WIND INFLUENCE ON THE POLLUTANTS EMITTED SPREAD BY MOTOR VEHICLES

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ABSTRACT

The known static and dynamic wind speed influence models on the urban air purification degree from CO emitted by urban transport are analyzed. Three optimization problems of adaptive motor transport traffic organization of are formulated and solved on the dynamic model. It is proposed to introduce a control function for the total emitted amount of wind speed CO depending. The optimal function type is calculated, at which the pollutant rise height reduced to a minimum. The solution of the second optimization problem made it possible to determine those most unfavorable conditions, at which the safe distance to highway for a nearby settlement can reach a maximum. As a result of solving the third optimization problem, it is shown that the minimum average value of CO concentration at a certain height can be achieved with a certain dependence of wind speed horizontal component on the height of point under consideration.

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1 Introduction

As noted in [1], currently 55% of the world's population lives in cities and by 2050 this figure will increase to 68%. Rapid urbanization has led to the fact that only 12% of city dwellers live in areas where air quality meets the requirements of the World Health Organization. Pollution of urban areas largely depends on the correct planning of urban development and taking into account such a natural factor of urban air purification as wind. As noted in [2-5], the distribution of air pollutants largely depends on the characteristics of the air flow in the urban environment.

At the same time, the problem of urban air pollution should be solved by proper planning of the urban transport network, taking into account the development and placement of densely populated areas. It is well known that the main air pollutants emanating from vehicles are CO, SO2, NO2 and aerosols. At the same time, the most potent of them on living organisms is carbon monoxide (CO). The study of the effect of wind on the spread of these pollutants to the level of permitted standards, carried out in [1], showed that under conditions of static wind, i.e. at constant wind speed, the decrease in pollutant concentration can be expressed as a decreasing exponential function of time

$$y = a_1 \exp(-a_2 t) \tag{1}$$

where a_1, a_2 are model indicators depending on wind speed; t is time. At the same time, it is obvious that wind speed is a dynamic parameter, which leads to the need to take this factor into account. In this regard, the most effective approach to solving this problem can be considered the mathematical model developed in the work [6], which took into account such indicators as CO emissions from the urban transport network, average atmospheric temperature, wind speed, traffic flow intensity, maximum permissible concentration of pollutants for the human body, and other indicators. Note that in many studies [7-10].

CO is indicated as the main air pollutant from vehicles, the maximum concentration of which is 10 mg/m^3 for 8 hours. According to the work [6], taking into account C = 0.01 g/m^3, the minimum safe distance Dmin between the highway and the settlement can be expressed through the standard deviations of the pollutant level along the coordinates y and

$$\text{z}\sigma_y = 0{,}32 D_{min} \tag{2}$$

$$\sigma_z = 0{,}24 D_{min} \tag{3}$$

In this case, Dmin is determined by the expression [6]

$$D_{min} = \frac{k \Delta h^{1/2} Q^{1/4}}{U^{1/4}} \tag{4}$$

where Δh is the elevation (lift) distance of the pollutant (m); U is the wind speed; h is the total volume of CO emissions from motor vehicles; k is the coefficient depending on the model parameters.

Note that formula (4) obtained in [6] allows us to formulate the following problems: (1) for a given $D_{\min}$, how should the Q parameter be controlled depending on the current wind speed in order to achieve the minimum value of Δh; (2) for a given Δh, how should the Q parameter be controlled in order to obtain the minimum value of $D_{\min}$ (3) determining the average value of Dmin taking into account the altitude distribution of wind speed, i.e. the function $U = U(\Delta h)$.

Materials and methods

Let us consider the possibility of solving the first problem. We will rewrite expression (4) in following form

$$\Delta h = \frac{D_{min}^2 U}{k^2 Q^{1/2}} \tag{5}$$

Let us introduce for consideration the function of controlling the degree of CO emission, i.e. the indicator Q depending on the wind speed U, i.e.

$$Q = f(U) \tag{6}$$

Note that the control of Q indicator can be implemented by prohibiting the entry of heavy-duty transit vehicles and passing them along bypass routes at low wind speeds. Taking into account (5) and (6), we obtain

$$\Delta h = \frac{D_{min}^2 U}{k^2 \sqrt{f(U)}} \tag{7}$$

Since, unlike the model proposed in [1], we are considering a dynamic model of wind impact, we will consider the case when, over a period of time Δt, the wind speed increases from zero to U_{max}. Consequently, the average value Δh is determined as

$$\Delta h_{cp} = \frac{1}{U_{max}} \int_0^{U_{max}} \frac{D_{min}^2 U}{k^2 \sqrt{f(U)}} dU \tag{8}$$

To solve the problem of determining the optimal function $f(U)$, we impose the following restrictive condition on this function

$$\int_0^{U_{max}} f(U)\, dU = C_1;\ C_1 = const \tag{9}$$

Taking into account expressions (8) and (9), we will form the target functional of unconditional variational optimization

$$F_1 = \frac{1}{U_{max}} \int_0^{U_{max}} \frac{D_{min}^2 U}{k^2 \sqrt{f(U)}} dU + \lambda_1 \left[\int_0^{U_{max}} f(U)\, dU - C_1 \right] \tag{10}$$

where λ is the Lagrange multiplier.

Solution to optimization problem (10) according to [11] must satisfy the condition

$$\frac{d\left\{ \frac{D_{min}^2 U}{U_{max} k^2 \sqrt{f(U)}} + \lambda_1 f(U) \right\}}{df(U)} = 0 \tag{11}$$

From condition (11)

$$-\frac{1}{2} \frac{D_{min}^2 U}{U_{max} k^2 f(U)^{3/2}} + \lambda_1 = 0 \tag{12}$$

From expression (12)

$$f(U) = \sqrt[3]{\frac{D_{min}^2 U^2}{4\lambda_1^2 k^4}} \quad (13)$$

when solving (13), F_1 reaches a minimum, since expression (12) always has a positive derivative with respect to $f(U)$. To calculate the value of λ, we can use formulas (9) and (13). We have

$$\int_0^{U_{max}} \sqrt[3]{\frac{D_{min}^2 U^2}{4\lambda_1^2 k^4}} dU = C_1 \quad (14)$$

From expression (14)

$$\sqrt[3]{4\lambda_1^2} = \frac{1}{C_1} \int_0^{U_{max}} \sqrt[3]{\frac{D_{min}^3 U^2}{k^4}} dU \quad (15)$$

From expression (15)

$$\lambda_1 = \frac{1}{4} \left[\frac{1}{C_1} \int_0^{U_{max}} \sqrt[3]{\frac{D_{min}^3 U^2}{k^4}} dU \right]^{3/2} \quad (16)$$

Let us consider the possibility of solving the second problem mentioned above. Taking into account expressions (4) and (6), we will form the following functional

$$D_{min.cp} = \frac{1}{U_{max}} \int_0^{U_{max}} \frac{\Delta h k^2 f(U)^{1/2}}{U} dU \quad (17)$$

To calculate the optimal function $f(U)$, we use the restrictive condition (9). Taking into account expressions (17) and (9), we form the following objective functional

$$F_2 = \frac{1}{U_{max}} \int_0^{U_{max}} \frac{\Delta h k^2 f(U)^{1/2}}{U} + \lambda_2 \left[\int_0^{U_{max}} f(U)\, dU - C_1 \right] \quad (18)$$

where λ_2 is the Lagrange multiplier.

The solution to problem (18) must satisfy condition

$$\frac{d\left\{ \frac{\Delta h k^2 f(U)^{1/2}}{U_{max} U} + \lambda_2 f(U) \right\}}{d f(U)} = 0 \quad (19)$$

From condition (19) we obtain

$$\frac{1}{2} \frac{\Delta h k^2}{U_{max} f(U)^{1/2} U} - \lambda_2 = 0 \quad (20)$$

From condition (20)

$$f(U) = \frac{\Delta h^2 k^4}{4 U_m^2 \lambda_2^2 U^2} \quad (21)$$

When solving (21), the functional F_2 reaches its maximum, since the derivative of expression (19) with respect to the desired function always turns out to be a negative value. To calculate λ_2, we can use expressions (9) and (21). We have

$$\int_0^{U_{max}} \frac{\Delta h^2 k^4}{4 U_m^2 \lambda_2^2 U^2} dU = C_1 \quad (22)$$

From condition (22)

$$\lambda_2 = \sqrt{\frac{\int_0^{U_{max}} \frac{\Delta h^2 k^4}{4U_m^2 \lambda_2^2 U^2} dU}{C_1}} \tag{23}$$

Thus, according to the solution of the second problem, the maximum average value of pollutant lift can be obtained at minimum *Q* and maximum wind speed. Obviously, such a regime is completely unprofitable and should be avoided.

Let us consider the solution of the third above-mentioned research problem. Next, we will study the optimal form of the function

$$U = U(\Delta h) \tag{24}$$

at which the average value D_{min} would reach its minimum value.

For the model solution of this problem, we will adopt the following restrictive condition

$$\int_0^{\Delta h_{max}} U(\Delta h) d(\Delta h) = C; C = const \tag{25}$$

Taking into account expressions (4) and (24), we define the target optimization functional as

$$F_1 = \frac{1}{\Delta h} \int_0^{\Delta h_{max}} \frac{k \Delta h^{\frac{1}{2}} Q^{\frac{1}{4}}}{U \Delta h^{\frac{1}{4}}} d(\Delta h) \tag{26}$$

Taking into account expressions (25) and (26), we will compose the objective functional F_0 of unconditional variational optimization

$$F_0 = \frac{1}{\Delta h_{max}} \int_0^{\Delta h_{max}} \frac{k \Delta h^{\frac{1}{2}} Q^{\frac{1}{4}}}{U \Delta h^{\frac{1}{4}}} d(\Delta h) + \lambda \left[\int_0^{\Delta h_{max}} U(\Delta h) d(\Delta h) - C \right] \tag{27}$$

where λ – is the Lagrange multiplier.

The solution to problem (27) according to [11] must satisfy the condition

$$\frac{d\left\{ \frac{1}{\Delta h_{max}} \frac{k \Delta h^{\frac{1}{2}} Q^{\frac{1}{4}}}{U(\Delta h)^{\frac{1}{4}}} + \lambda U(\Delta h) \right\}}{dU(\Delta h)} = 0 \tag{28}$$

From condition (28)

$$-\frac{1}{4} \frac{k \Delta h^{\frac{1}{2}} Q^{\frac{1}{4}}}{\Delta h_{max} U(\Delta h)^{\frac{5}{4}}} + \lambda = 0 \tag{29}$$

From condition (29)

$$U(\Delta h) = \frac{k^{\frac{4}{5}} h^{\frac{4}{10}} Q^{\frac{4}{20}}}{h_m \lambda} \tag{30}$$

Taking into account expressions (25) and (30), we obtain

$$\frac{k^{\frac{4}{5}}Q^{\frac{4}{20}}}{h_m\lambda}\int_0^{h_m} h^{\frac{4}{10}}dh = C \tag{31}$$

From condition (31)

$$\lambda = \frac{10}{14}\frac{k^{\frac{4}{5}}Q^{\frac{4}{20}}h_m^{\frac{4}{10}}}{Ch_m} \tag{32}$$

From expressions (30) and (32) finally obtain

$$U(\Delta h) = \frac{7}{5}\frac{C\Delta h^{\frac{2}{5}}}{h_m^4} \tag{33}$$

Thus, when condition (33) is met, the $D_{\min}$ indicator reaches a minimum on average. The fact that the minimum is reached is confirmed by the fact that the derivative of expression (29) with respect to the desired function is always a positive function.

We rewrite expression (33) as

$$U(\Delta h) = C_1 h^{\frac{2}{5}} \tag{34}$$

where

$$C_1 = \frac{7C}{5h_m^4} \tag{35}$$

Taking into account expressions (26) and (34), we calculate the minimum value of F_1 that can be achieved. We have

$$F_{1min} = \frac{1}{\Delta h_{max}}\int_0^{\Delta h_{max}} \frac{k\Delta h^{\frac{1}{2}}Q^{\frac{1}{4}}}{C_1^{\frac{1}{4}}(\Delta h)^{\frac{1}{10}}}d\Delta h = \frac{kQ^{\frac{1}{4}}}{C_1^{\frac{1}{4}}\Delta h_m}\int_0^{\Delta h_{max}} \Delta h^{\frac{4}{10}}d\Delta h = C_2\Delta h_{max}^{\frac{2}{5}} \tag{36}$$

where $C_2 = \frac{5kQ^{\frac{1}{4}}}{7C_1^{\frac{1}{4}}}$.

Discussion

The known static and dynamic models of wind speed influence on the urban air purification degree from CO emitted by urban transport are analyzed. It is noted that the known static model allows determining the time during which the concentration of CO in urban air can decrease to an acceptable level at a constant specified wind speed. A dynamic model of wind speed influence is considered, which allows calculating a safe distance to the highway at different wind speeds. Based on the dynamic model, two optimization problems are formulated and solved based on the adaptive organization of vehicle traffic. It is proposed to introduce the function $Q = f(U)$, i.e. the function of controlling the total emitted amount of CO depending on the wind speed. Physically, the implementation of such a mode means introducing a restriction for some types of transport depending on the wind speed. The optimal type of the introduced function is calculated, at which Δh to the highway decreases to a minimum.

The solution of the second optimization problem made it possible to determine an unfavorable condition for practice, under which the safe distance to the highway can reach a maximum. According to the solution of the third optimization problem, it was found that the minimum average value of CO concentration at a certain height can be achieved with a certain dependence of the wind speed horizontal component on the point under consideration height.

Key findings and conclusion

1. It was determined that static and dynamic models were developed with respect to the impact of wind speed on the degree of urban air purification, whereby the static model allows determining the air purification time, and the dynamic model allows calculating the safe distance to the highway.

2. Based on the dynamic model, two optimization problems were formulated and solved; according to the solution of the first problem, the conditions under which the height of the pollutant rise can reach a minimum were determined. According to the solution of the second problem, the most unfavorable conditions were determined under which the safe distance to the highway increases to a maximum.

3. If, under the assumptions made above, the growth of Δh is accompanied by an increase in the horizontal wind speed, then under the adopted restrictive condition, it is possible to achieve the minimum average value of CO concentration.

4. The growth of Δh max, while the previously adopted conditions remain unchanged, is accompanied by an increase in the achievable minimum average value of CO concentration.

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