A Vehicle Emission Dispersion Simulation Method Considering Obstructions in a Three-dimensional Scene

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***Abstract*—The simulation of vehicle emission dispersion in a three-dimensional (3D) scene is a hot spot and a difficult problem in the field of 3D visualization. The California line source dispersion (CALINE4) model is a classical vehicle emission dispersion model, however it does not applied in a 3D scene and not consider the obstruction effect of 3D objects, such as buildings and trees. Hence, this paper proposes a vehicle emission dispersion simulation method that considers obstructions. First, we introduce an obstruction coefficient and perform a fine division of the line sources to optimize the traditional CALINE4 model. Second, we identify the effective and ineffective line sources of roads based on visibility analysis. Finally, the proposed approach is experimentally validated using an expressway in a Beijing suburb in a 3D visualization system. The experimental validation indicates that the simulation results of pollutants are more in line with real transport and the dispersion law of pollutants from a global perspective. From local details, the pollutant concentration at the periphery of the obstructions is obviously blocked, and the degree of concentration change is obviously affected by the degree of obstruction.**

Keywords—vehicle emission dispersion; CALINE4 model; obstruction effect; 3D visualization

I. INTRODUCTION

Vehicle exhaust emission is one of the main factors of urban air pollution [1, 2]. Emission simulation has always been a hot and difficult research topic that explores the law of vehicle emission dispersion and seeks a control strategy to minimize its impact on the environment [3 - 5]. A Gaussian model is the most commonly used model for simulating the dispersion of atmospheric pollutants [6]. Due to their ease of use, many models such as the GM (General Motors) model [7], HIWAY (Highway) model [8], and CALINE (California line source dispersion) Model [9] have been developed to simulate the emission dispersion process of vehicles on flat & straight highways and low streets. Among them, the CALINE model has been widely used because of the convenience of parameter calibration, good accuracy and the characteristics of adaptive adjustment for different regions [10, 11]. In this paper, the fourth generation CALINE (CALINE4) model and its application in a three-dimensional (3D) scene are further studied and optimized.

CALINE4 is a line source pollution dispersion model based on the Gaussian dispersion equation and the concept of a mixed region, which also takes into account the deposition and settlement rate of pollutants. This model can be used to predict the concentration level of pollutants in the range of 150 m on both sides of the highway [12, 13]. Marmur & Mamane et al. [14] used this model to simulate the CO and NOx concentrations in some regions of Israel. Broderick et al. [15] applied this model to simulate CO concentrations in Ireland. Konar & Chakrabarty [16] applied Caline4 model for NOx in Kolkata Roadway. In India, CALINE4 vehicular pollution dispersion model is extensively use for prediction of air quality along the highway corridors [17-18]. Wang et al. [19] applied this model to simulate the vehicle emission pollution of four main roads in Beijing and Guangzhou, and adopted the actual measured data to correct the model according to the meteorological and traffic characteristics of each city. Previous studies have shown that mixing height along with wind speed determine the volume available for mixing and dispersion of pollutant [20, 21]. However, when calculating the pollutant concentration on both sides of the road with the CALINE4 model in the above mentioned researches, it was assumed that the area between the monitoring point and the road is open and vehicle emission can be directly diffused to the monitoring point without an obstruction. In fact, in a real 3D scene, there are usually obstructions between the monitoring point and the road, such as buildings and trees. At this time, the accuracy loss is large when the model is used to simulate the pollution concentration at the monitoring point in the obstruction area. Therefore, a vehicle emission dispersion simulation method that considers obstructions in a 3D scene is proposed in this paper. The model is optimized by considering the obstruction effect of the object to obtain a more reasonable pollution simulation value.

The remainder of the paper is organized as follows: Section 2 presents the traditional CALINE4 model and its limitations in a 3D scene. Section 3 introduces a vehicle emission dispersion simulation method considering obstructions, which includes CALINE4 model optimization and identification of effective road line sources based on visibility. Section 4 provides a series of experiments that were conducted to validate the effectiveness and reliability of the proposed method. This paper ends with some conclusions in section 5.

II. Related Work

A. CALINE4 Model

When calculating the pollutant concentration using the CALINE4 model in existing studies, it is always assumed that the area between the monitoring point and the road is open and the vehicle emission forms a continuous and stable dispersion source in the mixed area and diffuses directly and vertically to the monitoring point without obstruction [9]. In a specific calculation, the basic idea of the model is to divide the road into a series of line source units, calculate the contribution of pollutants emitted by each line source unit to the concentration of the receptor, and then calculate the sum of the pollution concentrations produced by the line sources of the whole road at the receptor [9]. The method of dividing the road into a series of line source units is shown in Fig. 1.

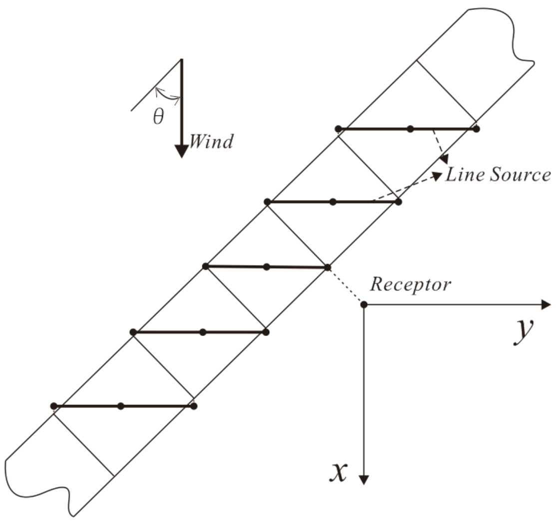


Figure 1. Schematic diagram for the division of line source units of the CALINE4 model.

The first road segmentation unit is located at the intersection point between the central axis of the road and the vertical line from the receptor to the road. The length of the first unit is equal to the width of the road, i.e., forming a square. The length of other units can be calculated in (1):

$$L_c = WL_f^n \quad (1)$$

where L_c is the length of the road segmentation unit; W is the road width; n is the road segmentation unit number and L_f is the length growth factor of the units, which can be calculated in (2):

$$L_f = 1.1 + \frac{\theta^3}{2.5\times10^5} \quad (2)$$

where θ is the included angle between the road and wind directions.

With an increasing distance between the road segmentation unit and the receptor, the length of the road segmentation unit also increases, and the effect of the road segmentation unit on the receptor decreases. When calculating the pollution concentration of the receptor, the receptor point is taken as the origin. The wind direction is taken as the positive direction of the x axis, and the vertical direction of the wind direction is taken as the positive direction of the y axis. Each road segmentation unit is regarded as a finite line source that passes through the road segmentation unit geometric center, whose direction is perpendicular to the wind direction (the y axis direction) with a length equal to the projection of this unit on the y axis. Then, the contribution of the line source to the receptor pollution can be calculated in (3):

$$C_n = \int_l cdl = \frac{Q_m}{\pi\sigma_y\sigma_z u}\exp\left(-\frac{z^2}{2\sigma_z^2}\right)\cdot\int_{y_1}^{y_2}\exp\left(-\frac{y^2}{2\sigma_y^2}\right)dy \quad (3)$$

where Q_m is the pollution source strength of this line source (mg/(m·s)); u is the wind speed in the surface layer (m/s); σ_y is the horizontal dispersion parameter; σ_z is the vertical dispersion parameters; z is the height of the receptor to the ground (m) and y_1 and y_2 are the ordinate values of two endpoints of a finite line source ($y_2 > y_1$).

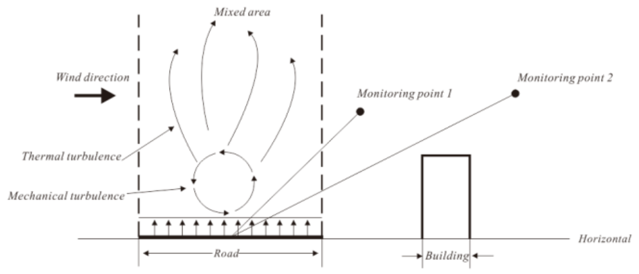
Then, the pollution concentration of the whole road at the receptor can be calculated in (4):

$$C = \sum C_n \quad (4)$$

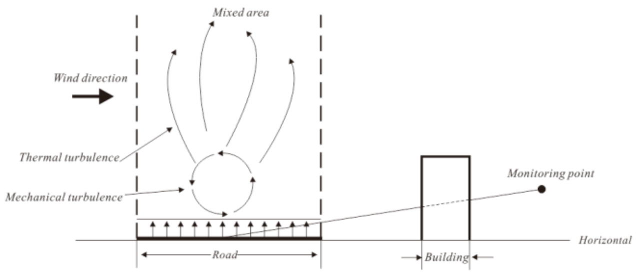
where C is the pollutant concentration at the spatial point (x,y,z) (mg/m^3) and n is the serial number of the line source unit.

B. Limitations of the CALINE4 Model in a Three-dimensional Scene

In the existing research, the visualization method of the CALINE4 model in 3D environment has not been seen yet. In addition, different from the assumptions set in a traditional model calculation, in fact, in a real 3D scene, there are usually obstruction objects between the monitoring point and the road, such as buildings and trees. When the monitoring point 1 and 2 is outside the obstruction range of these objects, the CALINE4 model can be directly applied to simulate the vehicle emission dispersion concentration at the monitoring point, as shown in Fig. 2 (a). When the monitoring point is within the obstruction range of these objects, the application of this model to simulate the vehicle emission dispersion concentration at the monitoring point will make the calculation result larger, as shown in Fig. 2 (b).



(a)



(b)

Figure 2. Limitation of the CALINE4 model in a 3D scene: (a) Monitoring point is outside of the obstruction range of objects and (b) Monitoring point is within the obstruction range of objects.

III. METHODOLOGY

In this paper, a vehicle emission dispersion simulation method that considers obstructions in 3D scenes is proposed on the basis of the CALINE4 model. The key steps include (1) introducing the obstruction coefficient to optimize the traditional CALINE4 model while considering the obstruction effect of objects in a 3D scene and (2) identifying the effective and ineffective line sources of roads based on the visibility analysis.

A. CALINE4 Model Optimization in a 3D Scene

To render the CALINE4 model more accordant with the emission dispersion law in a 3D scene, this paper introduces an obstruction coefficient to optimize the original line source pollution dispersion simulation equation, as shown in (5):

$$C_n = \alpha \bullet \frac{Q_m}{\pi \sigma_y \sigma_z u} \exp\left(-\frac{z^2}{2\sigma_z^2}\right) \cdot \int_{y_1}^{y_2} \exp\left(-\frac{y^2}{2\sigma_y^2}\right) dy \quad (5)$$

The value of α is calculated in (6):

$$\alpha = \begin{cases} 1, visibility = true \\ 0, visibility = false \end{cases} \quad (6)$$

For a divided series of line source units of roads, if there is no obstruction between the line source and the monitoring point, i.e., visibility, then the vehicle emission generated by the line source can normally diffuse to the monitoring point. This line source is called an effective line source. Otherwise, if there is an obstruction between the line source and monitoring point, i.e., no visibility, then the vehicle emission generated by the line source has no effect on the monitoring point. This line source is called an ineffective line source.

To more accurately express the influence of a finite line source (y_1, y_2) on emission dispersion, in this paper, the finite line source is further divided into n segments. The pollution concentration produced by a single finite line source at the monitoring point is the sum of the pollution concentration produced by each segment of the line source, i.e., formula (5) can be changed into:

$$C_n = \alpha \bullet \frac{Q_m}{\pi \sigma_y \sigma_z u} \exp\left(-\frac{z^2}{2\sigma_z^2}\right) \cdot \left(\int_{y_1}^{y_1+\frac{y_2-y_1}{n}} \exp\left(-\frac{y^2}{2\sigma_y^2}\right) dy + \int_{y_1+\frac{y_2-y_1}{n}}^{y_1+\frac{y_2-y_1}{n}\times 2} \exp\left(-\frac{y^2}{2\sigma_y^2}\right) dy + \ldots + \int_{y_1+\frac{y_2-y_1}{n}\times(n-1)}^{y_2} \exp\left(-\frac{y^2}{2\sigma_y^2}\right) dy \right)$$

(7)

The pollution concentration of the pollution source on the entire road at the monitoring point can be calculated in (8):

$$C = \sum C_n, \alpha = 1$$

(8)

As shown in Fig. 3, there is an obstruction between monitoring point 1 (receptor) and line source 2, 3, 4 (LS2, 3, 4), so the influence of these three line sources on the pollution concentration of the monitoring point is neglected. The pollution value of the monitoring point is generated by the superposition of the line source 1, 5 (LS1, 5) without obstruction.

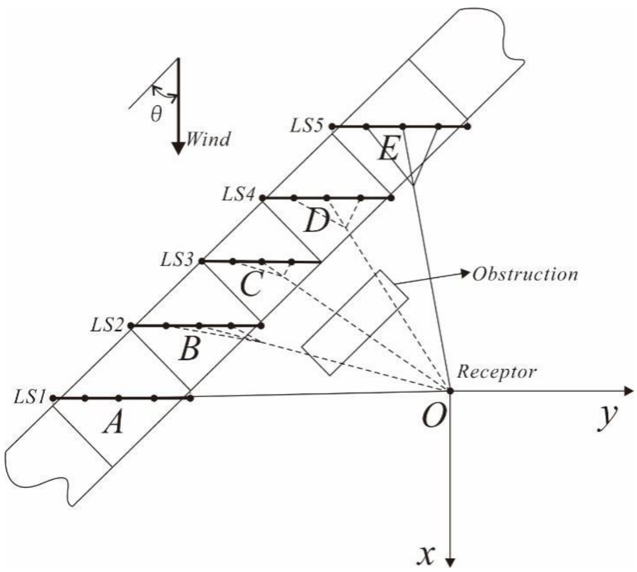


Figure 3. Optimization of the CALINE4 model in the 3D scene.

B. *Identification of Effective and Ineffective Line Sources*

To consider the obstruction effect of objects in a 3D scene, a monomer model is established for buildings, trees, etc. and is expressed in the form of a triangular mesh. The identification of effective and ineffective line sources based on visibility analysis, including the following steps:

(1) Set up the monitoring point, divide the road into a series of line source units according to the point, and calculate the midpoint of each line source unit to obtain the set of line source midpoints;

(2) Obtain the monomer model set of obstruction objects (*S*), take one obstruction object model S_i (i=1,2,…,n) from set *S* at random and record all the triangular facets that make up the model;

(3) Select a point LS_j (j=1,2,…,m) from the line source midpoint set *LS* and obtain the line between the point and the monitoring point;

(4) Calculate the intersection point between this line and the triangle facets of S_i, and judge whether or not the intersection point is in the triangle. If this point is in the triangle, then the line and the triangle facets are intersected and the visibility is not available between the line source and the monitoring point. LS_j belongs to ineffective line sources. Otherwise, the line and the triangle facets are not intersected, and the visibility is available between the line source and the monitoring point. LS_j belongs to effective line sources.

C. *Flow Diagram of the Proposed Method*

As depicted in Fig. 4, our proposed method for vehicle emission dispersion simulation is mainly composed of five key steps:

Step 1: Determine the monitoring points set, then obtain line sources by using formula (1) and their midpoints of the line source for each monitoring point;

Step 2: Select the effective line sources of each monitoring point via the proposed identification algorithm in section 3.2;

Step 3: Calculate the concentration value of each monitoring point via formula (7), which is the optimized CALINE4 model proposed in section 3.1;

Step 4: Obtain the result of each monitoring point by summing the concentration value of all effective line sources via formula (8);

Step 5: Get the final simulation result of the monitoring area after the concentration value for all monitoring points were calculated.

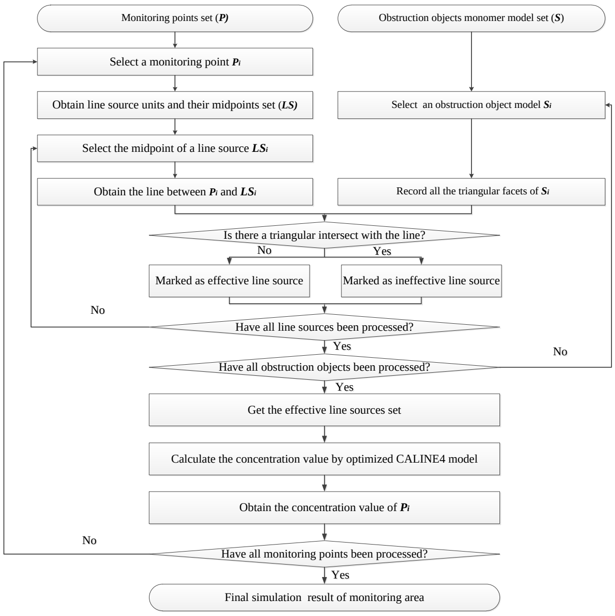


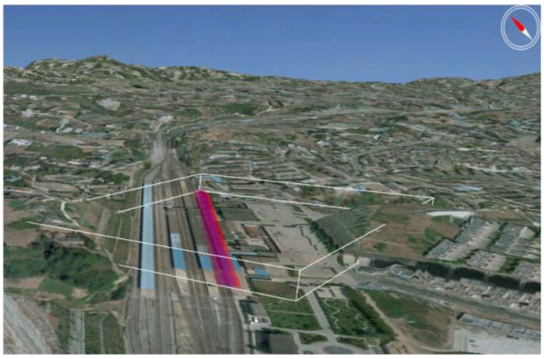
Figure 4. Flow diagram of the proposed method.

IV. Experiment and Analysis

A. *Experimental Data and Environment*

By relying on the Newmap World three-dimensional platform developed by the Chinese Academy of Surveying and Mapping, the vehicle emission dispersion simulation method that considers obstructions proposed in this paper is embedded and displayed dynamically in a 3D scene. The method of this paper is validated by choosing an expressway in a Beijing suburb as the line source, and a 3D space of 420, 280 and 20 meters in length, width and height, respectively, is set as the experimental area. There are sparse buildings around the experimental area, as shown in Fig. 5. The wind direction is northerly, the angle between the road and the wind is 40°, and the wind force is 4.55 m/s.

The system operation environment of the software is a 64-bit Windows 7 system with a Quadro M2000M graphics card and a 2.9 GHZ Quad-core processor. The graphics memory is 4G, and the physical memory is 16G.



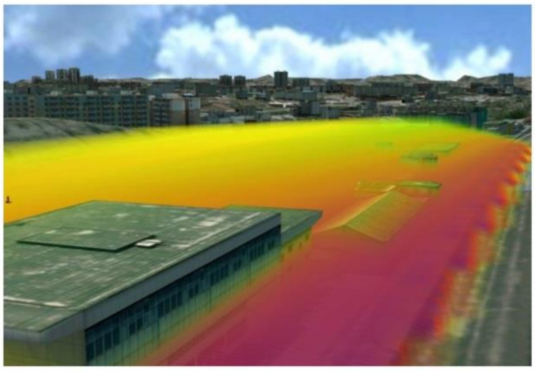
(a)

(b)

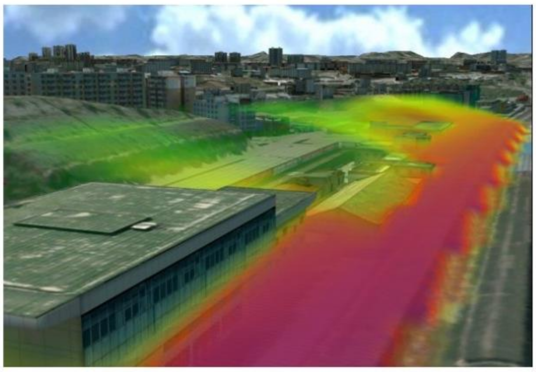
Figure 5. Experiment data: (a) Scope of the experiment area and (b) Road of the vehicle emission dispersion.

B. Effectiveness Analysis

To verify the effectiveness and reliability, the method proposed in this paper is compared with the CALINE4 model, which does not consider the obstruction effect. Fig. 6 shows the visualization effect of the pollutant concentration volume in the experimental area after processing with the two methods. Fig. 6a shows the side view of the pollutant dispersion process without considering the obstruction effect, and Fig. 6b shows the side view of the pollutant dispersion process considering the obstruction effect. As shown in Fig. 6a, the pollutants gradually diffuse with the wind direction, and the dispersion concentration is centered on the line source of the road pollution and gradually attenuates by distance. The buildings are submerged in pollutants and have no effect on the pollutant dispersion. The pollution concentration is the same in places with a similar spatial distance to the road, forming a visible strip effect with a regular distribution. As shown in Fig. 6b, the dispersion concentration is centered on the line source of the road pollution and gradually decreases by distance. However, the buildings have a significant impact on pollutant dispersion and show a significant blocking effect on pollutant dispersion at the periphery boundary of the buildings. The concentration of pollutants at the monitoring points in the obstruction areas of buildings decreases significantly, and the distribution of pollutants is no longer uniform and regular.



(a)



(b)

Figure 6. Global visualization results: (a) Pollutant dispersion results without considering obstructions and (b) Pollutant dispersion results considering obstructions.

To better illustrate the experimental results, three typical local areas are selected from the above experimental areas for specific analysis, as shown in Fig. 7. Among them, Fig. 7a and 7b show the comparison of the pollution concentration in the areas partially obstructed by buildings. It can be seen that the pollutant concentration at places close to ground with an obstruction effect obtained by the proposed method is obviously lower than that obtained by the original method, but the concentration of the two methods above the roof is basically the same. Fig. 7c and 6d show the comparison of the pollutant concentration in the alleys between buildings. The pollutant concentration obtained by the proposed method in this area is significantly lower than that obtained by the original method; Fig. 7e and 7f show the comparison of the pollutant concentration in the areas completely obstructed by buildings, and the pollutant concentration obtained by the proposed method in this area is basically 0.

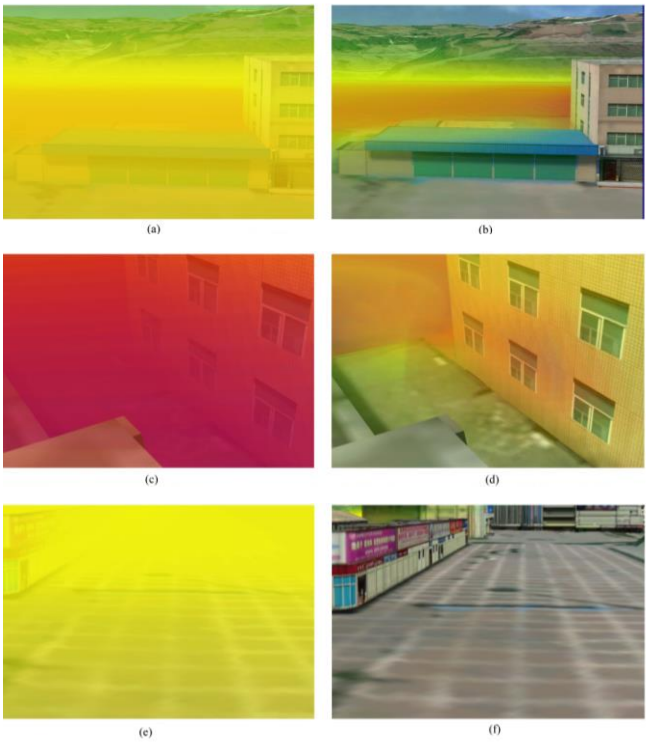


Figure 7. Visualized comparison diagram of the concentration in typical areas.

C. Quantitative Comparison and Analysis

In this paper, seven typical downwind points are selected to quantitatively test the influence of a building obstruction on the pollutant concentration. Fig. 8 shows the distribution of the test points. Among them, point 1 is in an open area, and its relative height is 2 m above the ground. There is a 3.43-meter-high building near point 2, and its relative height is 1.5 m above the ground. Points 3, 4 and 5 are located on the back of low buildings, and their relative heights are 2.5 m, 4.5 m and 1.6 m above the ground, respectively. Point 6 is on the roof of the building at the edge of the road, and its relative height is 4.5 m. Point 7 is in the alley at the edge of the road, and its relative height above ground is 0.2 m. The concentration values of each point that consider and do not consider the obstruction effect of buildings are compared, as shown in Table 1.

Figure 8. Distribution of typical monitoring points.

TABLE I. COMPARISON OF CONCENTRATIONS.

Unit: ug·m^{-3}

Point no.	Relative height (m)	Concentration value of the traditional model	Concentration value of the proposed method	Concentration variation value	Concentration variation rate (%)
1	2	25.29	25.29	0.0	0.00
2	1.5	39.80	38.03	1.77	4.45
3	2.5	34.90	15.29	19.61	56.19
4	4.5	16.47	10.19	6.28	38.13
5	1.6	34.11	10.39	23.72	69.54
6	4.5	35.29	24.50	11.79	33.41
7	0.2	35.68	11.76	23.92	67.04

TABLE II. COMPARISON OF DISTRIBUTION CHARACTERISTICS OF POLLUTANT CONCENTRATION

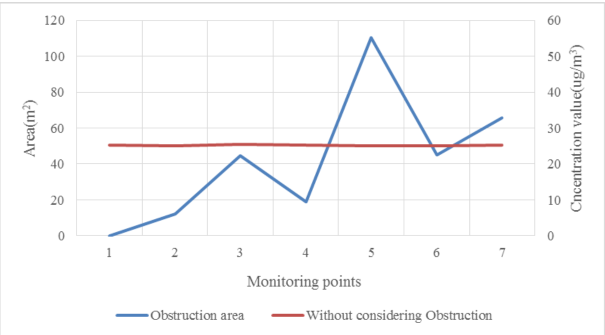
Unit: ug·m^{-3}

Point No.	Obstruction area (m^2)	Relative height (m)	Concentration value of the traditional model	Concentration Value of the proposed method
1	0	2	25.29	25.29
2	12.32	2	25.11	21.43
3	44.78	2	25.56	13.12
4	18.81	2	25.23	19.21
5	110.44	2	25.13	2.12
6	45.22	2	24.97	13.55
7	65.81	2	25.29	8.29

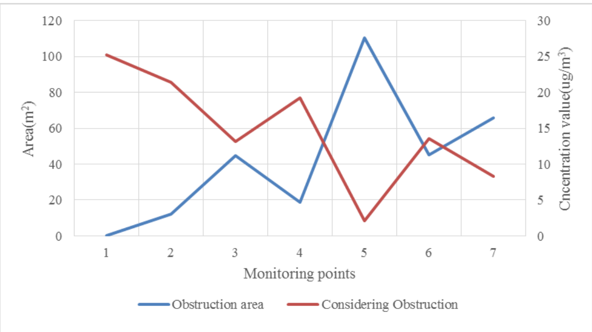
It can be seen from the table that the concentration values obtained by the two methods at point 1 are the same because there is no building obstruction in this open area, and the concentration variation value is 0. Points 2 and 4 are located behind the lower buildings. Point 6 is located on the roof of the building, but the influence of the building on this point is small. The concentration values obtained by this method are 1.77, 6.28, 11.79 lower than those obtained by the original method at these three points. Points 3 and 5 are located behind the higher buildings, and point 7 is located in the alley at the edge of the road, which is obviously affected by the obstruction effect. The concentration values obtained by this method are 19.61, 23.72 and 23.92 lower than those obtained by the original method at points 3, 5 and 7, respectively, with the maximum concentration variation rate reaching 69.54%.

To explore the relationship between the occlusion area and the abovementioned two methods, seven typical monitoring points in areas with the same horizontal and vertical distance from roads are selected. The concentration distribution characteristics of the two different methods are shown in Table 2.

The line chart from Table 2 is plotted, as shown in Fig. 9. As shown in Fig. 9(a), the concentration values of each monitoring point in the classical CALINE4 model are basically the same and have no relationship with the obstruction area. However, from Fig. 9(b), the concentration values of the monitoring points obtained by this method will change with the obstruction of buildings, and the trend of change is inversely proportional to the obstruction area.



(a)



(b)

Figure 9. Comparison of distribution characteristics: (a) calculated results with classical CALINE4 model and (b) calculated results with optimized model

V. CONCLUSIONS

The influence of buildings and other obstruction objects is not considered when applying the traditional CALNE4 model to simulate vehicle emission dispersion in a 3D scene, so this paper proposes a vehicle emission dispersion simulation method that considers obstructions. Through the verification of actual data, the following main conclusions are drawn:

(1) Compared with the traditional CALINE4 model, this method considers the influence of obstruction objects, such as buildings and trees, on vehicle emission dispersion in a 3D scene. The simulation results of pollutants from the global perspective are more in line with the real transport and dispersion law of pollutants.

(2) From local details, when using this method to simulate vehicle emission dispersion, the pollutant concentration at the periphery of the building is obviously blocked, and the degree of concentration change is obviously affected by the degree of obstruction. The higher the degree of obstruction is, the greater the regional concentration change is, and the maximum concentration change rate can reach 70%.

Future research will focus on the following aspects: first, the extent of the calculation involved in modeling the visualization of 3D scenes is large, so the calculation efficiency needs to be improved; and second, the auxiliary edge effect and other factors need to be considered to render the visualized expression of the emission dispersion closer to a realistic situation.

AUTHOR CONTRIBUTIONS: C.L. conceived the original idea for the study; all co-authors conceived and designed the methodology; P.W. and Y.W. conducted processing and analysis of the data; and P.W. and C.L. drafted the manuscript; all authors read and approved the final manuscript.

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