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Probability Distribution of Ratio of China Aviation Network Edge Vertices Degree and Its Evolutionary Trace Based on Complex Network

Cheng Xiangjun, Yang Fang, Wei Liying
School of Traffic and Transportation, Beijing Jiaotong University, Beijing, 100044, China

Abstract: In order to reveal the complex network characteristics and evolution principle of China aviation network, the probability distribution and evolution trace of ratio of China aviation network edge vertices degree were studied based on the statistics data of China civil aviation network in 1988, 1994, 2001, 2008 and 2015. According to the theory and method of complex network, the network system was constructed with the city where the airport was located as the network node and the route between cities as the edge of the network. Based on the statistical data, the ratio of edge vertices degree in China aviation network in 1988, 1994, 2001, 2008 and 2015 were calculated. Using the probability statistical analysis method and regression analysis approach, it was found that the ratio of edge vertices degree had linear probability distribution and the two parameters of the probability distribution had linear evolution trace.

Key word: Complex network, China aviation network, ratio of edge vertices degree, linear probability distribution, linear evolution trace.

1. Introduction

Aviation network is typical complex network with small world characters [1, 2]. The nodes of the network have multiple parameters such as degree, clustering coefficient, and average path length, which can be used as the basis for studying the characteristics of nodes, but the number of edges of the network is not only far greater than the number of nodes, but also the study of edge characteristics is more difficult to start for the network without edge weights. Here, the ratio of the edge vertices degree was used to describe the features of the edge, and the ratio of the two vertices degree of the edge was used as the mean obtained as the relevant parameters to describe the edge, which was used as the basis for studying the properties of the edge. The node degree of China aviation network has the probability distribution characteristics of power function [3] and the average degree of edge vertices has normal distribution [4]. But the probability distribution of the ratio of the edge vertices degree needs to be obtained after calculation and analysis. This paper faces to the aviation network of China through analyzing the passenger data [5] of civil aviation airlines in year 1988, 1994, 2001, 2008 and 2015 to reveal the complex network feature. According to complex network theory, network system of airports and airlines of China was constructed with airports regarded as nodes and airline regarded as edges to study the probability distribution of ratio of edge vertices degree and its evolution trace of China aviation network. Based on the statistical data, the ratio of the edge vertices degree in China aviation network in 1988, 1994, 2001, 2008 and 2015 were calculated. Using the probability statistical analysis method and regression analysis approach, it was found that the ratio of edge vertices degree had the linear probability distribution and the two parameters of the probability distribution had linear evolution trace.

Corresponding author: Yang Fang, Ph.D., lecturer, research fields: transportation management, traffic and transportation engineering.

2. Probability Distribution of Ratio of China Aviation Network Edge Vertices Degree

For network $G=(V,E)$, where $v_i \in V$ is the node of G. V is the set of nodes. E is the set of edges [6], $(v_i,v_j)\in E$. Matrix $A=(a_{i,j})_{n\times n}$ was constructed, where:

$$a_{i,j}=\begin{cases}1,(v_i,v_j)\in E\\ 0, otherwise\end{cases} \tag{1}$$

Matrix A was called adjacent matrix of network G. The degree of node v_i was defined as the number of edges connected to v_i. The ratio of edge vertices degree is defined as following:

$$D_{i,j}^{EVR}=\frac{k_i}{k_j} \tag{2}$$

In the Eq. (2): k_i – the degree of node v_i; k_j – the degree of other nodes v_j; $k_i \le k_j$; $(v_i,v_j)\in E$.

2.1 Probability Distribution of Ratio of Edge Vertices Degree in China Aviation Network in 1988

The adjacent matrix A_{1988} was gotten from statistic data [5]. The ratio of edge vertices degree D_n^{EVR} ($n=1,2,3,......,265$) of 265 edges in 1988 were gotten from A_{1988} and Eq. (2). The data in Table 1 was done statistics by these data according to the interval in Table 1. The scattered points in Fig. 1 were drawn by the data in Table 1. Let the interval median be the horizontal axis *x* and the probability be the vertical axis *y*. Let the quantity of edges be N, the quantity of interval be m, the spacing of interval i be δ, the times of appearance in interval i be k_i, the frequency of appearance in interval i be q_i, the probability of appearance in interval i be p_i. Here $N_{1988}^E=265$, $m_{1988}=5$, δ_{1988}=0.2. It could be known from the probability theory [7]:

$$q_i=\frac{k_i}{N_{1988}^E},\ \sum_{i=1}^{m_{1988}} q_i=1 \tag{3}$$

$$q_i=p_i\delta_{1988}\Rightarrow p_i=\frac{q_i}{\delta_{1988}},\ \sum_{i=1}^{m_{1988}} p_i=\frac{1}{\delta_{1988}} \tag{4}$$

$$r=\frac{L_{xy}}{\sqrt{L_{xx}L_{yy}}}=\frac{\sum_{i=1}^{n}(x_i-\overline{x})(y_i-\overline{y})}{\sqrt{\sum_{i=1}^{n}(x_i-\overline{x})^2\sum_{i=1}^{n}(y_i-\overline{y})^2}} \tag{5}$$

Here, $n=5$. Using the data in Table 1, the value of correlation coefficient r was calculated by Eq. (5), $r=-0.976$. The critical value of $r\big|_{\alpha=1\%, f=3}$ was 0.959 found in critical value table[8] at degree of freedom $f=n-2=3$ and level of significant α of 1%. Since $|r|=0.976>0.959=r\big|_{\alpha=0.01, f=3}$, the scattered points in Fig. 1 had significant linear correlation. Least square method [8] was used as an approach in Eq. (6) to fit the line with points in Fig. 1.

Table 1 Probability distribution of ratio of China aviation network edge vertices degree in 1988.

Interval	[0, 0.2]	(0.2, 0.4]	(0.4, 0.6]	(0.6,0.8]	(0.8, 1]
Median	0.1	0.3	0.5	0.7	0.9
Times	89	75	43	35	23
Frequency	0.336	0.283	0.162	0.132	0.087
Probability	1.680	1.415	0.811	0.660	0.434

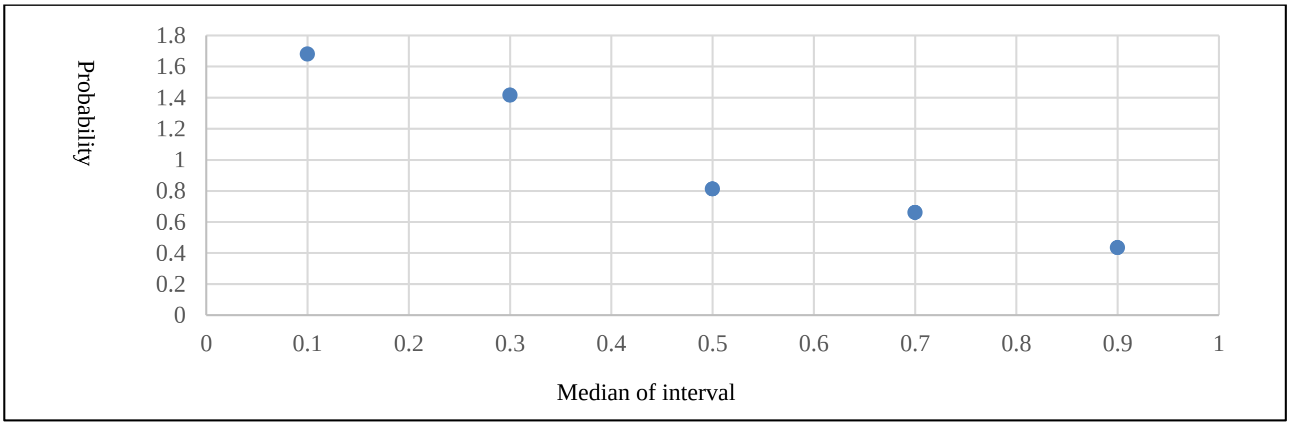

Fig. 1 Probability distribution diagram of ratio of China aviation network edge vertices degree in 1988.

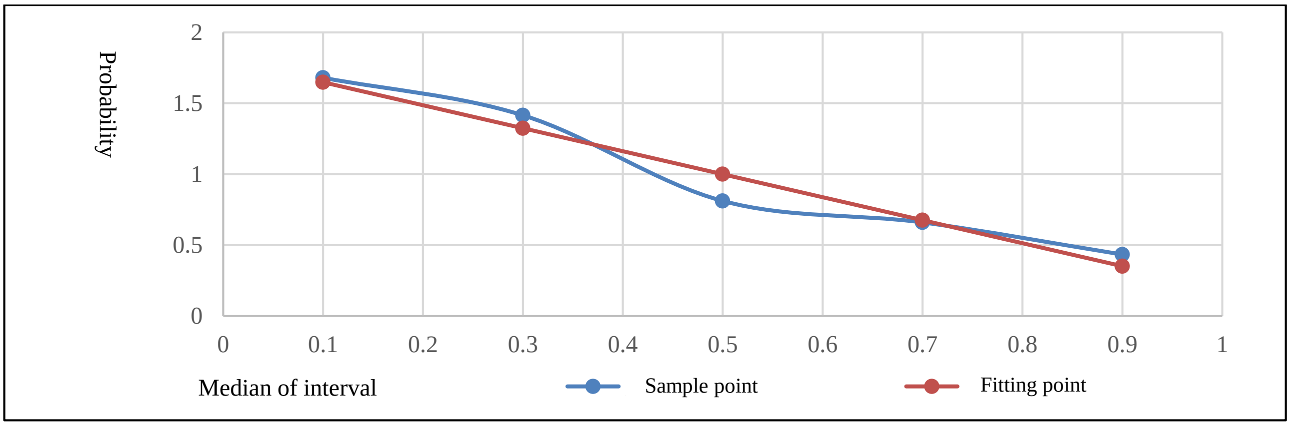

Fig. 2 Fitting effect diagram of probability distribution of ratio of edge vertices degree in 1988.

$$\begin{cases} \hat{\beta}_0 = \overline{y} - \hat{\beta}_1 \overline{x} = 1.812 \\ \hat{\beta}_1 = \dfrac{L_{xy}}{L_{xx}} = \text{-}1.623 \end{cases} \qquad (6)$$

The linear equation:

$$\hat{y} = 1.812\text{-}1.623x \qquad (7)$$

The fitting line Eq. (6) were drawn with the sample points in one diagram of Fig. 2 with good fitting effect.

To take t test [8] of Eq. (7), test hypotheses is: $H_0 : \beta_1 = 0$. When the hypotheses is true, there is

$$\hat{\beta}_1 \sim N(0, \frac{\sigma^2}{L_{xx}}) \qquad (8)$$

Here, $\hat{\beta}_1$ fluctuate near zero, statistic t is build.

$$t = \frac{\hat{\beta}_1}{\sqrt{\dfrac{\hat{\sigma}^2}{L_{xx}}}} = \frac{\hat{\beta}_1 \sqrt{L_{xx}}}{\hat{\sigma}} \qquad (9)$$

Where:

$$\hat{\sigma}^2 = \frac{1}{n-2} \sum_{i=1}^{n} (y_i - \hat{y}_i)^2 \qquad (10)$$

Statistic t was calculated by data in Table 1 and Eq. (7), Eq. (9), Eq. (10): $t = \text{-}7.84$

To check the t distribution table [8], at significant level α of 0.01 and degree of freedom $f = n-2 = 3$ the value of $t|_{\substack{\alpha=0.01 \\ f=3}}$ in table is 4.541.

So, $|t| = 7.84 > 4.541 = t|_{\substack{\alpha=0.01 \\ f=3}}$, null hypotheses H_0 is refused. The linear correlation of Eq. (7) is significant.

2.2 Probability Distribution of Ratio of Edge Vertices Degree in China Aviation Network in 1994

The adjacent matrix A_{1994} was gotten from statistic data. The ratio of edge vertices degree D_n^{EVR} ($n=1,2,3,......,589$) of 589 edges in 1994 were gotten from A_{1994} and Eq. (2). The data in Table 2 was done statistics by these data according to the interval in Table 2. The scattered points Fig. 3 were drawn by the data in Table 2. The definition of parameters and relationship of parameters were similar with Eq. (3) and Eq. (4) in (2.1). Here, $N_{1994}^{E}=589$, $m_{1994}=5$, δ_{1994}=0.2 .

Here, $n=5$. Using the data in Table 2, the value of correlation coefficient r was calculated by Eq. (5), $r=-0.935$. The critical value of $r|_{\alpha=5\%, f=3}$ was 0.878 found in critical value table at degree of freedom $f=n-2=3$ and level of significant α of 5%. Since $|r|=0.935>0.878=r|_{\alpha=0.05, f=3}$, the scattered points in Fig. 3 had significant linear correlation. Least square method was used as an approach in Eq. (11) to fit the line with points in Fig. 3.

$$\begin{cases}\hat{\beta}_0=\bar{y}-\hat{\beta}_1\bar{x}=1.468\\ \hat{\beta}_1=\dfrac{L_{xy}}{L_{xx}}=\text{-}0.935\end{cases} \tag{11}$$

The linear equation:

$$\hat{y}=1.468\text{-}0.935x \tag{12}$$

The fitting line Eq. (12) were drawn with the sample points in one diagram of Fig. 4 with good fitting effect.

To take t test of Eq. (12), test hypotheses is: $H_0:\beta_1=0$.

When the hypotheses is true, there is: Eq. (8), Eq. (9) and Eq. (10).

Statistic t was calculated by data in Table 6 and Eq. (12), Eq. (9), Eq. (10): $t=\text{-}4.48$

To check the t distribution table, at significant level α of 0.025 and degree of freedom $f=n-2=3$ the value of $t|_{\alpha=0.025, f=3}$ in table is 3.182.

So, $|t|=4.48>3.182=t|_{\alpha=0.025, f=3}$, null hypotheses H_0 is refused. The linear correlation of equation (12) is significant.

Table 2 Probability distribution of ratio of China aviation network edge vertices degree in 1994.

Interval	[0, 0.2]	(0.2, 0.4]	(0.4, 0.6]	(0.6,0.8]	(0.8, 1]
Median	0.1	0.3	0.5	0.7	0.9
Times	176	122	110	108	73
Frequency	0.299	0.207	0.187	0.183	0.124
Probability	1.494	1.035	0.934	0.917	0.620

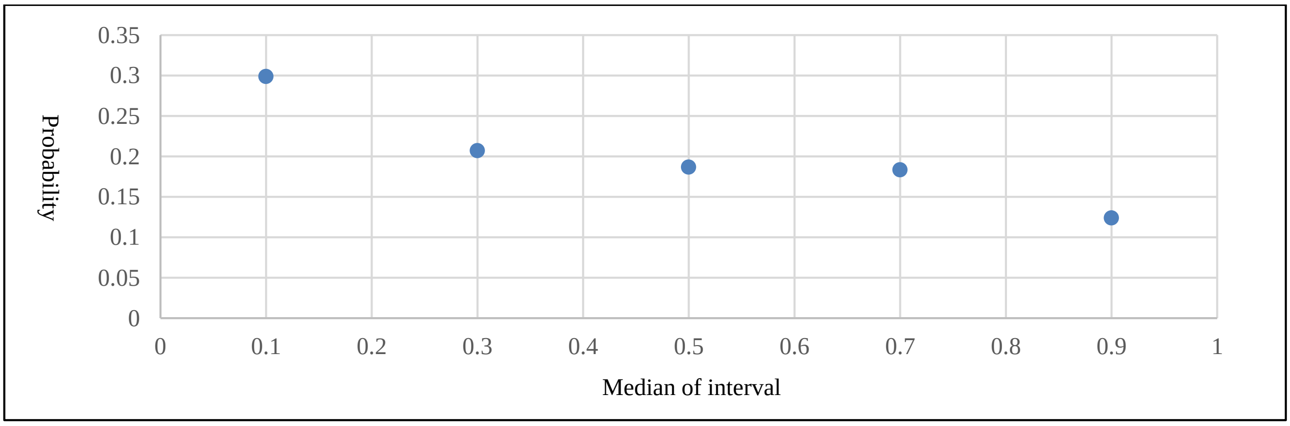

Fig. 3 Probability distribution diagram of ratio of China aviation network edge vertices degree in 1994.

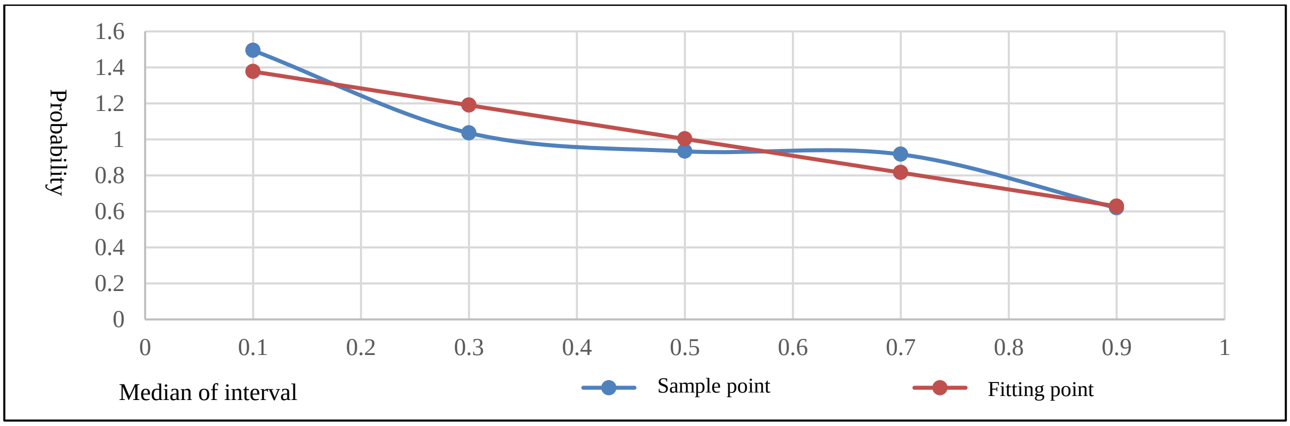

Fig. 4 Fitting effect diagram of probability distribution of ratio of edge vertices degree in 1994.

2.3 Probability Distribution of Ratio of Edge Vertices Degree in China Aviation Network in 2001

The adjacent matrix A_{2001} was gotten from statistic data. The ratio of edge vertices degree D_n^{EVR} ($n=1,2,3,......,730$) of 730 edges in 2001 were gotten from A_{2001} and Eq. (2). The data in Table 3 was done statistics by these data according to the interval in Table 3. The scattered points in Fig. 5 were drawn by the data in Table 3. The definition of parameters and relationship of parameters were similar with Eq. (3) and Eq. (4) in (2.1). Here, $N_{2001}^E = 730$, $m_{2001} = 5$, δ_{2001}=0.2.

Here, $n = 5$. Using the data in Table 3, the value of correlation coefficient r was calculated by Eq. (5), $r = -0.938$. The critical value of $r\big|_{\substack{\alpha=5\% \\ f=3}}$ was 0.878 found in critical value table at degree of freedom $f = n-2 = 3$ and level of significant α of 5%. Since $|r| = 0.938 > 0.878 = r\big|_{\substack{\alpha=0.05 \\ f=3}}$, the scattered points in Fig. 5 had significant linear correlation. Least square method was used as an approach in Eq. (13) to fit the line with points in Fig. 5.

Table 3 Probability distribution of ratio of China aviation network edge vertices degree in 2001.

Interval	[0, 0.2]	(0.2, 0.4]	(0.4, 0.6]	(0.6,0.8]	(0.8, 1]
Median	0.1	0.3	0.5	0.7	0.9
Times	210	147	148	127	98
Frequency	0.288	0.201	0.203	0.174	0.134
Probability	1.438	1.007	1.014	0.870	0.671

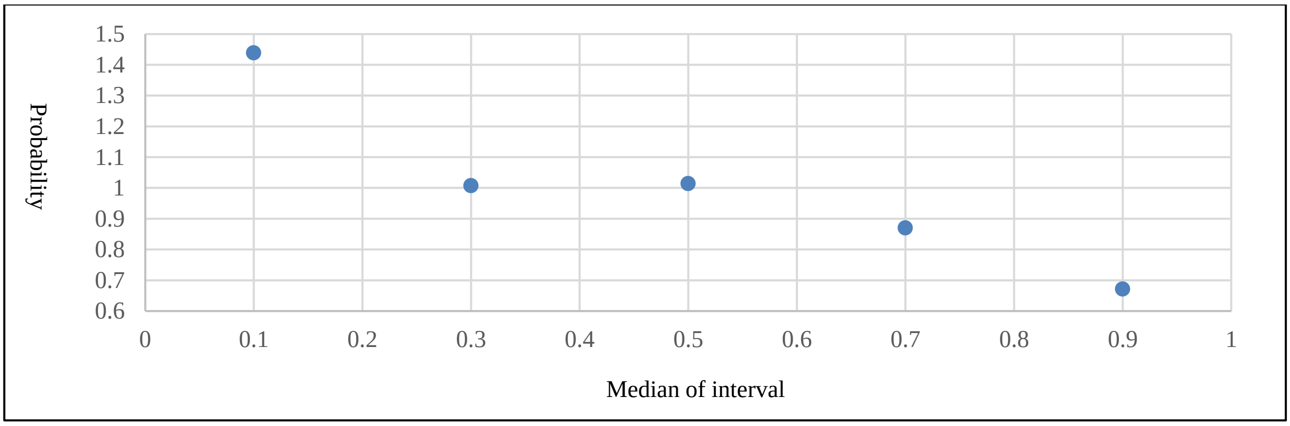

Fig. 5 Probability distribution diagram of ratio of China aviation network edge vertices degree in 2001.

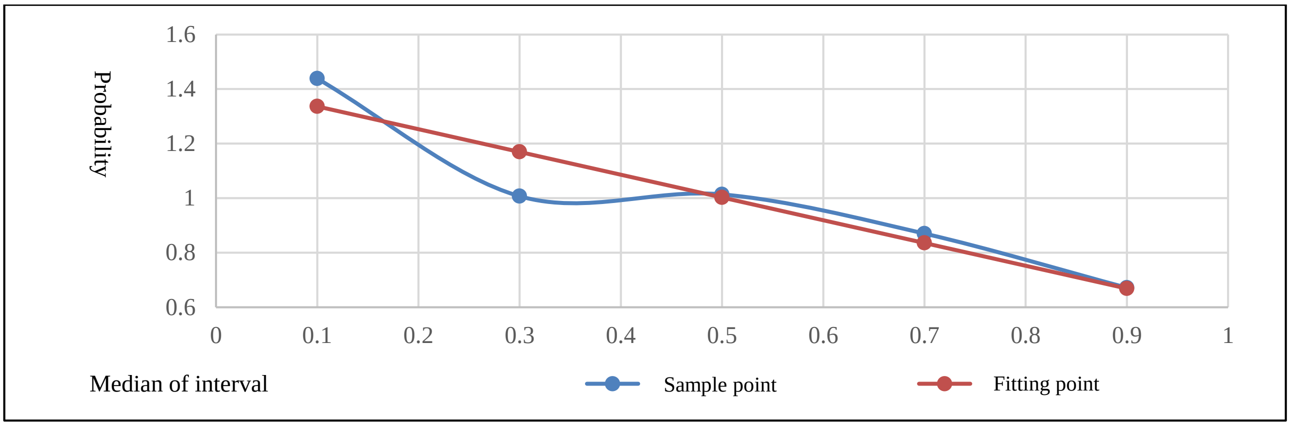

Fig. 6 Fitting effect diagram of probability distribution of ratio of edge vertices degree in 2001.

$$\begin{cases} \hat{\beta}_0 = \bar{y} - \hat{\beta}_1 \bar{x} = 1.418 \\ \hat{\beta}_1 = \dfrac{L_{xy}}{L_{xx}} = \text{-}0.835 \end{cases} \quad (13)$$

The linear equation:

$$\hat{y} = 1.418\text{-}0.835x \quad (14)$$

The fitting line Eq. (14) were drawn with the sample points in one diagram of Fig. 6 with good fitting effect.

To take t test of Eq. (14), test hypotheses is: $H_0 : \beta_1 = 0$.

When the hypotheses is true, there is: Eq. (8), Eq. (9) and Eq. (10).

Statistic t was calculated by data in Table 3 and Eq. (14), Eq. (9), Eq. (10): $t = \text{-}4.67$

To check the t distribution table, at significant level α of 0.01 and degree of freedom $f = n - 2 = 3$ the value of $t_{\left| \substack{\alpha=0.01 \\ f=3} \right.}$ in table is 4.541.

So, $|t| = 4.67 > 4.541 = t_{\left| \substack{\alpha=0.01 \\ f=3} \right.}$, null hypotheses H_0 is refused. The linear correlation of Eq. (14) is significant.

2.4 Probability Distribution of Ratio of Edge Vertices Degree in China Aviation Network in 2008

The adjacent matrix A_{2008} was gotten from statistic data. The ratio of edge vertices degree D_n^{EVR} ($n = 1, 2, 3, ..., 940$) of 940 edges in 2008 were gotten from A_{2008} and Eq. (2). The data in Table 4 was done statistics by these data according to the interval in Table 4. The scattered points in Fig. 7 were drawn by the data in Table 4. The definition of parameters and relationship of parameters were similar with Eq. (3) and Eq. (4) in (2.1). Here, $N_{2008}^E = 940$, $m_{2008} = 10$, $\delta_{2008} = 0.1$.

Here, $n = 10$. Using the data in Table 4, the value of correlation coefficient r was calculated by Eq. (5), $r = -0.728$. The critical value of $r_{\left| \substack{\alpha=0.05 \\ f=8} \right.}$ was 0.632 found in critical value table at degree of freedom $f = n - 2 = 8$ and level of significant α of 5%. Since $|r| = 0.728 > 0.632 = r_{\left| \substack{\alpha=0.05 \\ f=8} \right.}$, the scattered points in Fig. 7 had significant linear correlation. Least square method was used as an approach in Eq. (15) to fit the line with points in Fig. 7.

$$\begin{cases} \hat{\beta}_0 = \bar{y} - \hat{\beta}_1 \bar{x} = 1.5 \\ \hat{\beta}_1 = \dfrac{L_{xy}}{L_{xx}} = \text{-}0.998 \end{cases} \quad (15)$$

The linear equation:

$$\hat{y} = 1.5\text{-}0.998x \quad (16)$$

The fitting line Eq. (16) were drawn with the sample points in one diagram of Fig. 8 with good fitting effect

To take t test of Eq. (16), test hypotheses is: $H_0 : \beta_1 = 0$.

Table 4 Probability distribution of ratio of China aviation network edge vertices degree in 2008

Interval	[0, 0.1]	(0.1, 0.2]	(0.2, 0.3]	(0.3,0.4]	(0.4, 0.5]	(0.5, 0.6]	(0.6, 0.7]	(0.7, 0.8]	(0.8,0.9]	(0.9, 1]
Median	0.05	0.15	0.25	0.35	0.45	0.55	0.65	0.75	0.85	0.95
Times	189	129	65	85	94	89	79	74	76	60
Frequency	0.201	0.137	0.069	0.09	0.1	0.095	0.084	0.079	0.081	0.064
Probability	2.012	1.372	0.691	0.904	1	0.947	0.84	0.787	0.809	0.638

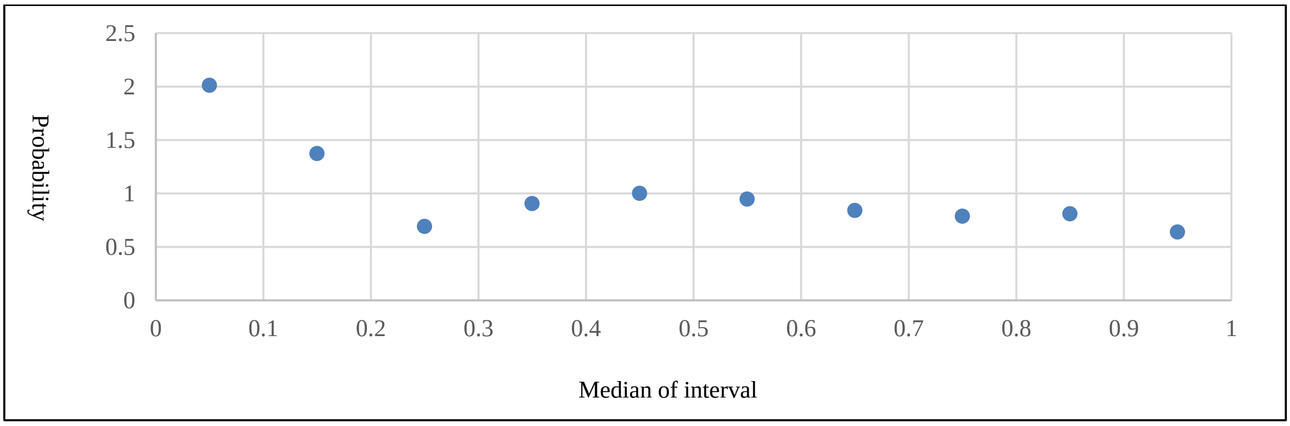

Fig. 7 Probability distribution diagram of ratio of China aviation network edge vertices degree in 2008.

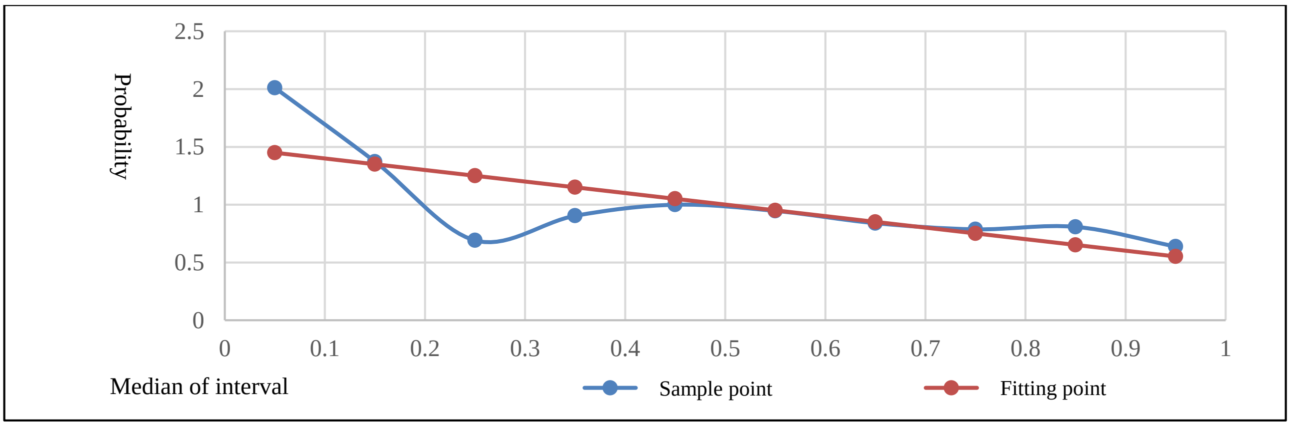

Fig. 8 Fitting effect diagram of probability distribution of ratio of edge vertices degree in 2008.

When the hypotheses is true, there is: Eq. (8), Eq. (9) and Eq. (10).

Statistic t was calculated by data in Table 3 and Eq. (16), Eq. (9), Eq. (10): $t = -3.02$

To check the t distribution table, at significant level α of 0.01 and degree of freedom $f = n-2 = 8$ the value of $t_{|_{\alpha=0.01, f=8}}$ in table is 2.896. So, $|t| = 3.02 > 2.896 = t_{|_{\alpha=0.01, f=8}}$, null hypotheses H_0 is refused. The linear correlation of Eq. (16) is significant.

2.5 Probability Distribution of Ratio of Edge Vertices Degree in China Aviation Network in 2015

The adjacent matrix A_{2015} was gotten from statistic data. The ratio of edge vertices degree D_n^{EVR} ($n = 1, 2, 3, ..., 1924$) of 1924 edges in 2015 were gotten from A_{2015} and Eq. (2). The data in Table 5 was done statistics by these data according to the interval in Table 5. The scattered points in Fig. 9 were drawn by the data in Table 5. The definition of parameters and relationship of parameters were similar with Eq. (3) and Eq. (4) in (2.1). Here, $N_{2015}^{E}=1924$, $m_{2015}=5$, $\delta_{2015}=0.2$.

Here, $n=5$. Using the data in Table 5, the value of correlation coefficient r was calculated by Eq. (5), $r=-0.917$. The critical value of $r|_{\alpha=5\%, f=3}$ was 0.878 found in critical value table at degree of freedom $f=n-2=3$ and level of significant α of 5%. Since $|r|=0.917>0.878=r|_{\alpha=0.05, f=3}$, the scattered points in Fig. 9 had significant linear correlation. Least square method was used as an approach in Eq. (17) to fit the line with points in Fig. 9.

$$\begin{cases}\hat{\beta}_0=\bar{y}-\hat{\beta}_1\bar{x}=1.803\\ \hat{\beta}_1=\frac{L_{xy}}{L_{xx}}=-1.605\end{cases} \quad (17)$$

The linear equation:

$$\hat{y}=1.803-1.605x \quad (18)$$

The fitting line Eq. (18) were drawn with the sample points in one diagram of Fig. 10 with good fitting effect

To take t test of Eq. (18), test hypotheses is: $H_0:\beta_1=0$.

Table 5 Probability distribution of ratio of China aviation network edge vertices degree in 2015.

Interval	[0, 0.2]	(0.2, 0.4]	(0.4, 0.6]	(0.6,0.8]	(0.8, 1]
Median	0.1	0.3	0.5	0.7	0.9
Times	736	426	303	256	203
Frequency	0.383	0.221	0.157	0.133	0.106
Probability	1.913	1.107	0.787	0.665	0.528

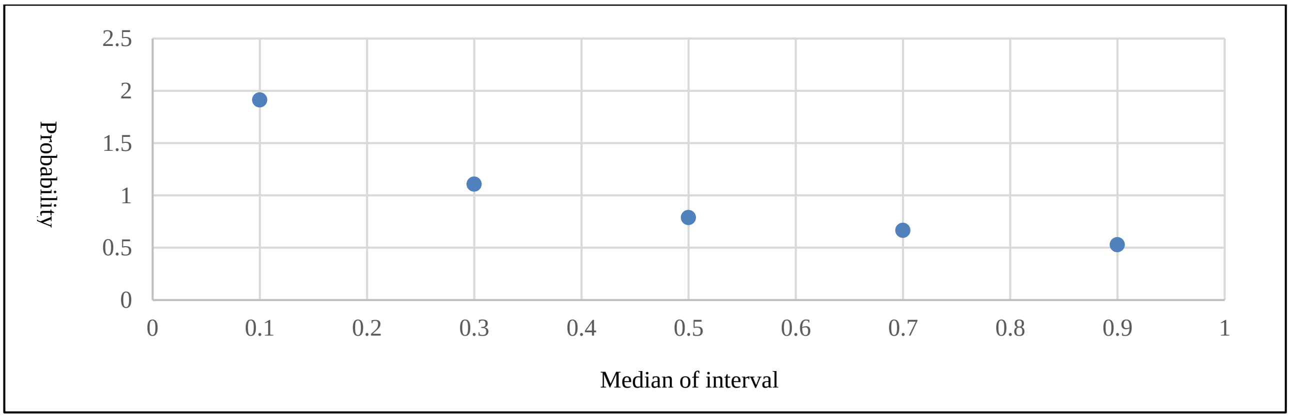

Fig. 9 Probability distribution diagram of ratio of China aviation network edge vertices degree in 2015.

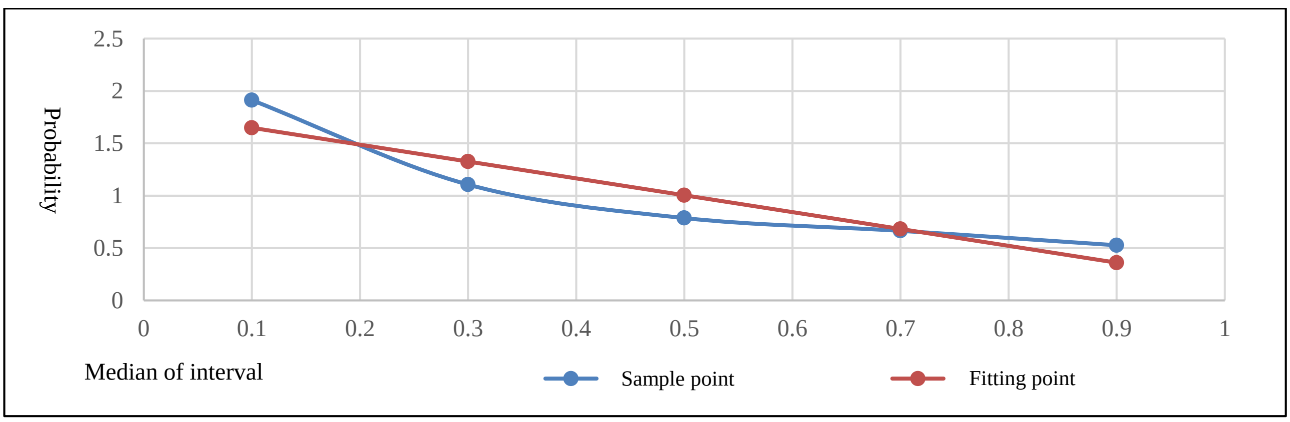

Fig. 10 Fitting effect diagram of probability distribution of ratio of edge vertices degree in 2015.

When the hypotheses is true, there is: Eq. (8), Eq. (9) and Eq. (10).

Statistic t was calculated by data in Table 3 and Eq. (18), Eq. (9), Eq. (10): $t = -4.01$

To check the t distribution table, at significant level α of 0.025 and degree of freedom $f = n - 2 = 3$ the value of $t|_{\alpha=0.025, f=3}$ in table is 3.182.

So, $|t| = 4.01 > 3.182 = t|_{\alpha=0.025, f=3}$, null hypotheses H_0 is refused. The linear correlation of Eq. (18) is significant.

2.6 Evolution of the Probability Distribution of Ratio of China Aviation Network Edge Vertices Degree

Plotting the linear Eq. (10), (12), (14), (16) and (18) of the probability distribution of ratio of China aviation network edge vertices degree in Fig. 11, it can be found that the five lines in Fig. 11 are the probability distributions of 1988, 1994, 2001, 2008 and 2015, and the lines all pass through the point (0.5.1). These lines are concentrated in a small area, intersecting in an "X" shape with approximate slopes and intersecting midpoints.

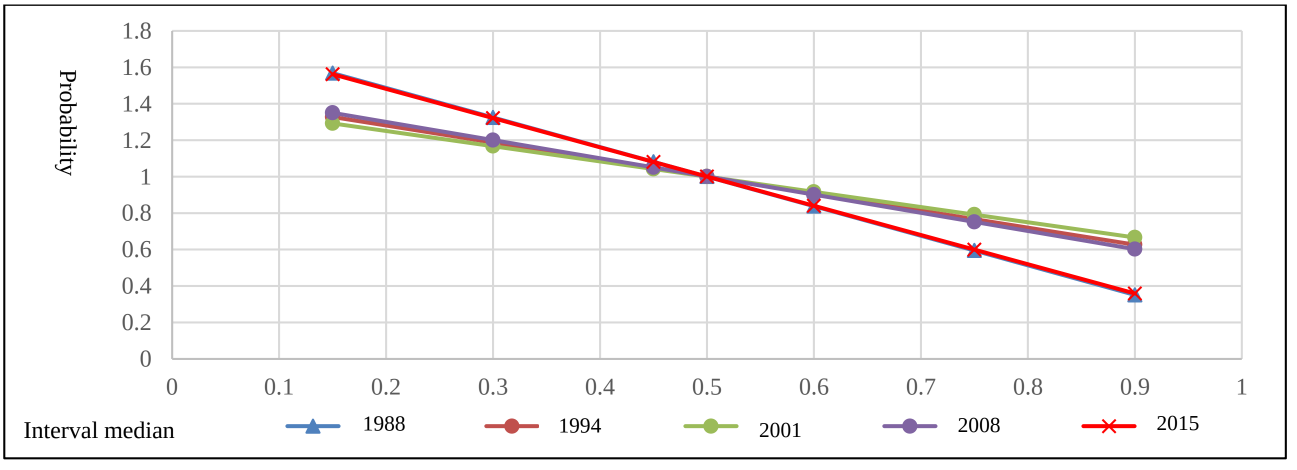

Fig. 11 The evolution diagram of probability distribution lines of ratio of China aviation network edge vertices degree.

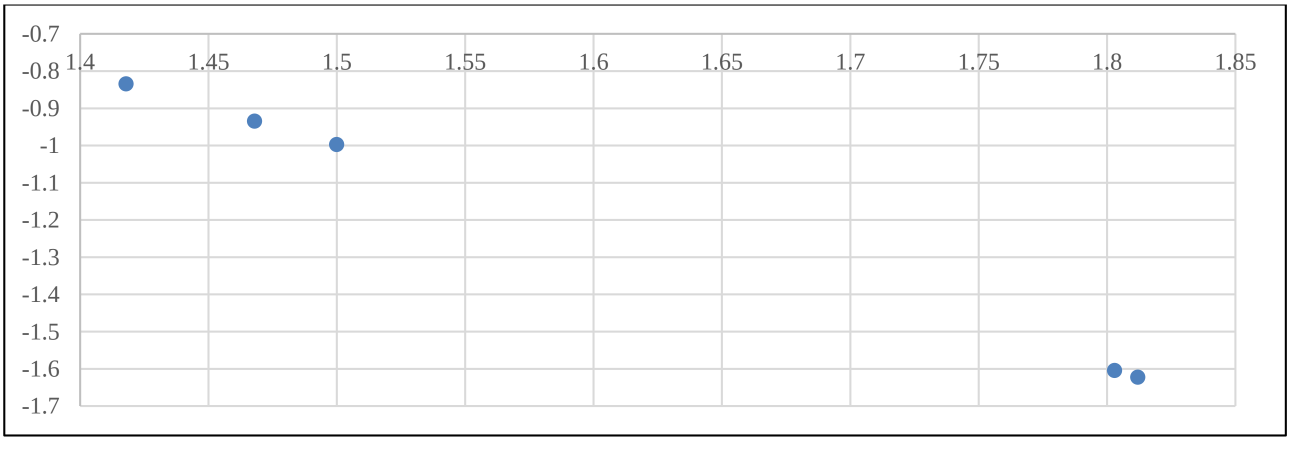

Fig. 12 The scattered points diagram of parameter relationship of probability distribution of ratio of edge vertices degree.

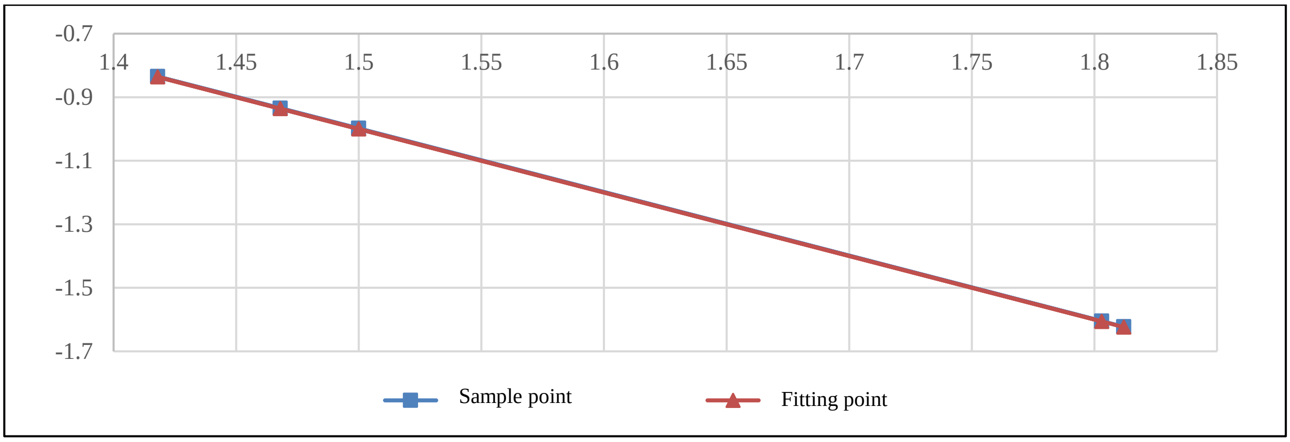

Fig. 13 The fitting effect diagram of linear relationship of probability distribution of ratio of edge vertices degree.

3. The Evolution Trace of Probability Distribution Parameters of Ratio of China Aviation Network Edge Vertices Degree

The evolution relationship between the probability distribution parameters of ratio of China aviation network edge vertices degree is investigated. The two parameters of the linear equation are taken as one point. There are five points in the five linear equations: $(1.182,-1.623)$, $(1.468,-0.935)$, $(1.418,-0.835)$, $(1.5,-0.998)$ and $(1.803,-1.605)$. These five points were drawn in Fig.12.

Here, $n=5$. The value of correlation coefficient r of Fig.12 was calculated by Eq. (5), $r=-0.999$. The critical value of $r_{|\alpha=1\%, f=3}$ was 0.959 found in critical value table at degree of freedom $f=n-2=3$ and level of significant α of 1%. Since $|r|=0.999>0.959=r_{|\alpha=0.01, f=3}$, the scattered points in Fig. 12 had significant linear correlation. Least square method was used as an approach in Eq. (19) to fit the line with points in Fig. 12.

$$\begin{cases} \hat{\beta}_0 = \bar{y} - \hat{\beta}_1 \bar{x} = 2 \\ \hat{\beta}_1 = \dfrac{L_{xy}}{L_{xx}} = -2 \end{cases} \tag{19}$$

The linear equation:

$$\hat{y} = 2\text{-}2x \tag{20}$$

The fitting line Eq. (20) was drawn with the sample points in one diagram of Fig. 13 with good fitting effect

To take t test of line Eq. (20), test hypotheses is: $H_0 : \beta_1 = 0$.

When the hypotheses is true, there is Eq. (8), Eq. (9) and Eq. (10).

Statistic t was calculated by Eq. (20), Eq. (9), Eq. (10): $t=\text{-}470$

To check the t distribution table , at significant level α of 0.01 and degree of freedom $f=n-2=3$ the value of $t_{|\alpha=0.01, f=3}$ in table is 4.541.

So, $|t|=470>4.541=t_{|\alpha=0.01, f=3}$, null hypotheses H_0 is refused. The linear correlation of Eq. (20) is significant. The linear relationship between two parameters in Fig. 13 illustrated that the evolution of probability distribution of ratio of China aviation network edge vertices degree had linear trace.

4. Conclusion

Based on the statistics of China civil aviation of in 1988, 1994, 2001, 2008 and 2015, the probability distribution and evolution trace of the ratio of China aviation network edge vertices degree were studied. According to the theory and method of complex network, the network system was constructed with the city where the airport was located as the network node and the route between cities as the edge of the network. The ratio of edge vertices degree was calculated, and it was found that it had linear probability distribution and the two parameters of the probability distribution had linear evolution trace.

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