Planar Distribution Model of Airport Pavement Traffic Volume

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Abstract: The current specification of airport pavement design and evaluation had seldom pointed out the longitudinal distribution of airport pavement traffic volume (APTV) except the wheel offset at the edge or the central section of the runway. In this study, the characteristics of APTV were pointed out, which revealed that every point of the pavement had a different traffic volume. Then using the longitudinal traffic factors, the planar distribution model was established. At last, influence factors of APTV including take-off probability ratio at one side, runway length, take-off running distance and lateral distribution were analyzed. Examples and analysis showed that only considering the lateral distribution of APTV would make the pavement design more conservative.

1. Introduction

Airport pavement traffic volume (APTV) refers to the aircraft passing through a certain section of the pavement plane during takeoff, landing, and skating, which determines the cumulative repeated actions of the wheel load [1]. It is one of the important indicators for the design of airport pavement. Influenced by the highway design specification, the APTV distribution model is limited to the lateral distribution, which has experienced the course from the uniform distribution to the normal distribution [2]. Pass-to-coverage ratio was put forward and uniform traffic volume distribution model was built by Vedros in USA Army Engineering Laboratory [3]. The field survey and analysis of aircraft distribution on airport pavement conducted by Brown and Hosang [4][5] indicated that the distribution is more nearly represented by a theoretical normal distribution function than by a uniform distribution function. The newly revised FAA Airport Pavement Design and Evaluation (AC 150/5320-6F) in 2016 assumed that the lateral APTV obeyed normal distribution. And repeated action numbers of wheel load were calculated by the pass-to-coverage ratio [6].

The first aircraft wheel track test in China was conducted by air force army. Li and Wang et al had recorded the takeoff and landing wheel track of different types of military aircraft, and all of them drawn the conclusion that the lateral APTV obeys the normal distribution [7][8]. Chinese specifications for asphalt pavement design of civil airports (MH/T 5010-2017) [9] adopted the cumulative damage curve design method also based on the normal distribution of lateral traffic volume. The researches of Lin and Li [10][11] showed that it is more accurate using normal distribution in
coverage calculation. The model of lateral traffic normal distribution had been widely used in the pavement design and the prediction of pavement remaining life [12]. Previous studies had seldom pointed out the longitudinal characters of APTV except the wheel offset at the edge or middle of the runway. This paper established a planar distribution model of APTV to describe its lateral and longitudinal features. The effect of probability of take-off/landing at one side of the runway, runway length, take-off/landing running distance and variance in lateral distribution on maximum value of APTV was analysis. The purpose of this study was to provide APTV guidance for dividing zone of airport runway and the design of pavement thickness. Besides, the model also could be used to develop a cumulative damage surface method for airport pavement design.

2. Planar distribution model of APTV
The Cartesian coordinate system was setup with the point at the mid-point of the runway edge. The lateral edge of the runway is in x-direction, and the center line of the pavement is y-axis.

2.1. Longitudinal distribution model of APTV
The longitudinal traffic factor, \( f_y(x, y) \), could be calculated by the following Eq. (1) to reflect the longitudinal distribution of APTV.

\[
f_y(x, y) = \frac{N_y}{N}
\]  

Where \( N_y \) is the traffic volume passing through the transverse section at y point, \( N \) is the total number of the traffic volume.

2.1.1. Longitudinal distribution model of APTV during landing
The research of Cai [12] had declared that the position of landing obeys the normal distribution, that is to say, \( y_l \sim N(\mu_l, \sigma_l^2) \). Supposing the aircraft landed at one side of the runway and departed the pavement at the end of the other side. The longitudinal traffic factor at point of y could be calculated by the shaded area in Figure 2.

Following the 3 \( \sigma \) criterion of normal distribution, Eq. (2) gives the calculating method of \( f_{y_l}(x, y) \).

\[
f_{y_l}(x, y) = \begin{cases} 
\frac{1}{\sqrt{2\pi\sigma_l^2}} \int_{-\infty}^{y_{-3\sigma_l}} e^{-\frac{(y-\mu_l)^2}{2\sigma_l^2}} dy, & \mu_l-3\sigma_l < y < \mu_l+3\sigma_l \\
1, & \mu_l+3\sigma_l < y < L
\end{cases}
\]  

Where \( f_{y_l}(x, y) \) refers to the longitudinal traffic factor of landing. \( \mu_l \) and \( \sigma_l \) are the mean value and the standard deviation of landing position, respectively. \( L \) is the length of the runway.

2.1.2. Longitudinal distribution model of APTV during take-off
Li [7] had conducted the study on runway length reliability design method. The test results of take-off point and departure point position all have a normal distribution, \( y_{q1} \sim N(\mu_{q1}, \sigma_{q1}^2) \), \( y_{q2} \sim N(\mu_{q2}, \sigma_{q2}^2) \).

At the point of \( y_1 \) and \( y_2 \), the longitudinal traffic factor during take-off could be obtained by the shaded area illustrated as Figure 3. In the distance of take-off run, \( \mu_{q1} + 3\sigma_{q1} < y < \mu_{q1} - 3\sigma_{q1} \), the \( f_{y_q}(x, y) \) equal to 1. The longitudinal traffic factor during take-off can be obtained from Eq. (3).
Where $\mu_{yq}$ and $\sigma_{yq}$ are the mean value and standard deviation of take-off point, $\mu_{yq}$ and $\sigma_{yq}$ are mean value and standard deviation of departure point.

2.2. Lateral Distribution Model of ATPV
Lukuan [13] revealed that the aircraft skews off the runway center line during take-off and rectifies the deviation during landing. The standard deviation varies linearly with the sliding distance. The lateral traffic factor of landing and take-off can be determined by Eq. (4) and Eq. (5).

$$f_{xl}(x, y) = \begin{cases} \frac{1}{\sqrt{2\pi\sigma_{yl}}} \int_{-\infty}^{\mu_{yl}} e^{-\frac{(y-\mu_{yl})^2}{2\sigma_{yl}^2}} dy, & \mu_{yl} - 3\sigma_{yl} < y < \mu_{yl} + 3\sigma_{yl} \\ 1, & \mu_{yl} + 3\sigma_{yl} < y < \mu_{yl} - 3\sigma_{yl} \\ \frac{1}{\sqrt{2\pi\sigma_{yq}}} \int_{-\infty}^{\mu_{yq}} e^{-\frac{(y-\mu_{yq})^2}{2\sigma_{yq}^2}} dy, & \mu_{yq} - 3\sigma_{yq} < y < \mu_{yq} + 3\sigma_{yq} \end{cases}$$

(3)

Where $\mu_{yl}$ and $\sigma_{yl}$ are the mean value and standard deviation of take-off point, $\mu_{yq}$ and $\sigma_{yq}$ are mean value and standard deviation of departure point.

Where $\mu_{xl}$ and $\sigma_{xl}$ are the mean value and standard deviation of the offset distance from the runway center line to the aircraft mid-line for landing point. $\mu_{xq}$ and $\sigma_{xq}$ are the same parameters for take-off initial point. $k_l$ and $k_q$ are the variation rate of the offset distance standard deviation along the runway for landing and take-off, which can be obtain from the following Eq. (6) and Eq. (7).

It is assumed that standard deviation remain constant within the $3\sigma$ distance.

$$k_l = \begin{cases} 0, & \mu_{jl} - 3\sigma_{jl} < y < \mu_{jl} + 3\sigma_{jl} \\ \frac{\sigma_{xl} - \sigma_{xl}}{L - (\mu_{jl} + 3\sigma_{jl})}, & \mu_{jl} + 3\sigma_{jl} < y < L' \\ 0, & L' < y < L \end{cases}$$

(6)

$$k_q = \begin{cases} 0, & \mu_{jq} - 3\sigma_{jq} < y < \mu_{jq} + 3\sigma_{jq} \\ \frac{\sigma_{xq} - \sigma_{xq}}{L - (\mu_{yq} + 3\sigma_{yq} + \mu_{yq} - 3\sigma_{yq})}, & \mu_{yq} + 3\sigma_{yq} < y < \mu_{yq} - 3\sigma_{yq} \\ 0, & \mu_{yq} - 3\sigma_{yq} < y < \mu_{yq} + 3\sigma_{yq} \end{cases}$$

(7)

Where $\sigma_{xq}$ is the standard deviation of the offset distance from the runway center line to the aircraft mid-line for take-off departure position at the point of $\mu_{yq} - 3\sigma_{yq}$. $L'$ refers to the mean value of distance when the velocity decreases to taxiing speed.

2.3. Planar Distribution Model of ATPV
Assuming that the numbers of take-off and landing ATPV are all $N$ times, and the probability ration of take-off and landing at one side to the other is $a : b$ ($a + b = 1$), the traffic volume for landing and take-off at any point of the runway, $N_{s,y}$, can be represented by Eq. (8) and Eq. (9), respectively.
It can be seen from the formulas that the longitudinal traffic factor is a probability representation of the total number of aircraft passing through a transverse section, while the lateral distribution is the "flow" of each point. Their joint distribution determines the APTV at every point of the pavement.

3. Simulation example

It is assumed that the aircraft can only take off and land at one side of the runway. The annual take-off and landing of a certain type of aircraft is 10000 times. The length of the runway is 2800m. The lateral distribution of the take-off and landing obeys normal distribution. The lateral mean value is 0m and the standard deviation is 0.775m at the take-off point. Then the standard deviation increases linearly to 1.550m at the point of take-off departure. The mean value and the standard deviation of lateral distribution are 0m and 1.55m at landing point. the standard deviation decreases linearly in the landing skid process, and the standard deviation changes to 0.755m when the aircraft slows down to the taxiing speed. And then the plane slides out of the pavement in the same lateral distribution. The longitudinal distributions of traffic volume are shown in Table 1.

| Take-off | Mean value at the take-off initial point | Standard deviation at the take-off initial point | Mean value at the take-off departure point | Standard deviation at the take-off departure point | Annual take-off traffic volume |
|----------|----------------------------------------|-----------------------------------------------|------------------------------------------|-----------------------------------------------|-------------------------------|
|          | 50m                                    | 10m                                           | 2000m                                    | 200m                                          | 10000m                        |
| landing  | Mean value at the landing point         | Standard deviation at the landing point        | Mean value of distance when the velocity decreases to taxiing speed | Standard deviation of distance when the velocity decreases to taxiing speed | Annual landing traffic volume |
|          | 200m                                    | 40m                                           | 1600m                                    | 160m                                          | 10000m                        |

Figure 1. (a) Perspective View

Figure 1. (b) Front View
Figure 1 and Figure 2 show the distribution surface of the APTV obtained from the above models. It is obvious that the aircraft tracks distribute on the whole runway. If only considered the lateral distribution of the traffic, the APTV is displayed in Figure 3 and Figure 4.
It can be seen that the traffic volume curve model, which only considers lateral distribution, is a special case of the planar model. In fact, the traffic volume in present FAA airport pavement design and evaluation (AC 150/5320-6F) is a marginal distribution of the planar model. Ignoring the longitudinal distribution of traffic volume will overestimate the APTV and make the pavement thickness design more conservative.

4. Conclusion
In this study, the planar model of airport pavement traffic volume was built. The following conclusions can be drawn from the research:

Characteristic of APTV indicated that the distribution of traffic volume on airport runway was a planar model. The longitudinal traffic factor was put forward to describe the longitudinal distribution.

Simulation that aircrafts only takeoff and land at one side of the runway was made. Comparison with the method proposed by FAA Airport Pavement Design and Evaluation (AC 150/5320-6F), the model in this research was more comprehensive. Ignoring the longitudinal distribution will make the pavement thickness design more conservative.

Acknowledgments
This research was founded by the two National Nature Science Foundations of China under grand number 51578540 and 51608526. The authors give special thanks to Liangcai Cai and Duoyao Zhang and Guanhu Wang for their contribution to the study.

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