: 47 (N = 0) | Min: 4.013 (N = 0) | Min: 8 (N = 0) |
|        | Median: 535.228 | Median: 83 | Median: 7.960 | Median: 19 |
|        | Max: 827.844 | Max: 135 | Max: 22.493 | Max: 38 |
|        | Mean (Std Deviation): 639.31 ± 164.16 | Mean (Std Deviation): 82.00 ± 34.74 | Mean (Std Deviation): 9.86 ± 7.24 | Mean (Std Deviation): 22.40 ± 12.01 |

| Runway | Mean (Std Deviation): 492.01 ± 120.57 | Mean (Std Deviation): 46.83 ± 11.74 | Mean (Std Deviation): 7.21 ± 0.98 | Mean (Std Deviation): 14.50 ± 4.32 |

N number of samples

Table 14  Flow count of off-peak arrival

| Runway | Travel type | Domestic | International | Total count |
|--------|-------------|----------|---------------|-------------|
|        |             | Heavy | Medium | Heavy | Medium |              |              |
|        | Wake |        |        |        |        |              |              |
|        | Direction |        |        |        |        |              |              |
| 7      | E     | 0     | 37     | 7     | 56     | 100            | 141            |
|        | W     | 0     | 6      | 7     | 28     | 41             | 41             |
| 12     | E     | 0     | 3      | 0     | 2      | 5              | 8              |
|        | W     | 0     | 3      | 0     | 0      | 3              | 3              |
| 25     | E     | 0     | 8      | 0     | 3      | 11             | 15             |
|        | W     | 0     | 2      | 0     | 2      | 4              | 4              |
| 30     | E     | 0     | 15     | 0     | 2      | 17             | 18             |
|        | W     | 0     | 0      | 0     | 1      | 1              | 1              |
TMA flow characteristics and behaviour. The framework allows cross-sectional comparison of runway operations and generates valuable insights about runway and TMA usage. The flow characterization can be used to diagnose delays and congestion in terminal airspace, understand the arrival and departure pattern, examine the factors that drive the selection of particular STAR/SID tracks, and discover feasible rerouting options during adverse weather situations or saturated operations. The key parameters provide extensive choices to frame the discussed interventions. For example, when a runway is oversaturated, aircraft can be re-directed to runways with comparatively similar track distance/time. The framework also provides ample freedom to observe the performance metrics at an hourly scale as well. In such cases, the presence of high variance in performance metrics on continuous operating hours may indicate lower efficiency in operations. The performance metrics categorized by different aircraft types and travel will further improve the level of airport and TMA performance assessment. Strategies and policy interventions for delay management can be devised separately for heavy or medium wake aircraft, domestic or international flights in arrivals/departures. Ultimately, the information about flows characterization obtained from the

| Runway | Flight distance (km) | Flight time (minutes) | Track distance (km) | Track time (minutes) |
|--------|----------------------|-----------------------|--------------------|---------------------|
|        | Min                  | Median                | Max                | Min                 |
|        | 29.632               | 809.324               | 2114.984           | 11                  |
|        | 400.032              | 689.87                | 825.992            | 51                  |
|        | 400.032              | 535.228               | 1440.856           | 50                  |
|        | 270.392              | 824.6 ± 389.8         | 829.696            | 25                  |
|        |                      |                      |                   |                     |
|        | Mean (Std Deviation) |                      |                   |                     |
|        | 824.6 ± 389.8        |                      |                   |                     |
|        |                      |                      |                   |                     |
|        |                      |                      |                   |                     |
| Runway | Travel type | Domestic | International | Total count |
|        | Wake | Heavy | Medium | Heavy | Medium |
|--------|------|-------|--------|-------|--------|
| 7      | E    | 0     | 0      | 0     | 1      | 1      | 18  |
|        | W    | 0     | 4      | 0     | 13     | 17     |
| 12     | E    | 0     | 0      | 0     | 0      | 0      | 3   |
|        | W    | 0     | 2      | 0     | 1      | 3      |     |
| 25     | E    | 0     | 0      | 0     | 0      | 0      | 2   |
|        | W    | 0     | 2      | 0     | 0      | 2      |     |
| 30     | E    | 0     | 2      | 0     | 3      | 5      | 5   |
|        | W    | 0     | 0      | 0     | 0      | 0      |     |
flight records may contribute to developing new strategies and decision support tools for efficient ATM.

Like any other research, this paper has its limitations. The primary limitation in this study is the availability of a small sample size in daily arrival and departure flows. This has led to the absence of metrics statistics in the cross-sectional observations. Hence, it limits the extent to which we can explore the flow characteristics. The limitations are primarily attributed to the traffic volume at Chennai airports, which are considerably lower than major airports worldwide. Generalizing the conclusions and findings from this study based on one day data remain another challenge. However, it is expected that studying the flow characteristics for a day can be appropriate making planning strategies for TMA airspace management. TMA airspace management heavily relies on TMA flow and contributes significantly to controller workload [28]. Studies show that airspace management and planning can no longer be for the peak period but must consider the whole day [29, 30]. The workload calculation and management strategies are majorly dependent on the flow characteristics of a day [29, 30]. These characteristics include the Total number of aircraft, Traffic mix, Airway configuration, Aircraft flight direction, Flow entropy, Amount of

| Runway | Flight distance (km) | Flight time (minutes) | Track distance (km) | Track time (minutes) |
|--------|---------------------|-----------------------|---------------------|----------------------|
|        | Min                 | Median                | Min                 | Median              |
| 7      | 288.912             | 755.41 ± 312.9        | 4.323               | 9.94 ± 5.91         |
|        | 43                  | 116                   | 43                  | 4                   |
|        | 248.924             | 751.77 ± 122.9        | 2.469               | 19.67 ± 15.57       |
|        | 55                  | 73                    | 87                  | 17                  |
| 12     | 757.468             | 481.52 ± 81.19        | 4.323               | 9.94 ± 5.91         |
|        | 116                 | 91                    | 12.00               | 20                  |
|        | 442.628             | 714.872               | 12.20               | 20                  |
|        | 87                  | 91                    | 12.20 ± 6.15        | 20                  |
|        | 25                  | 95                    | 12.20 ± 6.15        | 20                  |
|        | 255                 | 255                   | 30.76 ± 0.00        | 22.20 ± 12.91       |
| 25     | 1857.556            | 685.24 ± 52.94        | 27.179              | 30.76 ± 0.00        |
|        | 225                 | 225                   | 16.555              | 30.76 ± 0.00        |
|        | 653.756             | 727.836               | 27.179              | 30.76 ± 0.00        |
| 30     | 1857.556            | 685.24 ± 52.94        | 27.179              | 30.76 ± 0.00        |
|        | 225                 | 225                   | 16.555              | 30.76 ± 0.00        |
|        | 653.756             | 727.836               | 27.179              | 30.76 ± 0.00        |

N number of samples

| Runway | Travel type | Domestic | International | Total count |
|--------|-------------|----------|---------------|-------------|
|        |             | Heavy    | Medium        |             |
|        |             | Heavy    | Medium        |             |
| 7      | E           | 0        | 0             | 1           |
|        | W           | 0        | 12            | 3           |
| 12     | E           | 0        | 0             | 0           |
|        | W           | 0        | 2             | 0           |
| 25     | E           | 0        | 0             | 1           |
|        | W           | 0        | 3             | 1           |
| 30     | E           | 0        | 1             | 2           |
|        | W           | 0        | 0             | 0           |

Table 17 Morning peak-departure flow metric statistics for each runway

Table 18 Flow count of evening peak-departure

N number of samples

Like any other research, this paper has its limitations. The primary limitation in this study is the availability of a small sample size in daily arrival and departure flows. This has led to the absence of metrics statistics in the cross-sectional observations. Hence, it limits the extent to which we can explore the flow characteristics. The limitations are primarily attributed to the traffic volume at Chennai airports, which are considerably lower than major airports worldwide. Generalizing the conclusions and findings from this study based on one day data remain another challenge. However, it is expected that studying the flow characteristics for a day can be appropriate making planning strategies for TMA airspace management. TMA airspace management heavily relies on TMA flow and contributes significantly to controller workload [28]. Studies show that airspace management and planning can no longer be for the peak period but must consider the whole day [29, 30]. The workload calculation and management strategies are majorly dependent on the flow characteristics of a day [29, 30]. These characteristics include the Total number of aircraft, Traffic mix, Airway configuration, Aircraft flight direction, Flow entropy, Amount of

| Runway | Travel type | Domestic | International | Total count |
|--------|-------------|----------|---------------|-------------|
|        |             | Heavy    | Medium        |             |
|        |             | Heavy    | Medium        |             |
| 7      | E           | 0        | 0             | 1           |
|        | W           | 0        | 12            | 3           |
| 12     | E           | 0        | 0             | 0           |
|        | W           | 0        | 2             | 0           |
| 25     | E           | 0        | 0             | 1           |
|        | W           | 0        | 3             | 1           |
| 30     | E           | 0        | 1             | 2           |
|        | W           | 0        | 0             | 0           |
The flight distance, flight time, track distance, and track time metrics give a simplified measure of most of these metrics. Therefore, we are positive that the implications and findings of this study, even if based on a single day, have practical implications on TMA airspace management and can be generalized. Additionally, future efforts may focus on solving fuel optimization models, schedule allocation problems, and maximizing runway utilization based on the inferences obtained from studying the flow characteristics.

A clear road map and way forward is to use the inferences on track and flow metrics obtained from this methodological framework in formulating arrival and departure scheduling problems. Two critical ATM strategies in TMA are (i) departure/taxiway sequencing and scheduling and (ii) arrival sequencing and scheduling. The knowledge of track metrics and their variation can serve as input constraints to both types of problems. These inputs can come as holding time, travel time, travel distance, etc. Since the cross-sectional description will be available, the values of track-metrics offer the observed performance

| Runway | 7(N = 16) | 12(N = 2) | 25(N = 5) | 30(N = 3) |
|--------|-----------|-----------|-----------|-----------|
| Flight distance (km) | | | | |
| Min | 285.208 | 609.308 | 424.108 | 627.828 |
| Median | 509.3 | 624.124 | 716.724 | 716.724 |
| Max | 1692.728 | 638.94 | 755.616 | 727.836 |
| Mean (Std Deviation) | 598.77 ± 328.73 | 624.12 ± 20.95 | 612.64 ± 171.82 | 690.80 ± 54.81 |
| Flight time (minutes) | | | | |
| Min | 37 | 55 | 65 | 58 |
| Median | 54.5 | 56.5 | 106 | 110 |
| Max | 220 | 58 | 118 | 120 |
| Mean (Std Deviation) | 71.75 ± 46.25 | 56.50 ± 2.12 | 97.20 ± 21.30 | 96.00 ± 33.29 |
| Track distance (km) | | | | |
| Min | 2.469 | 10.806 | 7.853 | 30.763 |
| Median | 6.887 | 18.992 | 7.853 | 30.763 |
| Max | 32.370 | 27.179 | 21.635 | 30.763 |
| Mean (Std Deviation) | 9.85 ± 7.17 | 18.99 ± 11.58 | 12.35 ± 6.41 | 30.76 ± 0.00 |
| Track time (minutes) | | | | |
| Min | 4 | 25 | 21 | 15 |
| Median | 9 | 25.5 | 24 | 26 |
| Max | 29 | 26 | 55 | 29 |
| Mean (Std Deviation) | 12.06 ± 8.96 | 25.50 ± 0.71 | 30.60 ± 13.94 | 23.33 ± 7.37 |

N number of samples

Table 20: Flow count of off-peak departure

| Runway | Travel type | Domestic | International | Total count |
|--------|-------------|----------|---------------|-------------|
|        |             | Heavy | Medium | Heavy | Medium |
|        |             | Wake Direction | 7 | E | 0 | 7 | 5 | 5 | 17 | 130 |
|        |             | W | 0 | 44 | 9 | 60 | 113 |
|        |             | 12 | E | 0 | 0 | 0 | 1 | 1 | 16 |
|        |             | W | 0 | 9 | 1 | 5 | 15 |
|        |             | 25 | E | 0 | 1 | 0 | 7 | 8 | 24 |
|        |             | W | 0 | 11 | 0 | 5 | 16 |
|        |             | 30 | E | 0 | 2 | 1 | 16 | 19 | 19 |
|        |             | W | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
Characteristics of TMA. This will enable researchers to obtain more practical solutions to the discussed problems.

Summary and Conclusions

This paper proposes a flight record driven descriptive framework for a better understanding of TMA traffic behaviour. The study applies four key performance metrics, flight distance, flight time, track distance, and track time, which can be used for simplified analysis and characterization of air traffic flows in TMA. This paper also proposed a framework to extract these parameters from the well-documented flight record through a three-step methodology; (i) SID and STAR track assignment—gives the set of STAR or SID track points traversed by each arrival or departure in the flight record; (ii) Runway allocation—assigns runways to any particular arrival or departure in the flight record; (iii) Flow characterization—perform cross-sectional descriptive analysis (minimum, maximum, median, mean and standard deviation) of the flow metrics. We investigated the flow counts, operational and performance differences of arrival and departures in the TMA with this systematic descriptive approach. The results suggested that Runway 07-25 handles more than 80% of the daily arrivals and departures. Interestingly, this runway pair generally serves short-distance flights as compared to Runway 12-30. The results also highlighted that Runway 07-25 has a higher propensity to congestion and delay as it handles most incoming and outgoing traffic. This high traffic is attributed to the lower track distance and track time, leading to lesser fuel consumption. Lower metrics for Runway 07-25 are due to straight course with minimal turns, as documented in SID and STAR charts of Chennai airport. Finally, the track distances vary with aircraft wake, as heavier aircraft tend to traverse longer tracks. Moreover, the variances in track distance and track time indicate the overall operation delays.

The results and discussions have an important implication on TMA traffic management. An extensive understanding of the performance metric statistics will enable authorities to diagnose delays and congestion in terminal airspace, understand the arrival and departure pattern, examine the factors that drive the selection of particular STAR/SID tracks, and discover feasible rerouting options during adverse weather situations or saturated operations. These interventions are instrumental in improving flight efficiency in the TMA. Although the results are limited due to the small sample size, the framework is easy to comprehend and provides ample scope to increase the level of airport and TMA performance through a simple descriptive analysis of key parameters. The implications from this study can help

Table 21 Off peak-departure flow metric statistics for each runway

| Runway | 7 (N = 130) | 12 (N = 16) | 25 (N = 24) | 30 (N = 19) |
|--------|------------|------------|------------|------------|
| Flight distance (km) | | | | |
| Min | 153.716 | 440.776 | 100.008 | 503.744 |
| Median | 757.468 | 563.934 | 650.978 | 722.28 |
| Max | 1868.668 | 1676.06 | 1737.176 | 811.176 |
| Mean ± Std Deviation | 745.36 ± 349.00 | 652.83 ± 305.89 | 699.52 ± 460.13 | 689.33 ± 70.80 |
| Flight time (minutes) | | | | |
| Min | 35 | 43 | 39 | 53 |
| Median | 106 | 79 | 110 | 110 |
| Max | 480 | 224 | 720 | 660 |
| Mean ± Std Deviation | 127.26 ± 85.53 | 89.19 ± 43.00 | 164.67 ± 180.73 | 138.68 ± 129.71 |
| Track distance (km) | | | | |
| Min | 1.513 | 1.513 | 5.294 | 6.084 |
| Median | 9.752 | 9.752 | 21.635 | 30.763 |
| Max | 40.479 | 34.552 | 141.478 | 30.763 |
| Mean ± Std Deviation | 10.77 ± 7.23 | 11.83 ± 10.73 | 23.48 ± 27.16 | 29.46 ± 5.66 |
| Track time (minutes) | | | | |
| Min | 3 | 1 | 2 | 5 |
| Median | 8.5 | 11 | 22.5 | 14 |
| Max | 60 | 36 | 45 | 30 |
| Mean ± Std Deviation | 12.12 ± 9.23 | 14.88 ± 12.21 | 22.25 ± 12.66 | 14.63 ± 7.90 |

N number of samples
in the development of particular alternative solutions for TMA traffic management.

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