[EN-A-010] Research on the Measure and Division of the Busyness Level of Airspace Waypoints

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Abstract: At present, China's air traffic is getting busier with the growing demand. An Accurate evaluation of the busyness of each airspace unit is an important prerequisite for making efficient traffic management strategies. To measure the busy level of the intersections and convergence points of the air routes and air lines, a calculation method based on the spatiotemporal distribution of segment flow is designed by analyzing the physical structure between the segments connected by the waypoint. This method can reflect the running state of the traffic flow at the waypoint, thus characterizing its busyness. Furthermore, this paper conducts a statistical analysis of the busyness level of the calculated waypoints, and a level division method based on probabilistic aliquot is proposed, which allows us to judge the busyness level of each waypoint quickly and effectively.

Keywords: Air traffic management; Traffic complexity; Busyness Level; Level division

1. INTRODUCTION

With the increasing demand of air traffic in China, flight delays have become a prominent problem. We have to find a balance between safety and efficiency in the air traffic. However, the imbalance of China's economic development has brought an imbalance distribution of air traffic flow in the airspace, what is reflected by the huge difference in the busy degrees of different airspace units. This difference leads to the different traffic characteristics and control requirements of different regions. To avoid the waste of airspace service resources caused by the extensive traffic management, it is necessary to take some finer flow management strategies. However, to develop refined traffic management strategies with rationality and applicability, we must master the busy degree and trend of each airspace unit. Therefore, how to evaluate the busyness of an airspace unit and classify its level has become the first problem that should be effectively solved.

In this paper, by taking the waypoint as the research object, we first construct a busyness calculation model based on the physical structure of the connecting segments and the spatiotemporal distribution of the traffic flow at the waypoint. By using this model, we can calculate the busyness of some waypoints, and proposed a probability based 5-level division method after the statistical analysis of the busyness.

2. RELATED WORKS

Air traffic system is a complex system, which mainly consists of aircraft, airspace and air traffic control personnel. To evaluate the busyness of air traffic system, many influential factors and indicators need to be considered. In the air traffic area, the research focuses on analyzing the busy degree of airspace unit based on the workload and complexity of the controller. Since the consumption of control resources embodied in the complexity of air traffic can represent the busy degree of airspace operation [1]. The representative study is dynamic density (DD), a classic assessment index of air traffic complexity, which focuses on the density and interaction of aircraft in airspace, and the controller workload is used as a basis for the complexity classification[2]; Marchitto M et al. used the controller's eye behavior to assess the workload and studied the impact of the aircraft conflict to the controller's cognitive complexity by simulation. This method describes the traffic complexity by human factors, which is subject to subjective influence [6]. From objective view, H. R. Idris used covariance and Koening metric to represent the inherent complexity of the aircrafts and airspace relative structure based on the 4-dimensional track. This method is based on the relative motion characteristics of aircrafts, highlighting the impact on airspace complexity caused by the disorder and perturbation of aircrafts[3]; Based on the inherent complexity of airspace, Chen Zhang et al. established the multi-dimensional spatial complexity model and index system by using the measurement indexes of different traffic states, which can be applied for the overall air traffic system comprehensive analysis of each aspect[4,5]; Wang H Y et al. used the weighted network model to analyze the interaction between aircraft pairs to characterize the complexity based on the complex network theory, which can describe the microscopic characteristics of aircraft operation [7]. In addition to the study of measurement indexes, the airspace busyness should be classified to facilitate the refined management. Qiongfang Zhang divided the busyness level of the sector Based on the sector structure, traffic flow characteristics and the controllers' workload [8]; Xuebo Lv applied the grey correlation analysis to finding the relationship between the congestion indexes of sector, which is used as the evaluation index of busyness division[9]; Yaru Dang and other scholars assessed the control capacity of some control areas based on the airspace structure, traffic characteristics, navigation equipment performance, but did not consider the ability difference of the controllers; Wei Cong et al. used complexity index system and the K-means method to classify the sector structure complexity and operation complexity[11].

The researches mentioned above are mainly aimed at sectors, including the study of the interaction between the complex structure of airspace blocks and the aircrafts, but don't include the study of the busyness of the intersection / convergence points of the air routes / lines. Moreover, the above researches compare the busyness of airspace units based on a single dimensional index, ignoring the influence of the differences between airspace units on the index range and the level spans.

3. MODELING OF WAYPOINT BUSYNESS

3.1 Definition of waypoint busyness

Here, busyness refers to the concentrated distribution of aircrafts in time and space. The concentrated distribution in time leads to congestion, and the concentrated distribution in space leads to the possibility of conflict. The concentrated distribution occupies a large number of airspace capacity and control resources, which will dramatically increase the complexity of airspace operation. In order to facilitate the partition control of the aircrafts, airspace is divided into several sectors based on the structure of the air routes / lines network. The waypoints are the inherent nodes in the route network and the intersections and convergence points of the air routes / lines are actually the crux of congestions and conflicts. In general, the actual flow in the air traffic system is the interactive result of all the complicated factors in the operation process, and contains the information of the complex system. It can be used as an index to evaluate the running status of the air traffic system. Therefore, we aim at the intersections and convergence points of the air routes / lines in this paper, and define the waypoint busyness by analyzing their temporal and spatial distribution of flow in connected segments.

3.2 Calculation model of waypoint busyness

Air traffic is the interactive result of the airspace structure and the aircrafts in it. Therefore, the busyness calculation model of a waypoint must contain the influence of the airspace structure on the traffic flow. Figure 1 shows the airspace structure of two waypoints. It's obvious that waypoint i has a much more complex structure than waypoint j, from which we can know waypoint i should be more busy that waypoint j.

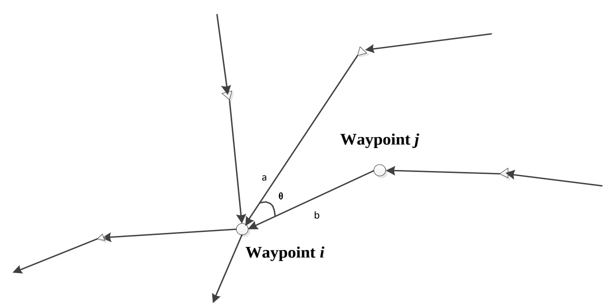

Figure. 1 The airspace structure of the waypoints

Definition 1：Segment Busyness r_i

$$r_i = r_i^{in-in} + r_i^{out-out} + r_i^{in-out} \quad (1)$$

To construct the waypoint busyness calculation model, we should first calculate the busyness of any two segments connected to the waypoint. Generally, segments connected a waypoint can be classified into two types: in-segments and out-segments. The relationships between these two type segments are named: in-in, out-out, in-out. Assume waypoint i has n in-segments and m out-segments, and the in-in, out-out, in-out busyness of waypoint i can be calculated as follow:

$$r_i^{in-in} = \sum_{a=1}^{n-1} \sum_{b=a+1}^{n} \left(\left(f_a^{in} + f_b^{in} \right) \times r_{a,b} \right) \quad (2)$$

$$r_i^{out-out} = \sum_{c=1}^{m-1}\sum_{d=c+1}^{m}\left(\left(f_c^{out} + f_d^{out}\right)\times r_{c,d}\right) \quad (3)$$

$$r_i^{in-out} = \sum_{e=1}^{n}\sum_{f=1}^{m}\left(\left(f_e^{in} + f_f^{out}\right)\times r_{e,f}\right) \quad (4)$$

Where f_a^{in}, f_b^{in}, f_e^{in} are the flow of in-segments, f_c^{out}, f_d^{out}, f_f^{out} are the flow of out-segments $r_{a,b}$, $r_{c,d}$, $r_{e,f}$ are the relationship busyness of two connected segments, which can be calculated as follow:

$$r_{a,b} = r_{a,b}^{level} \times r_{a,b}^{angel} \quad (5)$$

Where $r_{a,b}^{level}$ is the flow attribute of a height level, and $r_{a,b}^{angel}$ is the angle of two connected segments. $r_{a,b}^{level}$ can be calculated as follow:

$$r_{a,b}^{level} = \begin{pmatrix} \sum_{x=1}^{n} f_{a,x} \times STD_{level}\left(f_{a,x}\right) \times mixture_{a,x} \times STD_{time}\left(f_a\right) \\ +\sum_{y=1}^{m} f_{b,y} \times STD_{level}\left(f_{b,y}\right) \times mixture_{b,y} \times STD_{time}\left(f_b\right) \end{pmatrix} \times \gamma \quad (6)$$

In this formula, $f_{a,x}$ is the total flow of segment a in height level x, with $1 \le x \le n$, and $f_{b,y}$ is the total flow of segment b in height level y, with $1 \le y \le m$. $STD_{level}\left(f_{a,x}\right)$ and $STD_{level}\left(f_{b,y}\right)$ are the spatial distribution standard deviations of segment a and segment b in all height levels. $STD_{time}\left(f_a\right)$ and $STD_{time}\left(f_b\right)$ re the time distribution standard deviations of segment a and segment b in all height levels, with a 15minutes interval. $mixture_{a,x}$ and $mixture_{b,y}$ are the mixture ratios of aircraft types. γ is the correction coefficient for height level change, given by experts.

$r_{a,b}^{angel}$ can be calculated as follow:

$$r_{a,b}^{angel} = \left(\cos\left(\theta + 25^\circ\right) + 1\right) \times \delta_{a,b} \quad (7)$$

θ the angle between the two segments, and $\delta_{a,b}$ is the correction coefficient, reflecting the impact of connected or unconnected segments at the same angle. $\cos\left(\theta + 25^\circ\right) + 1$ is from the formula of collision risk and segment angle.

Definition 2: Out-in Complexity d_i

$$d_i = \left(d^{in} + d^{out}\right) \times \left(d^{in}/d^{out} + 1\right) \quad (8)$$

Where, d_i indicates the influence to a waypoint busyness caused by the quantity and traffic flow direction of all the segments connected to it. d^{in} and d^{out} in the formula represent the in-degree and out-degree of the waypoint, and $d^{in}/d^{out}+1$ is used to correct the effect of discrepancy between its in-degree and out-degree.

Finally, we get the formula to calculate the waypoint busyness.

Definition 3: Waypoint Busyness $Busy_i$

$$Busy_i = f_i / F \times d_i \times r_i \quad (9)$$

Where, f_i is the traffic flow through waypoint i in a certain period of time, and $F = \sum_{i=1}^{n} f_i$ is the total traffic flow of all waypoints. It can be seen that, $Busy_i$ includes the air route/line structure, traffic flow and other factors of a waypoint, and can objectively reflect the relative busyness of all the waypoints.

3.3 Calculation examples of waypoint busyness

In this section, we calculate the busyness of the 15 waypoints using the busyness formula defined in section 3.2. The traffic data used for the calculation is composed of spatial structure data and dynamic flight data. The spatial structure data contains information such as the location of the waypoints, coverage and height of the segments, and the subordinate relationships of segments and waypoints. The dynamic flight data is the real-time flight plans and secondary radar data collected by southern region authority of China civil aviation. We select the 10 intervals traffic data from 8:00 to 18:00 in one day for one month, and count the traffic flow of each connected segments by every 15 minutes. Busyness values of some waypoints are calculated and the results are listed in Table 1, and their comparison is shown in Figure. 2(Note the index of each waypoint at the bottom of Figure.2).

It can be seen from Table 1 and Figure 2, the busyness values of the waypoints in same airspace and same period have huge difference, and for the same waypoint, its busyness values at different time also show large gaps. Furthermore, we count the number of 0, means, standard deviations of the busyness values of the 15 waypoints at 31*24 hours in one month, the results are showed in Table 2.

Table.1 Busyness values of 15 waypoints

Waypoint	8	9	10	11	12	13	14	15	16	17
GYA	756.854	3906.0	1701.6	1752.2	2135.1	3408.3	2640.4	2016.5	948.253	1210.7
TAMOT	0	0.025	0	4.880	0.298	4.349	1.023	0	1.931	0.735
VIBOS	0.929	1.800	0.481	0.937	0.469	3.415	1.397	3.553	2.974	1.988
SHL	398.343	253.974	97.873	132.806	452.089	272.583	190.598	294.232	203.284	340.927
POU	74.740	410.206	294.420	316.499	673.101	853.416	352.230	851.108	249.370	218.122
NLG	30.947	90.192	278.118	107.009	150.564	143.408	151.321	128.817	62.133	46.242
GLN	3.272	15.787	2.144	3.767	4.294	6.647	49.057	7.699	16.586	25.528
KIBAS	0	1.955	0	0.049	0	0.223	2.133	0.477	0	1.059
KEVAR	0.732	38.358	41.349	3.805	30.495	32.850	57.397	73.841	12.672	46.870
SAREX	2.376	11.735	14.089	12.205	16.561	14.504	9.299	22.715	7.089	7.431
NOMAR	0.058	2.851	10.887	5.578	6.976	1.256	1.801	5.199	2.277	3.535
TEPID	40.965	112.345	28.417	81.822	61.609	52.889	59.150	104.297	72.806	74.275
VIPAP	0.331	1.037	0.297	0.805	0.816	0.397	9.578	16.310	11.965	4.414
IDUMA	3941.7	4346.3	966.648	3147.3	6945.0	4375.6	2668.0	2388.1	2276.2	3674.8
ZUH	36.793	360.673	131.735	52.166	120.509	407.319	87.029	394.170	272.782	618.336

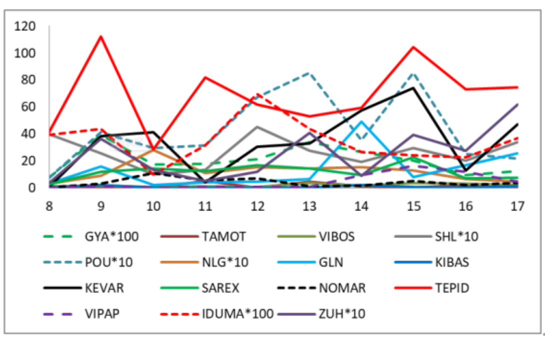

Figure 2 Busyness comparison of 12 waypoints

As can be seen from Table 2, the statistical results of the waypoints busyness are still quite different. For the idle waypoints, more than 80% of the intervals are with the busyness of 0. For the busy waypoints, More than 80% of the intervals are in busy states. The statistical results indicate the actual role and effect of every waypoint in the target airspace. For either idle waypoint or busy one, its busyness changes a lot in different intervals, with a very discrete distribution.

Table.2 Statistic of the waypoint busyness

Waypoint	Busyness					
	0（%）	Max	Mean	Mean/0	SD	SD/0
GYA	17.20%	23144	1749.4	2113.0	2575.4	2691.4
IDUMA	16.40%	35826	2063.9	2468.7	3772.4	4035.6
ZUH	34.01%	5662.7	180.575	273.621	514.440	63.011
VIBOS	57.26）	42.213	1.409	3.297	3.320	4.425
POU	22.58%	4612.5	327.798	423.406	491.563	521.231
NLG	23.66%	2572.8	102.701	134.524	199.945	219.315
TEPID	27.02%	1085.9	53.187	72.874	93.525	102.730
KEVAR	34.01%	629.153	18.761	28.428	49.648	58.841
GLN	50.81%	726.233	10.379	21.098	38.510	52.840
VIPAP	61.02%	432.191	3.439	8.824	20.083	31.453
TAMOT	83.60%	167.963	1.806	11.015	9.729	21.886
SAREX	30.65%	169.015	10.902	15.719	18.809	20.845
NOMAR	62.10%	57.980	2.878	7.564	6.742	9.178
KIBAS	91.67%	70.962	0.842	10.103	4.525	12.420
SHL	13.31%	2835.1	159.854	184.389	247.139	256.780

4. LEVEL DIVISION OF THE WAYPOINT BUSYNESS

Due to the huge difference of the waypoints busyness in the target airspace, it is impossible to use one standard to divide the busyness levels of all waypoints. Instead it is necessary to respective standard for each waypoint base on its busyness distribution, to ensure that such division is objective and reasonable for the waypoint.

4.1 Statistical analysis of the waypoint busyness

In this section, the busyness probability distribution of each waypoint is analyzed. In order to express the distribution and trend of the busyness clearly, some data in the tail is deleted from the dataset, and the curve is smoothed by interpolation function. Figure 3 shows the probability distributions of the six waypoints.

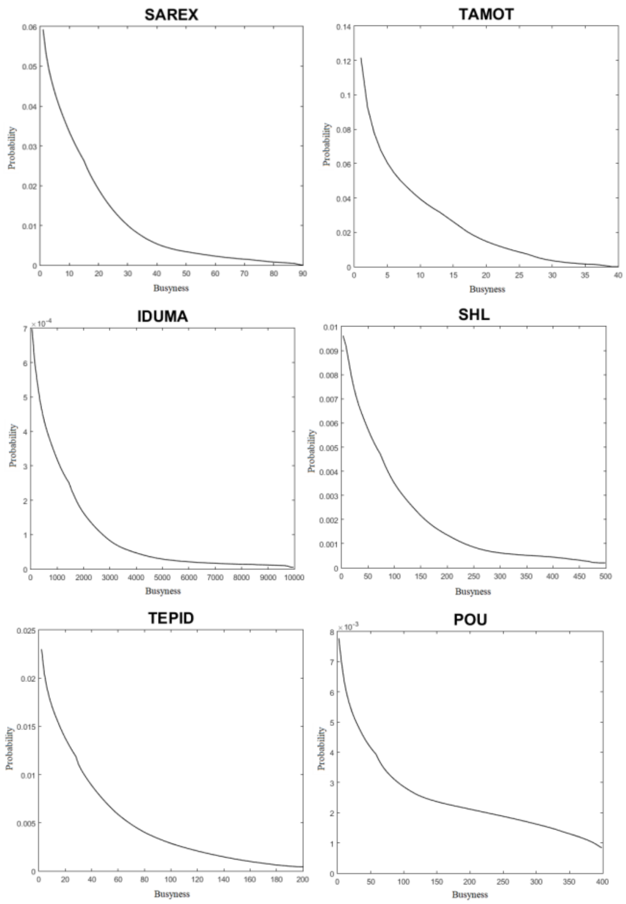

Figure 3 Probability distributions of waypoints busyness

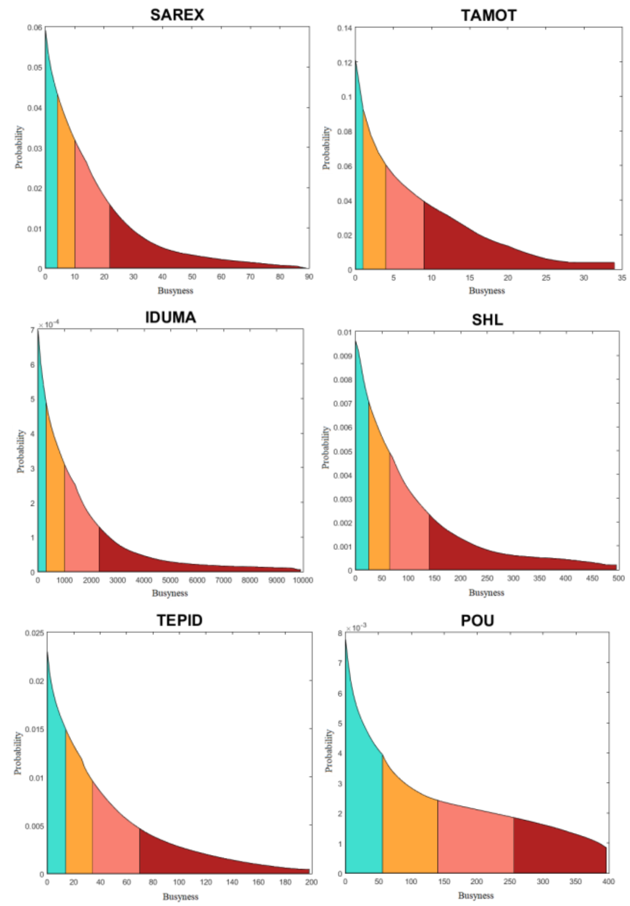

Figure 4 Level division of waypoint busyness

4.2 The busyness level division based on distribution

From Figure.3 we can know that, the distributions of the busyness of different waypoints all have sharp decline in the trend, that is, the higher the busyness is the less it appears. A reasonable division should not only take into account every possible value, but also it probability, to decide the appropriate intervals. For example, the high probability segment of the curve should be finely divided, while the low probability segment can be divided roughly. In this paper, we use the method of probability equalization to divide each curve into four segments, which mean five levels. The intuitive explanation of this method is to divide the area that enclosed by the probability curve, x axis and y axis in Figure 3 into four parts with same area. The division results of the six waypoints in Figure 3 are shown in Figure 4, where the deeper the color, the higher the busyness level. The division points in x axis for five levels of each waypoint are listed in Table3.

Table.3 Division points for five levels

Waypoints	level1	level2	level3	level4
GYA	344	1127	2473	10000
IDUMA	337	947	2404	10000
POU	82	222	445	1000
SHL	28	84	178	500
ZUH	24	64	138	400
NLG	24	62	141	400
TEPID	18	43	88	200
KEVAR	11	25	54	170
SAREX	4	9	21	100
KIBAS	3	5	8	20
GLN	3	8	18	80
TAMOT	2	4	8	30
NOMAR	2	5	10	50
VIPAP	1	2	5	36
VIBOS	1	2	4	20

This probability equalization based division method is reasonable in practical application of air traffic control. It can distinguish the different busyness levels clearly, which is helpful to identify the busyness intervals with small probabilities. Moreover, we used the historical traffic data in the experiments, the operations of all aircrafts were truly undertaken by airspace services. The states with high probability and low complexity are very normal in air traffic, which is consistent with the cognition of the controllers.

5. CONCLUSIONS

Air traffic flow management is the basis of the safe, orderly and efficient operation of aircrafts. Adopting corresponding traffic management strategies based on different busyness levels of airspace units is a prerequisite for centralized control of resources and efficient flight operation. Taking the intersections and convergence points of the air routes / lines as research objects, this paper proposed a busyness assessment model for waypoints based on the temporal and spatial distribution of their traffic flow. After the statistical analysis of the busyness probability distribution, a method of probability area aliquot was applied to divide the busyness levels of each waypoint. The proposed division method entirely relies on the daily running data of each waypoint, which can not only reflect the relative busyness of a waypoint objectively, but also update the division points according to the new data coming constantly.

6. REFERENCES

[1] Hilburn, Brian. "Cognitive complexity in air traffic control: A literature review." Journal of the EEC note. April, 2004.

[2] Mogford, Richard H. "Development of Metrics for Measuring Complexity and Dynamic Density in Air Traffic Control." Proceedings of the Eleventh International Symposium on Aviation Psychology. Columbus, Ohio, (USA). March, 2001.

[3] Delahaye, Daniel, et al. "A new air traffic complexity metric based on dynamical system modelization." Proceedings of the Digital Avionics Systems Conference. Irvine, CA, (USA). vol. 1. IEEE, December,2002. p. 4A1-4A2.

[4] Cook, Andrew, et al. "Applying complexity science to air traffic management." Journal of Air Transport Management, vol. 42, January, 2015, p,149-158.

[5] Delahaye, Daniel, and S. Puechmorel. "Air Traffic Complexity based on Dynamical Systems." Proceeding of the 2010 49th IEEE Conference on Decision and Control (CDC). Atlanta, GA, (USA), 2010. p, 2069-2074.

[6] Marchitto, Mauro, et al. "Air traffic control: Ocular metrics reflect cognitive complexity." International journal of industrial ergonomics. vol. 54, July, 2016. p,120-130.

[7] Wang, Hong Yong, Y. F. Zhao, and R. Y. Wen. "Air Traffic Complexity Metrics Based on Complex Networks." Journal of Systems Engineering. vol. 3, March, 2014.

[8] Christien, R, et al. "Air traffic complexity indicators & ATC sectors classification." Proceeding of the 21st Digital Avionics Systems Conference. Irvine, CA, (USA). October, 2002. IEEE, vol.1, December, 2002. p, 2D3-1-2D3-7.

[9] Chi, Jeonghee, S. Do, and S. Park. "Traffic flow-based roadside unit allocation strategy for VANET." Proceeding of the International Conference on Big Data and Smart Computing, Hong Kong, (China), January, 2016. IEEE, March, 2016. p, 245-250.

[10] Al-Romaithi, Shareef Abdulla Kaddas, "National Culture: Understanding the Impact of Cross-culture on Airline Pilots' Safety Performance in the Middle-East and North Africa (MENA) Region" (2014). Dissertations and Theses. 152.

[11] Cong, W., et al. "An evaluation method of sector complexity based on metrics system." Nanjing University of Aeronautics & Astronautics, 2015.

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