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Research article

Research on en route capacity evaluation model based on aircraft trajectory data

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Abstract: For the sake of refined assessment of airspace operation status, improvement of the en route air traffic management performance, and alleviation of the imbalance of demand-capacity and airspace congestion, an en route accessible capacity evaluation model (based on aircraft trajectory data) is proposed in this paper. Firstly, from the perspective of flux, the en route capacity is defined and expanded from a two-dimensional concept to a three-dimensional concept. Secondly, based on the indicators of spatial flow and instantaneous density, an evaluation model of en route capacity is given. Finally, a case study is performed to validate the applicability and feasibility of the model. Results show that the en route accessible capacity, instantaneous density, and spatial flow can describe the temporal and spatial distribution of air traffic flow more precisely, as compared to the conventional indicators, such as route capacity, density, and flow. The proposed model envisages three innovations: (i) the definition of airspace accessible capacity with reference to capacity of road traffic, (ii) the computation model for flux-based airspace accessible capacity and en route accessible capacity, and (iii) two indicators of en route characteristics named instantaneous density and spatial flow are introduced for evaluating the micro-state of the en route. Furthermore, because of the capacity depiction of the spatial and temporal distribution of air traffic congestion within an airspace unit, this model can also help air traffic controllers balance the distribution of traffic flow density, reduce the utilization rate of horizontal airspace, and resolve flight conflicts on air routes in advance.

Keywords: airspace assessment; en route accessible capacity; flight density; air traffic flow; flux

1. Introduction

As stated in the report issued by the Aviation Industry Corporation of China, the revenue passenger kilometer (RPK) will increase to 3.3 trillion passenger kilometers by the year 2039, which is 175% more than in 2019 with an average annual growth of 5.3% in China. It is also predicted that the air traffic demand in China continues to outpace the ability of the air transportation system to provide adequate services [1]. These statistics implies that the air traffic management (ATM) system is under significant stress, and will be challenged to handle the imbalance of demand-capacity and flight delays, which may cause safety and congestion issues in the future. As such, it is critical to improve the performance of ATM system from the aspects of increasing capacity and efficiency of the airspace, such as terminal maneuvering area (TMA) and area control center (ACC). Compared with TMA, the en route traffic congestion in ACC becomes more and more prominent in crowded airspace around the world [2]. Therefore, the utilization of en route resources and the evaluation of en route operation status have very practical significances. Recently, the issue of en route capacity has attracted considerable attention in the academic literature [3−11]. Nevertheless, most researchers address the structural optimization of airspace or novel operation strategies, and not the issues of en route capacity improvement from the perspective of establishment of precise evaluation approaches (they are rarely discussed in current studies). Another motivation for this paper is that scholars and experts at home and abroad usually use airspace capacity, flow, and other indicators to evaluate or measure the airspace status [12−19]. Airspace capacity is an overall inter area quantity, which quantifies the overall service capacity or congestion characteristics of an airspace unit. Nonetheless, air traffic controllers (ATCO) command the aircraft flow, based on the parameters of hourly flow or flight rate in minutes. Therefore, airspace capacity and other indicators cannot accurately describe the airspace operation status. Furthermore, to the best of the author's knowledge, no finely en route evaluation model with aircraft historical trajectory data has been comprehensively analyzed yet.

The primary goal of our research is to present an en route capacity evaluation model to more precisely describe the en route congestion situation, alleviate the imbalance of demand-capacity and airspace congestion, and promote the improvement of the en route air traffic management performance in the long run. Thus, an en route capacity evaluation model based on aircraft trajectory data is proposed in this paper. The main developments are summarized as follows: (i) development of the computation model for flux-based airspace accessible capacity; (ii) introduction of two indicators for evaluating the micro state of the en route. Finally, a real-world case study is promoted to demonstrate the validity of the proposed approach, and the comparison is conducted between these metrics and the conventional indicators, such as route capacity, density, and flow.

The remainder of this paper is organized as follows: Section 2 discusses previous related work and presents the contributions of this paper, Section 3 demonstrates the proposed en route capacity assessment model with two indicators, while Section 4 describes the results of the application of the proposed model. Finally, Section 5 summarizes the research conclusions and provides directions for future study.

2. Literature review

The capacity in the air traffic system can be expressed as the maximum number of aircraft services provided per unit time by the airspace units, such as runway, ATC sector, air routes, and TMA.

Although there is a lot of research on the capacity evaluation for the runway, the focus of this paper is on the airspace capacity evaluation model, so the literature on runway capacity evaluation will not be discussed in this section. Currently, the capacity evaluation methods of the air traffic system mainly includes mathematical model analysis, historical data analysis and fitting, computer simulation calculation, and controller workload evaluation.

The method of analysis and fitting, based on historical data, is to fit the airspace capacity experience curve on the basis of historical operating experience data, determine the maximum capacity point, and obtain the operating capacity [20,21]. This approach requires a large amount of data to obtain the estimated capacity from the appearance, and the evaluation results have a great relationship with the quality of sample collection. In addition, the evaluation method, based on computer simulation calculation, is a reproduction of the actual operation state, which can objectively evaluate the airspace from the micro scale to obtain the airspace capacity evaluation value [22]. Further, many excellent fast simulation models have emerged in recent years, such as SIMMOD, TAAM, and Air Top [23,24]. They all belong to microscopic, dynamic, and comprehensive airport simulation software, which can simulate the operation of aircraft on various parts of airspace and airports, but also require more detailed portrayal and coupling of each functional module. Research on capacity assessment, based on human factor methods, has focused on the impact of controller workload limitations on capacity. After Noriyasu proposed the controller workload-based sector capacity assessment method, scholars have successively proposed and improved the controller behavior model, sector environment model, and workload model [25]. The controller behavior model, sector environment model, and workload model have been developed and refined, and the controller workload measurement and sector delineation have been combined to optimize the workload. Reinhardt et al. considered the workload of controllers as one of the important factors affecting air traffic capacity, so a controller assistant tool (Cato) was proposed to improve its work efficiency, and increase air traffic capacity [26].

The capacity assessment method based on mathematical modeling is one of the earlier and more commonly used capacity assessment methods of today. As being utilized in this paper, the main overview analysis of the method is presented below. Hu Yong considered two objective and subjective factors: sector controller load and airline network operation, which introduced two characteristic indexes: control load degree and network saturation degree, and established a sector capacity model. Using a combination of mathematical modeling and system simulation, a sector capacity simulation evaluation method is proposed [27]. Chang et al. discussed the impact of convective weather on capacity reduction. The stochastic programming models for the single sector air traffic flow management problem have been introduced for improving the efficiency of the air transportation system [28]. Sunil et al. believed that, not only will the airspace structure affect the air traffic capacity, but the air traffic structure will also have an impact on the traffic capacity, where the relationship between the air traffic structure and the traffic capacity can be deduced from the influence of the change of traffic demand on the measurement of safety, efficiency, and stability [29]. Zhang proposed a handover workload classification and measurement method for sector handover point capacity assessment, based on controller handover workload, and used Dempster's synthetic law to integrate the impact of each factor on sector handover point capacity, and adjusted the capacity value based on evidence theory [30]. Hoekstra et al. focused on the influence of airspace design on air traffic capacity, and used algebraic methods to determine the relationship between layered airspace design parameters and air traffic capacity [31]. Çetek et al. proposed a route multi entry point allocation model based on genetic algorithm from the perspective of aircraft access path. The available single entry point sector configuration and its multiple entry point assignment alternatives were compared for various traffic scenarios. Multiple entry point configurations provided up to 10% increase in throughput, and significant reductions in average delay per aircraft compared to the single point entry configuration [32]. Ellerbroek et al. proposed the relationship between decentralized airspace conceptual structure and traffic capacity, and derived the relationship model between traffic stability and capacity. The results indicate that the predictions of the analytical model are close to that of the previous semi-empirical approach. Thus, the analytical model can be used to obtain a first-order estimate of the maximum theoretical capacity [33]. Chen et al. established a model from the perspective of traffic speed to balance route traffic demand to maximize route traffic volume, and solved a flow optimization problem for enforcing capacity constraints with the minimum operational cost using a dual decomposition method [34]. Wang et al. analyzed the capacity of route network nodes under different configurations from the perspective of route structure. According to flight plans and the direction of air routes, they confirmed the location, quantity, and congestion of 93 nodes, providing the 3 most congested nodes and 4 flight information regions, and put forward the method to improve the node capacity [35]. Wang et al. studied the capacity of the terminal area approach route intersection, analyzed the capacity of the terminal area approach route intersection from the perspective of aircraft and route, and discussed in depth the impact of aircraft flight speed, aircraft type combination, and route angle on the capacity [36]. Wang et al. established a sector static capacity model to quantify the various effects of weather, and proposed a dynamic sector capacity model from the perspective of controller load to study the dynamic and static sector capacity [37,38].

In a nutshell, this research focused primarily on the analysis of the conventional concept of capacity and related indicators in the field of airspace capacity evaluation study. However, very little of them considered the essence of the airspace capacity from the point view of controllers, and the metrics which can depict en route characteristics spatiotemporally are rarely discussed. In addition, the historical trajectory data of aircraft are not commonly used to deal with the problem of capacity assessment method based on mathematical modeling. Finally, a very limited number of studies have been found for the TMA and en route scenario in the research aspects of capacity evaluation. To this end, this paper aims to propose a computational model for en route accessible capacity and related indicators that can evaluate the micro state of the en route.

3. Methodology

Currently, the en route indicators proposed by most researches mostly depict the overall traffic characteristics of the routes, such as capacity, flow, density, etc. To more precisely describe the congestion situation inside the route, this section first introduces the definition of airspace accessible capacity with reference to capacity of road traffic, and then determines the computation model for flux-based airspace accessible capacity, and finally analyzes the calculation formula of en route accessible capacity in combination with the specific characteristics of the route. In addition, two indicators for evaluating the micro state of the en route are proposed to reflect the complex relationship between the internal structure of the route and the traffic flow from different aspects.

3.1. Definition of airspace accessible capacity

In the field of road traffic, capacity characterizes the ability of a road to divert or handle traffic flow. Referring to the theory of road traffic capacity, we define airspace accessible capacity in air traffic management as the maximum volume of traffic per unit time passing through a given cross section in the airspace, on the premise of ensuring the minimum safety separation between aircrafts. Therefore, airspace accessible capacity is a spatiotemporal related multi-dimensional value, which can be defined by establishing three-dimensional cross sections.

In contrast to traditional airspace capacity, which is an overall existing interval volume of the airspace, the airspace accessible capacity is the maximum amount of traffic for the actual operating process at a point or section. Consequently, the threshold of airspace accessible capacity is the key to judge whether the traffic is congested or not.

3.2. Notations

To facilitate the model elaboration, the notations and definitions used hereafter are summed up in Table 1.

Table 1. Parameters and notations.

Parameters	Explanations	Unit
ϕ	Flux of the flow field	/
W	Capacity of a designated airspace or air route	/
v	Velocity of the fluid	$\frac{m}{s}$
S	Area of the cross section of a designated airspace or air route	m^2
n	Normal of the surface	/
θ	Angle between velocity and normal line of the surface	º
v_1	Average speed of aircrafts that enter the airspace cross section	$\frac{m}{s}$
v_2	Average speed of aircrafts that exit the airspace cross section	$\frac{m}{s}$
ρ	Density of air traffic flow near the cross section	$\frac{flights}{m^3}$
A	Width of the air route	m
H	Minimum vertical separation of aircraft	m
D	Minimum longitudinal separation of aircraft	m
L	Number of flight levels available for aircraft	/
N	Number of aircraft passing through the cross section in a given time	/
v_i	Fractional speed along the route direction of the i^{th} aircraft	$\frac{m}{s}$
ρ_i	Density of air traffic flow at the location of the i^{th} aircraft	$\frac{flights}{m^3}$
D_i	Longitudinal separation between the i^{th} aircraft and its succeeding aircraft	m
T_i	Time interval between the i^{th} aircraft and its succeeding aircraft	s
$S(t, x)$	En route state function	/

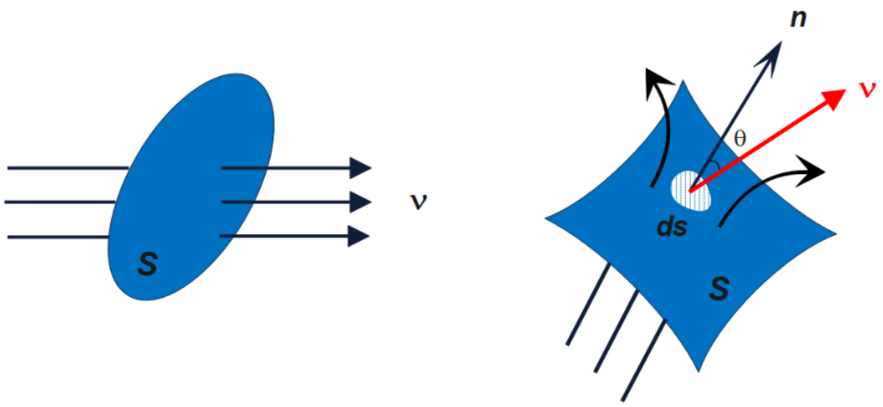
Continued on next page

Parameters	Explanations	Unit
$q(x_0)$	En route spatial flow	$flights/minute$
$\rho(t_0)$	En route instantaneous density	$flights/km/S$
x_0	Position of the en route cross section	m
t_0	Designated time	/

3.3. Computation model of airspace accessible capacity based on flux

In physics, the spatio-temporal distribution of a physical quantity is often referred to as a field. A vector field, the most common type of field, is a vector quantity that exists at various points in space, and whose magnitude and direction are a function of spatial position and time. If a vector field does not vary with time, its magnitude and direction are functions of spatial position. In fluid dynamics, the velocity v is a vector point function, i.e., each point in the fluid has a definite velocity v, and the whole fluid is a velocity field.

As shown in Figure 1(a), if a plane S is made perpendicular to the flow velocity in a uniform flow field, then $v * S$ represents the flow rate per unit time through the section, that is, the flux ϕ. Figure 1(b) displays the non-uniform flow velocity field with the arbitrary curved surface S. If any small surface element on the surface is dS, θ is the angle between the flow velocity v and the normal n of the surface element there, and the volume of fluid flowing through the surface element dS per unit time is $v * dS$, then the flux ϕ through the whole surface equals to $\iint_S \vec{v}\, d\vec{S}$.



(a) Uniform flow velocity field (b) Non-uniform flow velocity field

Figure 1. Schematic diagram of flow velocity field.

Since the concept of airspace accessible capacity is similar to the concept of vector field flux in field theory, the defining equation of flux-based airspace accessible capacity is presented as follows,

$$W = \rho * \left(\left|\iint_S \overrightarrow{v_1} d\vec{s}\right| + \left|\iint_S \overrightarrow{v_2} d\vec{s}\right|\right) \tag{1}$$

where W refers to the airspace accessible capacity; S is the area of the given cross section; v_1 and v_2 represents the average speed of the aircraft penetrating into and out of the cross section; ρ means the density of traffic flow in the airspace near the cross section.

From Eq (1), it can be seen that the positive and negative results of the flux-based airspace accessible capacity are related to the magnitude of the selected area element and the angle of the velocity direction. The purpose of taking the absolute value of the integral of the surface in the formula is to ensure that the calculation result is positive, and its original positive or negative value is irrelative to the meaning of the model. Additionally, it can be concluded that the essence of the computation model for flux-based airspace accessible capacity is to calculate the volume of traffic flow per unit time through a given cross section, multiply it by the traffic fluid density, and finally obtain the number of aircraft per unit time through the cross section.

Furthermore, compared to airspace capacity, the flux-based airspace accessible capacity evaluates the spatial and temporal distribution of air traffic congestion within an airspace unit, not just the overall measurement of the airspace.

3.4. Computation model of en route accessible capacity

Air routes are one of the most commonly used airspace units in aircraft operations. In this subsection, the computation model of en route accessible capacity will be established based on the definition of airspace accessible capacity proposed in Section 3.3. Moreover, the vector calculation method discussed in Section 3.3 can be simplified to a numerical calculation approach, due to the simplicity of the computation model of the en route accessible capacity.

For the convenience of calculation, several assumptions are made:

- The shape of the en route cross section is rectangular, and the width of the rectangle A equals to width of the route.
- The en route traffic flow is evenly distributed.
- Aircraft are not allowed to change their flight levels.
- Aircraft fly with minimum vertical separation, H, and minimum longitudinal separation, D.

Based on the above assumptions and illustrations, the en route accessible capacity can be derived according to the following steps.

1) Firstly, determine the number of flight levels for a given cross section of the aircraft crossing the air route. As L flight levels form $L-1$ interlayers, the number of flight levels L is formulated as follows,

$$L = \frac{S}{H*A} + 1 \tag{2}$$

2) Secondly, the density of air traffic flow, i.e., the number of aircraft per unit volume, is calculated. While there is one, and only one, aircraft per unit longitudinal safety separation, the linear density of air traffic flow is $\frac{1}{D}$. When the air route is operating at full capacity with an aircraft on each available flight level, the air traffic flow density ρ is

$$\rho = \frac{L}{D*S} \tag{3}$$

3) Finally, by multiplying the volume of air traffic flow passing through a given cross section per unit time with the volume density, the en route accessible capacity can be obtained as follows,

$$W = v * S * \rho = \frac{L * v}{D} \tag{4}$$

Obviously, in the actual operation of aircraft, the ideal situation described above does not exist in most cases. With a view to resolving conflicts or reducing congestion, ATCO will direct en route aircrafts to perform lateral offsets or path stretches, in addition to providing instructions for altitude and speed adjustments.

In the cuboid airspace exhibited in Figure 2, the blue lines represent two air routes, and the red lines are the different flight trajectories of multiple aircrafts on the routes. As can be seen from Figure 2, the actual flight trajectory of the aircraft is not always consistent with the direction of the route when it passes through a given red, translucent cross section. Thus, the product of the velocity vector and the cross section vector is not equal to the product of the two norms. This means it will be very troublesome to use Eq (1) to compute the en route accessible capacity for the actual operation.

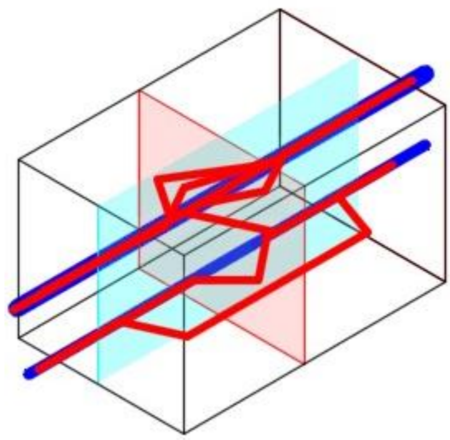


Figure 2. Schematic diagram of actual en route traffic flow.

In order to solve the problem, this paper uses the orthogonal decomposition method of mechanical motion to decompose the motion of aircrafts on the air route into three sub-motions: The sub-motions along the route direction, perpendicular to the route direction at the same altitude, and vertical direction, where the velocity direction of the first sub-motion is perpendicular to the given cross section, and the velocity direction of the last two sub-motions are parallel to the given cross section, respectively. Then, the original Eq (1) can be transferred into Eq (5),

$$W = \frac{S}{N} * \sum_{i=1}^{N} \rho_i * |v_i| = \frac{S}{N} * \sum_{i=1}^{N} \frac{|v_i|}{S * D_i} = \frac{1}{N} * \sum_{i=1}^{N} \frac{1}{T_i} \tag{5}$$

where N is the total number of aircraft passing through the en route cross section in a given time; v_i is the fractional speed along the route direction when the i^{th} aircraft passes through the cross section; ρ_i is the air traffic flow density at its location of the i^{th} aircraft; D_i is the longitudinal separation between the i^{th} aircraft and its succeeding aircraft; T_i is the time interval between the i^{th} aircraft and its succeeding aircraft.

3.5. *En route spatial flow and instantaneous density*

The en route accessible capacity proposed in this paper is a parameter related to the cross section of the air route, which is an assessment and description of the traffic congestion inside the route. In order to provide a more detailed portrayal of the internal characteristics of the en route, this subsection introduces two indicators of en route spatial flow and instantaneous density on the basis of en route accessible capacity.

The en route spatial flow is specified as the number of aircraft passing through a certain cross section or a certain point in a given time. In consequence, the en route accessible capacity is the maximum value of the en route spatial flow.

The en route instantaneous density is defined as the number of aircrafts in a given unit space, plane, or length at a certain time.

In order to facilitate the figuring of these two indicators, an en route state function $S(t, x)$ is proposed, which represents the number of aircraft on the route at the position with coordinate x at time t.

Accordingly, the en route spatial flow $q(x_0)$ can be expressed as Eq (6),

$$q(x_0) = \frac{\sum_{t \in (t_1, t_2)} S(t, x_0)}{\Delta t} \tag{6}$$

where x_0 denotes the position of the en route cross section; (t_1, t_2) means the given time interval. In most cases, the flight time of aircrafts in a certain segment of the route will not exceed 1 hour. As a consequence, when $\Delta t = 1h$ and the traffic flow reaches its peak, the number of aircrafts passing through any cross section is equal to the number of aircrafts passing through the entire route. Hence, the maximum hourly en route spatial flow is equivalent to the maximum hourly flow of the route as a whole.

Similarly, the en route instantaneous density $\rho(t_0)$ can be formulated as Eq (7),

$$\rho(t_0) = \frac{\sum_{x \in (x_1, x_2)} S(t_0, x)}{\Delta x} \tag{7}$$

where t_0 is the designated time; (x_1, x_2) is the given length of the route. When Δx is taken as the total length of the route, the en route instantaneous density is the same as the overall density of the route.

4. Case study

4.1. *Data selection*

To analyze the characteristics of the proposed en route accessible capacity, spatial flow, and instantaneous density, this paper takes one route from the Xi'an control area in the northwest of China as the case study. The selected route is part of air route G212 from waypoints WJC to OKVUM, whose length is 128 kilometers and magnetic course is 57 degrees, as shown in Figure 3.

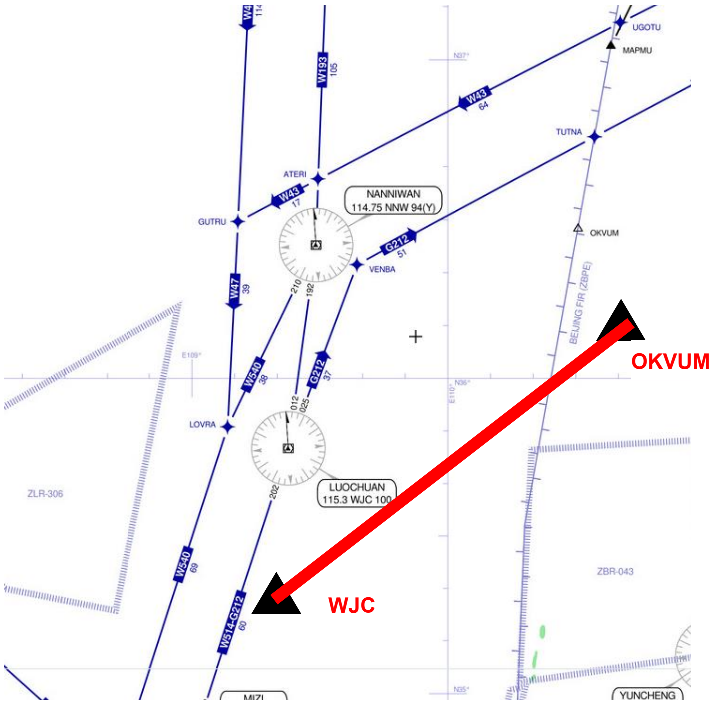


Figure 3. Route selected in the case study.

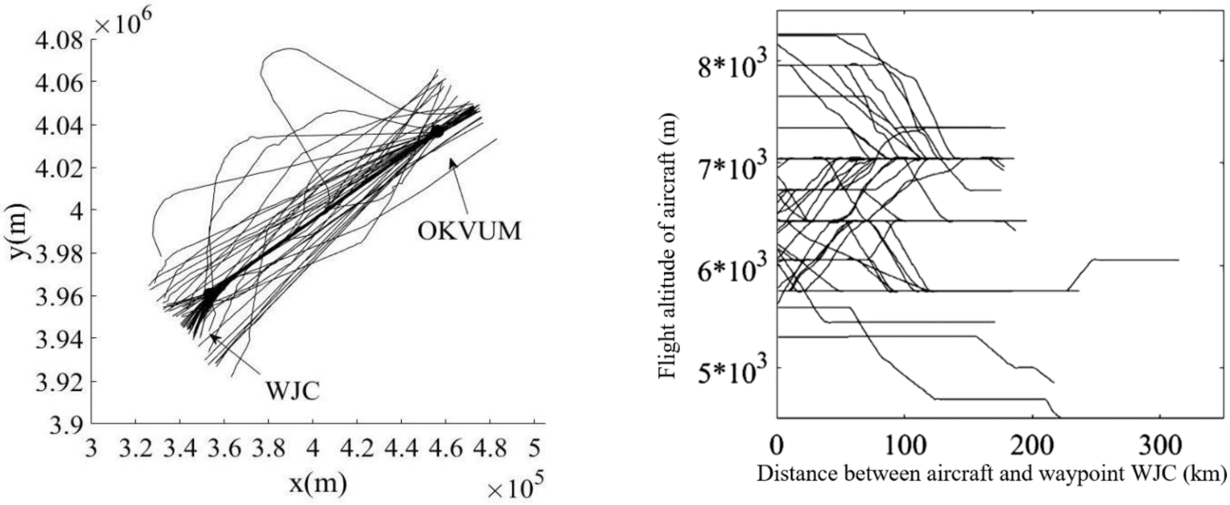
The aircraft trajectory data used in this paper is the ATC radar data derived from the ATC automation system, which is updated every 4 seconds, taken from a total of 7 days. After parsing and transcribing, it is saved in a format that is easy to read and manipulate, such as txt format. Figure 4 illustrates an example of the data header and part of the trajectory data of one aircraft. The data header includes the information of the aircraft, such as the track number, aircraft call sign, and the number of recorded trajectory points. Trajectory data of each line denotes the flight time, longitude, latitude, altitude, airspeed, and magnetic heading of the aircraft from left to right.

trackID=0001047E callSign=[] [19]

10:08:59	116.9660	36.1014	6004	566	1.00
10:09:03	116.9650	36.1062	6004	556	11.00
10:09:07	116.9650	36.1117	6004	556	11.00
10:09:11	116.9570	36.1299	6004	810	19.00
10:09:15	116.9640	36.1263	6004	587	9.00
10:09:19	116.9590	36.1387	6004	686	13.00
10:09:23	116.9580	36.1455	6004	686	13.00
10:09:27	116.9540	36.1562	6004	743	15.00
10:09:31	116.9530	36.1637	6004	746	15.00
10:09:35	116.9540	36.1689	6004	714	13.00
10:09:39	116.9520	36.1764	6004	723	14.00
10:09:43	116.9500	36.1836	6004	723	14.00

Figure 4. Historical trajectory data of the aircraft.

In Figure 5, the plan view and vertical profile of the en route aircraft trajectory on a particular day are depicted. Figure 5(a) demonstrates the plan view of the aircraft trajectory. It can be revealed that many aircrafts do not strictly maintain the straight line between waypoint WJC and OKVUM, and some conduct path stretching, i.e., the aircrafts deviate from the route at an angle and fly back as directed by ATCO. Controllers occasionally issue instructions to adjust the separation between the front and rear aircraft, and maintain downstream air traffic flow. Figure 5(b) exhibits the vertical profile view of the aircraft trajectory, where the horizontal axis indicates the distance between the aircraft and the waypoint WJC, and the vertical axis is the flight altitude of the aircraft. It can be found that many aircrafts climb or descend on this route segment, where some are required by the flight plan, and some are due to the controller's instructions to avoid flight conflicts.



(a) Plan view of aircraft trajectory

(b) Profile view of aircraft trajectory

Figure 5. En route aircraft trajectory on a particular day.

4.2. Calculation process

With the utilization of the aforementioned data, the data processing and calculation of the proposed indicators were accomplished as follows:

1) Convert the latitude and longitude coordinates of the raw data into plane coordinates (X, Y) using the universal Mercator projection.

2) Find the closest points to the waypoints WJC and OKVUM in each trajectory, and eliminate the trajectory data outside the route (20 trajectory points are retained). In addition, to ensure that the analyzed aircraft is not in the flight phase of arrival and departure, the trajectory data with an altitude of less than 3000 meters are excluded.

3) Project the selected trajectory onto the connection line between the waypoints WJC and OKVUM.

4) Perform coordinate translation and rotation transformation of the points in the original (X, Y) coordinate system, as presented in Eq (8),

$$\begin{cases} x' = (x - x_{WJC}) * \cos\alpha - (y - y_{WJC}) * \sin\alpha \\ y' = (x - x_{WJC}) * \sin\alpha - (y - y_{WJC}) * \cos\alpha \end{cases} \tag{8}$$

where (x, y) denotes the original coordinate; (x', y') means the transformed coordinate; α is the inverse number of the angle between the line connecting waypoints WJC and OKVUM, and the X-axis of the original coordinate system; the transformed x' is the track vector that takes waypoint WJC as the origin and points to waypoint KVUM.

5) Perform data discrepancy check on x' and adjust the duplicate values. By combining x' with the time corresponding to each point, the route state function of the actual traffic flow is obtained.

6) Use the spline interpolation method to establish the continuous displacement function of each trajectory. According to Eqs (6) and (7), use the histogram function of MATLAB to compute the en route spatial flow and en route instantaneous density under the setting of distance interval of 1 km and time interval of 1 minute.

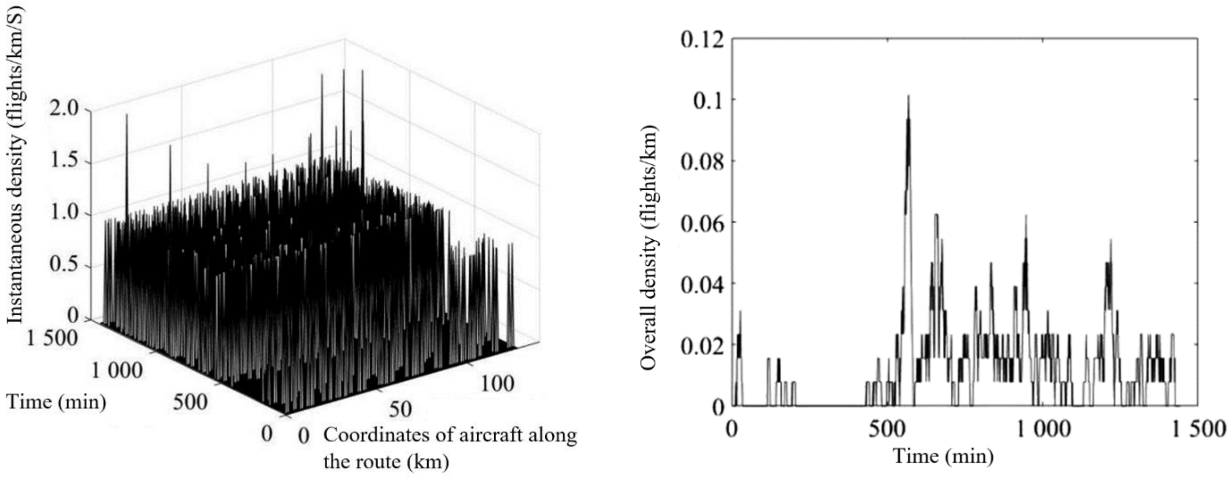
7) Determine the maximum spatial flow per minute, and use the sliding time window method to figure out the maximum hourly spatial flow.

8) Find the position with the maximum flow per minute every day, and determine the time series of all aircraft passing through the cross section at this position within that minute, that is, the time taken for the next aircraft to pass through the cross section after each aircraft passes through the section. Then, substitute it into Eq (5) to calculate the en route accessible capacity.

4.3. Model results and analysis

To demonstrate the advantages of the proposed en route capacity assessment metrics, this subsection uses the sixth day, which has the largest number of flights among the seven days, as an example, to consider the variation of en route spatial flow and en route instantaneous density with time and location, and compares them with the pairs of traditional index route hourly flow and route density.

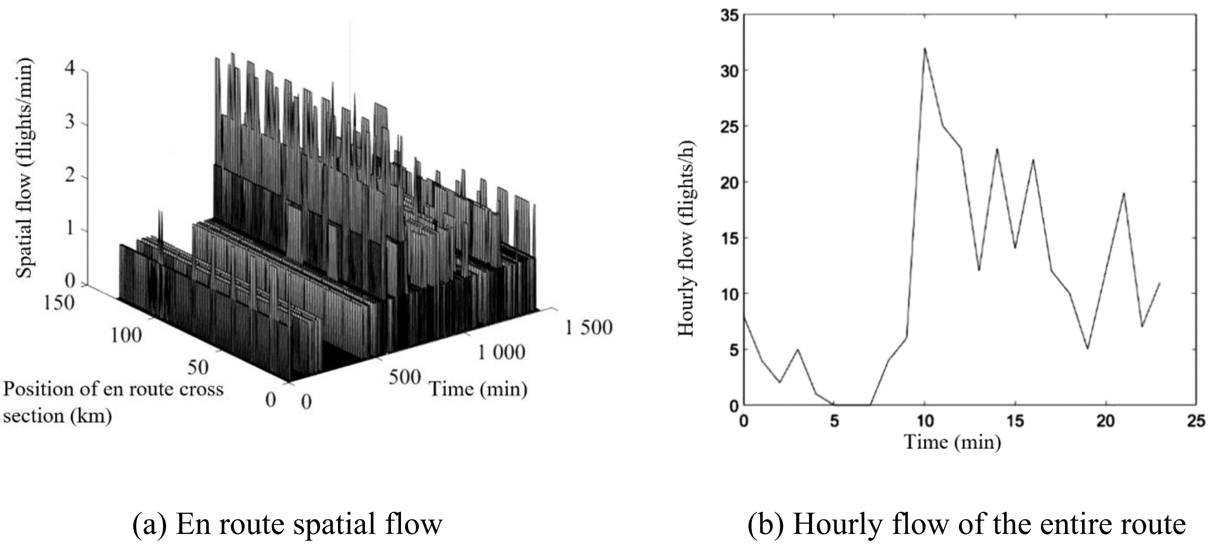
In Figure 6, the en route instantaneous density and the density of the entire route on a particular day are illustrated. Figure 6(a) shows the distribution of instantaneous density with time and space for this route. It can be seen from Figure 6(a) that the instantaneous density is mostly 0 or 1 $flights/km/S$. The maximum value is no more than 2 $flights/km/S$ when there are two aircrafts flying in the same or opposite direction, or with different altitudes at this position. For the variation characteristics of instantaneous density with time, it is relatively uniform, except for nighttime when it is almost 0. Further, the variation characteristics of instantaneous density with position is wholly average. Figure 6(b) displays the distribution of the overall density for this route. The maximum value of the overall density is no more than 0.12 $flights/km$, and the variation characteristics of the overall density with time is also orderly. Obviously, compared with the en route instantaneous density of the route, the overall density of the route can only describe its change with time, and is less useful for ATCO.



(a) En route instantaneous density (b) Density of the entire route

Figure 6. En route instantaneous density versus density of the entire route.

Moreover, the en route spatial flow and the hourly flow of the entire route on a particular day are demonstrated in Figure 7. Figure 7(a) shows the distribution of spatial flow with time and space for this route. The value of spatial flow ranges from 0 to 4 $flights/minute$. It can also be inferred that, for the characteristics of spatial flow with time, the maximum value occurs mostly at about 10:30 a.m., and other times are relatively stable; for the characteristics of spatial flow with position, the overall is more average. Figure 7(b) presents the hourly flow of the entire route. The value of hourly flow ranges from 0 to 32 $flights/h$. Besides, the hourly flow fluctuates greatly with time. In addition, contrary to the hourly flow, the en route spatial flow can more accurately reflect the changes of air traffic conditions.



(a) En route spatial flow (b) Hourly flow of the entire route

Figure 7. En route spatial flow versus hourly flow of the entire route.

For the sake of a more detailed analysis of the en route characteristics, various parameters are summarized in Table 2, based on all 7 days of historical track data, including number of aircrafts throughout the day, maximum hourly spatial flow, maximum minutely spatial flow, en route accessible capacity, observation time of accessible capacity, observation position of accessible capacity, percentage of aircraft that experience path stretching, and percentage of aircraft that change flight levels.

Table 2. En route characteristic parameters in seven days.

Day / Parameters	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
Number of aircrafts throughout the day	135	160	49	61	161	233	73
Maximum hourly spatial flow	26	29	16	14	22	35	11
Maximum minutely spatial flow	3	3	2	2	3	4	2
En route accessible capacity	19.2	19.5	10.3	2.6	4.9	40.8	5.7
Observation time of accessible capacity	10:20~ 10:21	10:19~ 10:20	16:42~ 16:43	12:52~ 12:53	14:26~ 14:27	10:19~ 10:20	15:08~ 15:09
Observation position of accessible capacity	127,000	127,000	61,000	0	45,000	62,000	54,000
Percentage of path stretching aircrafts	18%	15%	16%	13%	15%	15%	16%
Percentage of flight level crossing aircrafts	59%	62%	73%	62%	68%	64%	66%

According to the parameters of the route characteristics provided in Table 2, the following conclusions can be drawn:

- The en route spatial hourly flow and spatial minute flow share similar trends.
- Both of the en route accessible capacity and spatial flow are defined based on the cross section perpendicular to the route, and their maximum values occur on the same day. However, when the spatial flows are the same, the accessible capacity are not. By using MATLAB's corrcoef function to calculate the degree of correlation between the two, the value is 0.85, which indicates a high correlation.
- The time and location when the en route accessible capacity reaches its maximum value is not fixed. In terms of time, it occurs in the morning or afternoon; in terms of location, it occurs near the beginning of the route segment for 3 days, and in the middle of the segment on the other 4 days.

- When ATCO directs the aircraft to divert or fly across different flight levels, the speed vector of the aircraft is not perpendicular to the cross section. Nonetheless, in terms of time, the proportions of aircrafts that conduct path stretching or flight level crossing every day are about 15 and 65%, respectively, which are relatively uniform. Referring to the instantaneous density distribution in Figure 6(a), it can be determined that the instantaneous density distribution is more balanced during the daytime, which means that, regardless of whether the route is busy or not, ATCO can make the air traffic density or interval distribution more uniform throughout the route by using a moderate path stretching strategy or timely crossing flight level instructions, thus spreading the local safety risk evenly throughout the route.

To conclude, in contrast to capacity, which is a relatively macroscopic perspective, the proposed en route accessible capacity, instantaneous density, and spatial flow analyze the state of airspace operations in detail from a microscopic perspective. Ideally, for a unidirectional route with constant velocity air traffic flow, any cross-section perpendicular to the route will yield equal values of en route accessible capacity everywhere, and equal to the capacity of the entire route. Additionally, based on the actual aircraft trajectory data, the en route instantaneous density and spatial flow can finely reflect the spatial and temporal distribution of air traffic flow, which can provide richer characteristic information to ATCO.

5. Conclusions

The problem of airspace congestion has increasingly drawn the attention of specialists, policy makers, and researchers in the ATM community. Current studies put their main focus on the structural optimization of airspace or novel operation approaches, so there is still room for further inspection of the en route capacity evaluation model. Moreover, precise assessment of airspace operation status is the premise for analyzing the structural contradictions of airspace, and establishing refined airspace management mechanisms. In this paper, an en route accessible capacity evaluation model, based on the aircraft historical trajectory data, is proposed to study the airspace operation state in detail from a microscopic point of view. Compared with existing techniques, the proposed model envisages three innovations: (i) the definition of airspace accessible capacity with reference to capacity of road traffic, (ii) the computation model for flux-based airspace accessible capacity and en route accessible capacity, and (iii) two indicators of en route characteristics, named instantaneous density and spatial flow, are introduced for evaluating the micro state of the en route. A case study is performed to validate the applicability and feasibility of the model. Results show that the en route accessible capacity, instantaneous density, and spatial flow can describe the temporal and spatial distribution of air traffic flow more precisely, as compared to the conventional indicators, such as route capacity, density, and flow. Even though the experimental results are inspiring in terms of the advances of the proposed capacity evaluation model to resolve en route instances, the determined theoretical capacity may not be feasible to manage real traffic. Thus, further investigation is needed to: (i) certify that the proposed model works well on other airspace units, such as sectors and terminal areas; (ii) ensure the feasibility of proposed models on instances that more closely resemble real-world cases (i.e., considering of dynamics of individual aircrafts); and (iii) testify the applicability of the model, and determine lower and upper bounds of the en route capacity, based on the different air traffic conditions, aircraft categories, and flight directions in a simulation environment.

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Conflict of interest

The authors declare there is no conflict of interest.

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