Research on Influence and Prediction Model of Urban Traffic Link Tunnel curvature on Fire Temperature Based on Pyrosim–SPSS Multiple Regression Analysis

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Abstract. The underground space, also known as the “fourth dimension” of the city, reflects the efficient use of urban development intensive. Urban traffic link tunnel is a typical underground limited-length space. Due to the geographical location, the special structure of space and the curvature of the tunnel, high-temperature smoke can easily form the phenomenon of “smoke turning” and the fire risk is extremely high. This paper takes an urban traffic link tunnel as an example to focus on the relationship between curvature and the temperature near the fire source, and use the pyrosim built different curvature fire model to analyze the influence of curvature on the temperature of the fire, then using SPSS Multivariate regression analysis simulate curvature of the tunnel and fire temperature data. Finally, a prediction model of urban traffic link tunnel curvature on fire temperature was proposed. The regression model analysis and test show that the curvature is negatively correlated with the tunnel temperature. This model is feasible and can provide a theoretical reference for the urban traffic link tunnel fire protection design and the preparation of the evacuation plan. And also, it provides some reference for other related curved tunnel curvature design and smoke control measures.

1. Introduction
Urban traffic tunnel is a new type of underground link tunnel, which combines the characteristics of underground buildings and urban road tunnels[1]. Due to geographical location, complex functions, and environmental specialities, the spatial structure and fire risk are quite different from those of general traffic tunnels. The tunnel is limited narrow space and the cross section relatively small. The driving vehicle is complex, and the location of the fire is random. There are many connections with underground garages and traffic arterial roads. In order to avoid dense buildings and underground pipelines and other facilities, many use different curvature tunnel[2,3]. The greater the curvature of the tunnel, the more difficult it is to ensure that the sight distance within the tunnel is highly likely to cause a fire accident and form a large number of dead corners where high-temperature flue gas accumulates. Due to the presence of curvature, the phenomenon of “smoke swirling” is easily formed at the circular path. According to the relevant research, the maximum temperature of the tunnel fire can reach 1200-1365°C, and the temperature at the circular path will be higher when the curvature is...
affected\cite{4-5}. Therefore, it is very important to explore the relationship between the curvature of urban traffic link tunnel and the environmental temperature of fire.

The first underground orbit on the earth was built in London in 1863\cite{6-7}. China’s underground rail transit started relatively late and was first constructed by Beijing and Tianjin. Domestic and foreign scholars have conducted research on tunnel fire fighting design and many other aspects. The United States Memorial tunnel fire ventilation test program is currently the most comprehensive flue gas control experiment in the study of tunnel ventilation experiments. This experiment studied the parameters such as temperature, smoke, and visibility in the tunnel under different ventilation modes in the 854m long tunnel\cite{8}, Kurioka et al\cite{9}, explored the temperature field near the fire source in 2003 through a full-size tunnel, a 1/2 model-size tunnel, and a 1/10 model-size tunnel test. Based on the Alpert maximum temperature equation, Ji Jie\cite{10} and others analysed the maximum temperature equation of the subway platform and obtained the equation of the maximum temperature of the fire source at different distances from the side wall through small-scale experiments. Dong Xing guo\cite{11} used the FDS software in 2014 to determine the optimal flue gas control program by changing the vertical wind speed in the UTLT tunnel and the exhaust smoke volume at the exhaust outlet. In 2015, Tao Du\cite{12} et al. proposed a new method of longitudinal smoke extraction from circular tunnels by dividing the exhaust smoke network into a branch network. In 2016, Li Sicheng\cite{13} simulated the boundary conditions of heat release rate and longitudinal ventilation velocity of UTLT tunnels by numerical simulation and small-scale model, and obtained parameter prediction models such as maximum fire temperature and flue gas return length.

The underground space is also called the “fourth dimension space” of the city. The layout methods mainly include three types: annular linkage, ridge axis driving, and dendritic growth. The “network island chain” and “compact polymerization” of the morphological structure restrain “city disease” and enabled the efficient transformation of underground space in the space-time dimension\cite{14-22}. However, most tunnel fire researches are conventional straight tunnels. There are few studies on the environmental impact of complex curved tunnel structures such as urban traffic link tunnel, and there are few reports on the influence of curvature of the tunnel on the temperature of the fire. This paper takes an urban traffic link tunnel as an example, uses pyrosim to establish a different curvature fire model, uses SPSS to carry out multiple regression analysis on tunnel curvature and fire temperature simulation data, and finally puts forward a prediction model of the impact of tunnel curvature on the temperature near the fire source. The research results can provide a theoretical reference for the design code of fire protection in urban traffic link tunnel and preparation of personnel evacuation plans. At the same time, it can provide some reference for other relevant curve tunnel curvature design and smoke control measures.

2. Research object profile

Based on the previous research, this paper takes an urban traffic link tunnel as the research object. The length of the main tunnel in the city center is 2800m, the net height and the net width are 4m and 11m respectively and there are 42 points in the tunnel. There are eight entrances and exits for the lanes and ground contact passages, with one-way counterclockwise three lanes. Due to the existence of curvature, there are many curved tunnels in the tunnel. The detailed diagrams of the tunnel building plan, part of the structure diagram and tunnel curve structure are shown in Figs. 1 to 3.
3. **Research methods**

3.1 **Introduction to PyroSim Numerical Simulation**

FDS is one of the most widely used fire dynamics simulation software based on the field model in the field of fire protection [24]. PyroSim is pre-processing and post-processing software developed by Thunderhead Engineering in the US on the basis of FDS. The most important feature of PyroSim is that it not only accurately simulates changes in smoke parameters such as smoke temperature, visibility, and CO concentration in the fire, but also enables visual editing and three-dimensional graphical pre-processing [3,24]. Compared with FDS, the calculation method is more optimized and modeling is more fasted. In this paper, Pyrosim software is used to model and analyze the urban tunnel fire.

3.2 **Multivariate regression model**

To study the relationship between the quantitative change of a dependent variable affected by two or more independent variables, called multiple regression analysis [25]. Establish a relationship between the dependent variable Y and n independent variables, and describe the equation of the dependent variable Y with the independent variable and the error term as a multiple regression model. Expressed as [25]:

\[ Y = \beta_0 + \beta_1 \chi_1 + \beta_2 \chi_2 + \cdots + \beta_n \chi_n + \varepsilon \]

In the formula, \( \beta_0, \beta_1, \beta_2, \cdots, \beta_n \) are regression parameters; \( \varepsilon \) is an error term.

After finding the regression model, a significant test was performed. Hypothesis [24-25]:

\[ H_0 : a_1 = a_2 = \cdots = a_p = 0 \]

The sum of the square of the total deviation of the dependent variable Y from the average is:

\[ Q_T = \sum_{i=1}^{n} \left( Y_i - \hat{Y} \right)^2 = \sum_{i=1}^{n} \left( Y_i - \hat{Y} \right)^2 + 2 \sum_{i=1}^{n} \left( Y_i - \hat{Y} \right) \left( Y_i - \hat{Y} \right) + \sum_{i=1}^{n} \left( \hat{Y} - \bar{Y} \right)^2 \]

Because of:

\[ \sum_{i=1}^{n} \left( Y_i - \hat{Y} \right) \left( Y_i - \hat{Y} \right) = \mathbf{v}^T A \mathbf{\beta} = 0 \]

And so:

\[ R^2 = \frac{Q_T}{Q_T}, \quad 0 \leq R^2 \leq 1 \]

Hypothesis:
\[ F = \frac{Q_p}{\sigma^2} \frac{1}{p-1} = \frac{Q_p}{\sigma^2} (n - p - 1)^{-1} \sim F(p, n - p - 1) \]

Through the level of significance, and check the F distribution table, we can conclude if \( F > F(p, n - p - 1) \), \( H_0 \) is rejected. That means the regression model has significant effect \([24-25]\).

4. Model establishment and analysis

4.1 Pyrosim model

According to the actual size of urban underground tunnel, Pyrosim fire numerical simulation software was used to establish the tunnel fire model. During the simulation process, the growth rate of the fire environment is set to \( t \) rapid growth. Refer to relevant domestic and foreign data and conservatively consider that in this study, the fire source power is taken as 10MW, and the mesh is divided into \( 0.2 \times 0.2 \times 0.2 \text{m} \). This study mainly analyzes the influence of the curvature of the circle on the temperature of the fire field under the conditions of curvature ratios of 1/10, 1/20, and 1/30. The location of the fire source is set at the bend of the tunnel, and the ventilation speed is taken according to relevant fire design specifications. The value is 3m/s without considering the slope effect. In order to determine the temperature change of the attachment of the fire source, multiple temperature measurement points were set at the location of the ring fire source at a position 30 meters apart from the downwind direction and 2 meters from the bottom of the tunnel. The final fire simulation dynamic model is shown in Figure 4.

![](Figure 4. Urban traffic link tunnel Pyrosim Model)

4.2 Analysis of Fire Temperature in Pyrosim Model

Fig. 5 to Fig. 7 are simulations of temperature changes in the vicinity of a fire source in a circular path under different curvatures, and Fig. 8 is a graph showing the relationship between temperature and curvature of the tunnel at different positions near the fire source obtained from the analysis of simulated calculation data. From the figure, it can be analyzed that the higher the temperature near the fire source with the increase of the curvature, the temperature of the fire source is higher, and the highest temperature up to 450°C when the curvature is 1/30 compared to the other two curvature conditions. With the increase of the distance from the fire source, the temperature of the tunnel gradually decreases. Ventilation factors affect high-temperature smoke more easily gather in the
downwind direction, so the lower temperature is higher than the upper wind direction. At a distance of 10m or 30m from the location of the fire source, the larger the curvature is, that is, the smaller the radius of the tunnel is, the more difficult the high-temperature flue gas is to diffuse. The curvature is one of the main factors affecting the tunnel temperature.

Figure 5. Temperature Near Fire Site of Curvature 1/10

(a) 300s fire temperature  (b) 600s fire temperature

Figure 6. Temperature Near Fire Site of Curvature 1/20

(a) 300s fire temperature  (b) 600s fire temperature

Figure 7. Temperature Near Fire Site of Curvature 1/10

(a) 300s fire temperature  (b) 600s fire temperature
4.3 Multiple regression model establishment and analysis

The temperature of the urban traffic link tunnel is affected by many factors. This study has conducted multiple regression analysis of the curvature of the tunnel and the temperature near the fire source. Build a predictive regression model:

\[ Y = \beta_0 + \beta_1 \chi_1 + \beta_2 \chi_2 + \cdots + \beta_n \chi_n + \epsilon \]

The model factors are shown in Table 1:

| Variable name       | Numeric type | Factor description                                                                 |
|---------------------|--------------|-----------------------------------------------------------------------------------|
| Dependent variable Y| Temperature (℃)Y | Continuous This article only discusses the prediction model of the influence of the curvature of the tunnel on the |
The Pyrosim simulation data was analyzed by SPSS software. The results are shown in Table 2. According to Table 2, the available coefficient R2 is 0.585, and the standard error is 118.76084. It shows that there is a linear correlation between the temperature near the tunnel fire source and the curvature of the tunnel X1, the time X2, the distance from the fire source X3, and the wind direction X4.

The coefficients of each variable obtained by regression model coefficient table 3 are:

\[ \beta_0 = 362.474, \beta_2 = 0.060, \beta_3 = -9.653, \beta_4 = 0.013. \]

Therefore, the regression mathematical model for the temperature around the fire source curvature is:

\[ Y = -266.724X_1 + 0.060X_2 + -9.653X_3 + 0.013X_4 + 362.474 \]

### Table 3. Regression coefficients

| Model | Unstandardized Coefficients | Standardized Coefficients | t  | Sig. |
|-------|-----------------------------|---------------------------|----|------|
|       | B                           | Std. Error                | Beta |      |     |
| (Constant) | 362.474 | 16.074 | .174 | 22.550 | .000 |
| X2    | .060 | .010 | .174 | 6.303 | .000 |
| X3    | -9.653 | .717 | -.744 | -13.466 | .000 |
| X4    | .013 | 12.415 | .000 | .001 | .999 |
| X1    | -266.724 | 172.171 | -.043 | -1.549 | .122 |

### 4.4 Test of regression model

Through calculations, we can see from Table 4 that the F statistic is 191.850, and the critical value for which the degree of freedom (p, n-p-1) can be determined by examining the F distribution table is F0.05(4, 544) =2.37. Obviously, the F is much larger than the critical value, so reject H0, the regression equation is significant, that is, and all the independent variables have a significant influence on Y.

The diagonal line in the residual P-P diagram shows a normal distribution with a mean of zero. The scattered points are densely distributed near the diagonal line, indicating that the random variable residual obeys the normal distribution, that is, the selected sample also obeys the normal distribution, and further explains the reliability of the model.
5. Conclusions

Based on Pyrosim and SPSS multiple regression analysis, this paper analyzes and predicts the influence of curvature on the temperature of a fire in urban traffic link tunnel. The results show that:

1) The urban traffic link tunnel is a typical narrow and confined space. The greater the curvature, the more likely the smoke will form a “circling circle”, which will seriously affect the safety evacuation.

2) The higher the temperature, the more difficult to diffuse high temperature smoke. Curvature is one of the main factors affecting the temperature of the tunnel.

3) Multiple regression analysis shows that the curvature of the tunnel is negatively correlated with the temperature near the fire source. The established regression model has certain reliability and can provide reference for the fire protection design of the relevant curve tunnel.

The fire temperature of the urban traffic link tunnel is affected by many factors. This article focuses on the influence of the curvature of the tunnel on the temperature near the fire source, and establishes a mathematical model. The influence of multi-factor coupling will be further studied.

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