Study on prediction method for air quality control for complex road structures

Y. OTA
Chiyoda Engineering Consultants Co Ltd.

This paper presents a prediction method for air quality control for trenched road structures with partially covered roof or intermittent tunnels, in which the traffic piston action is expected to drive polluted matter along the road axis and affect the concentration in a way that is similar to the respiration action.

After explaining the respiration action and a method to set the air volumes of this action (section 2), the prediction method is described (section 3), which consists of calculations for wind velocity and concentration distribution, discussed separately.

NOMENCLATURE

W	:	width of open part	(m)
B	:	width of traffic space	(m)
H	:	tunnel height	(m)
H1	:	height of side wall at the open part	(m)
q_b, q_e	:	unit respiration values	($m^3/s \cdot m^2$ = m/s)
Q_e	:	unit volume of emitted matter from open section	(ml/s)
q_0	:	non-dimensional respiration volume	(-)
U_r	:	wind velocity	(m/s)
U_t	:	traffic velocity	(m/s)
n	:	traffic density	(veh/m)
A_r	:	cross sectional area of the carriage way	(m^2)
A_t	:	projected front area of vehicle	(m^2)
CD	:	drag coefficient	(-)
A_m	:	equivalent projected resistance area of vehicle	(m^2)
ζ_{in}	:	the tunnel entrance loss coefficient	(-)
λ	:	friction loss coefficient between air and structure surface	(λ =0.025)
L_r	:	length section r	(m)
D_r	:	hydraulic representative diameter	(m)
ρ	:	air density	(0.1224 kg/m^3 at 20˚C)
C	:	gaseous concentration	(ppm)
g	:	emitted gas volume per unit length	(ml/s)
qd	:	emission volume	(ml/s/m)

1. APPLICATION

It is desirable that a calculation method for road structures like partially covered or intermittent tunnels, in which the traffic piston action is expected to drive polluted matter along the road axis and affect the concentration, depends on a respiration phenomenon which takes into account the respiration action as a natural ventilation.

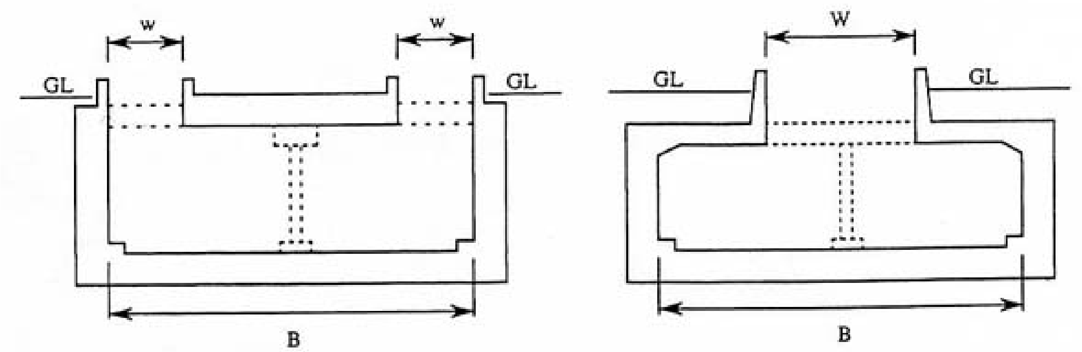
Also in case the road is a trenched structure with an open ceiling part and several intermittent tunnel structures from which the air stream influences the downstream, it is necessary that the concentration is investigated with the traffic piston action in mind.

The calculation method is applicable to the following general road structures:

a. Trenched structures in which the width of the open part is smaller than the width of the traffic space. For the layout of the open part, a center opening and a lateral opening should be taken into consideration. According to an experiment carried out in Japan, the basic phenomena of the respiration activity of the central opening may be called similar to those for the lateral opening.

b. Trenched structures with several covered parts (tunnel structures) of which the exhaust gas distribution should be uniformed by the traffic piston action.

Figures 1.1, 1.2 and 1.3 show typical trenched structures that make use of natural ventilation, in Germany (lateral opening) and Japan (central opening).



a. Lateral opening b. Central opening

Figure 1.1 Typical cross sections of trenched structures with natural ventilation

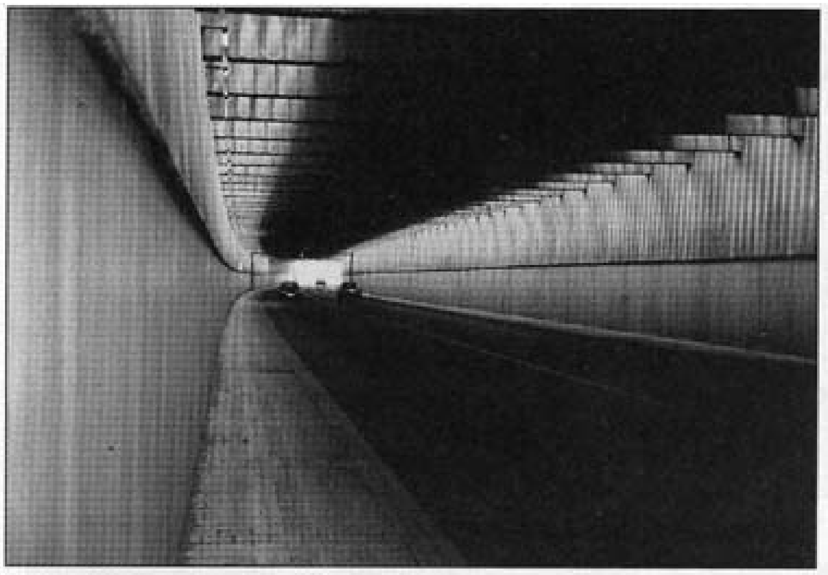


Figure 1.2.a. Lateral opening, suburbs of Stuttgart Germany : Roadway space

Figure 1.2.b. Lateral opening, suburbs of Stuttgart Germany : Surroundings (Picture by ZUBLIN)

Figure 1.3.a Central opening, Tokyo Japan: Roadway space

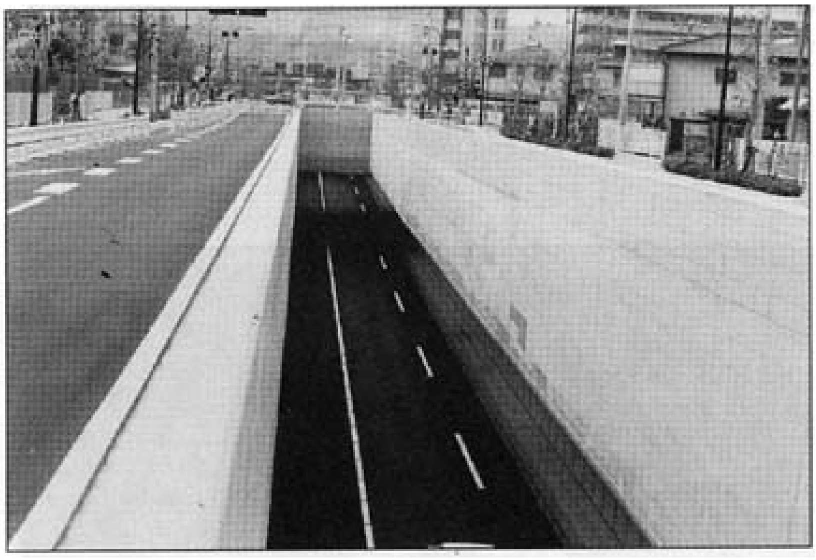


Figure 1.3.b Central opening, Tokyo Japan: Surroundings

2. THE RESPIRATION EFFECT IN TRENCHED STRUCTURES

2.1 Basic concept of the respiration phenomenon

The principle of the respiration effect caused by the vehicle movement in trenched structures with open part is shown in figure 2.1. The air pressure in front of a moving vehicle is higher than the atmospheric pressure and the air is pushed from the carriage way into the open air. At the same time, fresh air is pulled into the trenched structure behind the vehicle, since the air pressure behind a moving vehicle is lower than the atmospheric pressure. This circulation, caused by the traffic movement, is called the respiration effect.

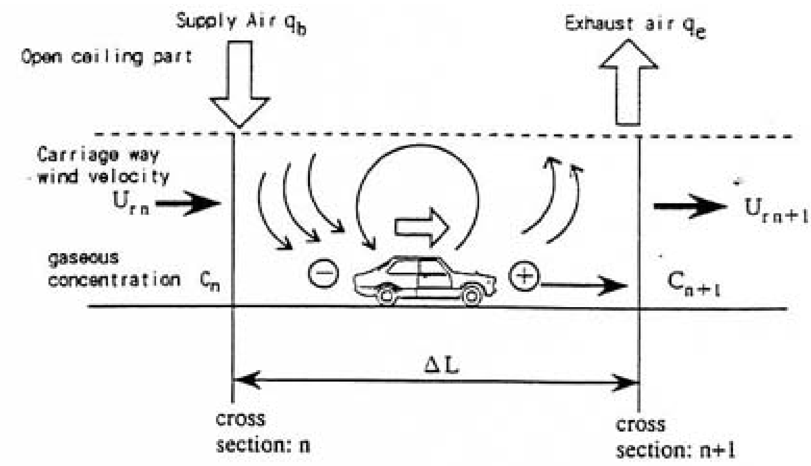


Figure 2.1 Respiration effect principle

The respiration air volumes that are used in the prediction method differ depending on the road structure and the traffic conditions, and are in fact very difficult to calculate theoretically in an accurate way. In practice, therefore, tracer gas experiments, wind tunnel experiments in scale models, etc. are carried out.

2.2 Scale model experiment for respiration effect

2.2.1 Objective

As for the impact to the ambient air along the roadway, calculation models exist to predict the exhaust gas emitted from trenched road structures with overhang if these include a tunnel structure with natural ventilation. The existing models consider the respiration effect that is caused by the pressure difference inside and outside the depressed structure due to vehicle movement. The objective of scale model experiments is to clarify the respiration effect and the impact to the ambient air quality along the road space

2.2.2 Experiment description

Experiments often consist of the following two items:

(1) Measurement. With a running apparatus for scale model vehicles and a scale model of the road structure in question, including several open ceiling parts, the respiration volumes in the trenched structure are investigated.

(2) Data analysis. With the use of the measured data, the emission rate from the open ceiling parts is calculated, and the relation is clarified between the road structure conditions, the traffic volume and the point extraction ventilation volume.

2.2.3 Experiment execution

Figure 2.2 shows a very typical running apparatus for experiments to set the respiration volumes in trenched road structures.

In order to satisfy the requirements of similarity, it is necessary to carry out the scale model experiment in the same flow field as in reality. The Reynolds number (Re) should be at least 1.0×10^4. We consider a Reynolds Number for a scale of 1/200~1/100. The vehicle velocity on the running apparatus should be similar to reality, up to 80 km/h (=2,222 cm/s). Figure 2.3 shows the layout of the whole section. Figure 2.4 shows the cross section of a possible scale model at the open ceiling part of the road structure.

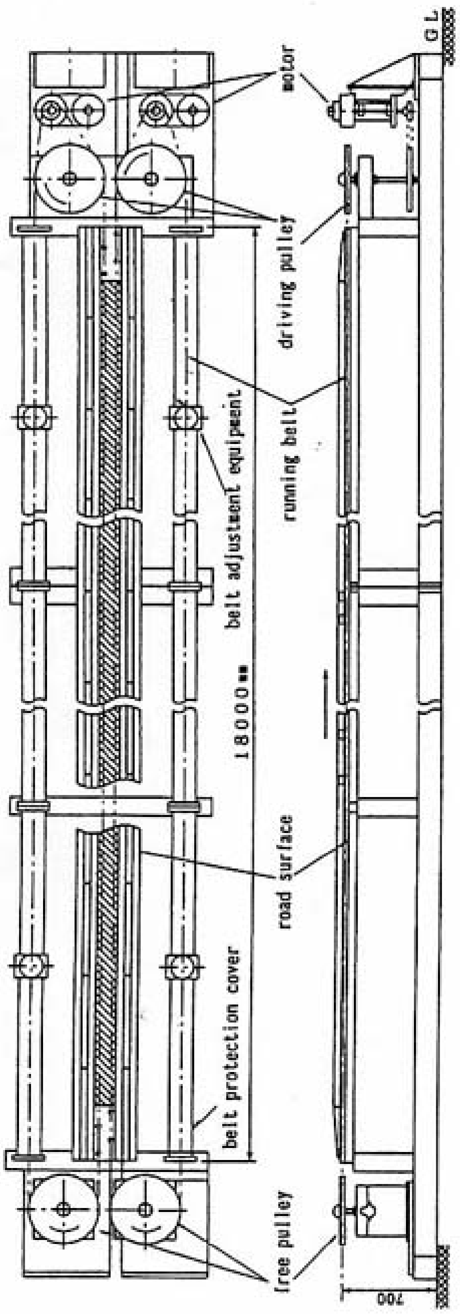


Figure 2.2 Running apparatus

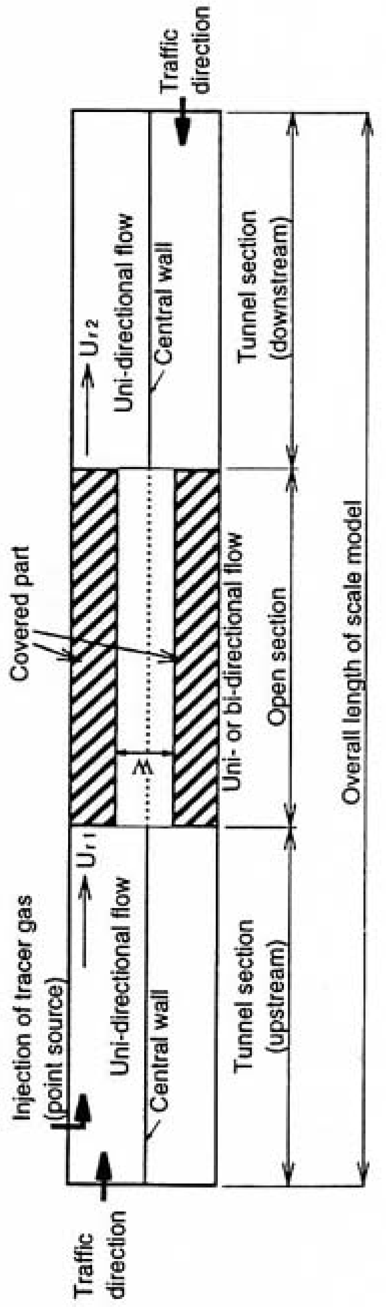


Figure 2.3 Basic layout of experimental scale model of trench structure

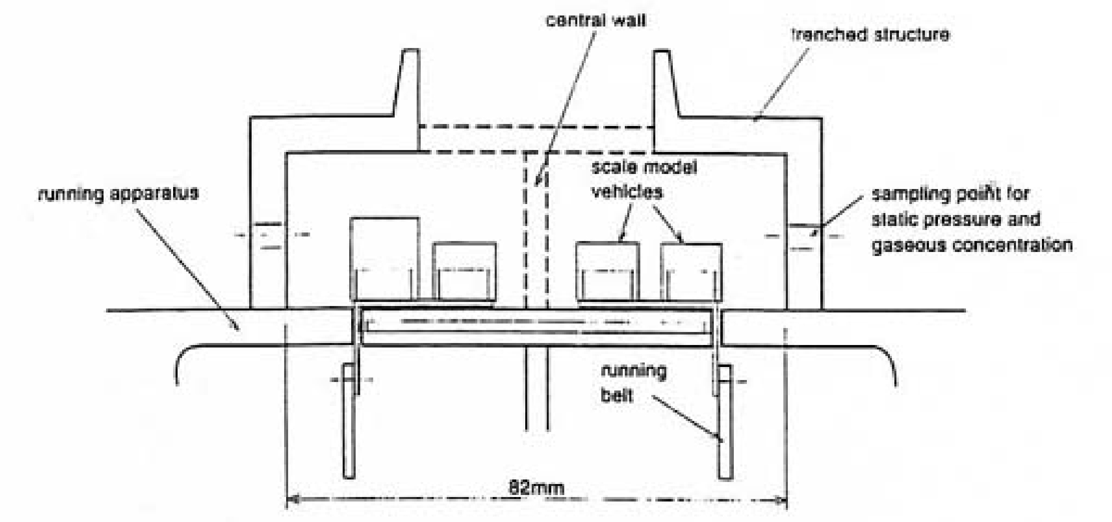


Figure 2.4 Cross section of scale model at open ceiling part

2.3 Setting of respiration volumes

Figure 2.5 indicates the theoretical distribution of gaseous concentration in the experimental apparatus, if gas is released as point source from upstream in a tunnel with open ceiling sections of width W in a section with length Δ L, and is exchanged by the respiration action at the open sections.

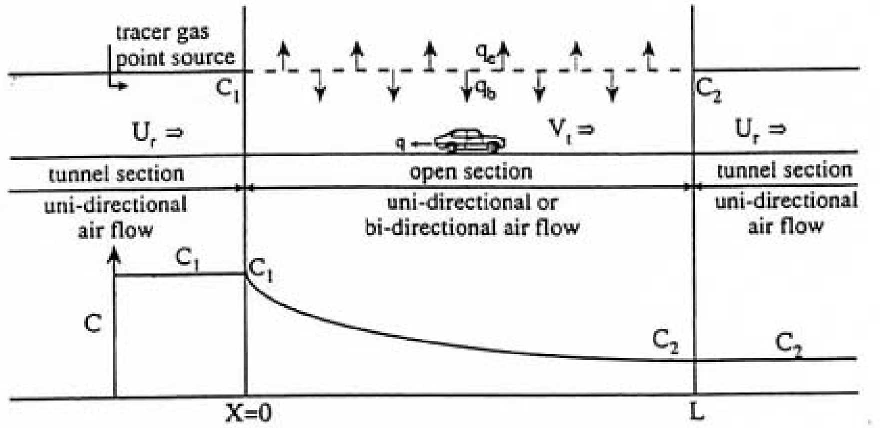


Figure 2.5 Theoretical distribution of gaseous concentration in relation to the respiration action

The theoretical air velocity at the tunnel exit can be obtained by injecting tracer gas, measuring the concentration level, and calculation with equation 2.1

$$U_r = \frac{q_{tr}}{A_r \cdot c_{tr}} \tag{2.1}$$

where q_{tr} : tracer gas volume (ml/s)

c_{tr} : gaseous concentration at tunnel exit (p.p.m.)

If dx is a minute change in length of the open section (Figure 2.6), equation 2.2 can be obtained from the law of conservation of mass.

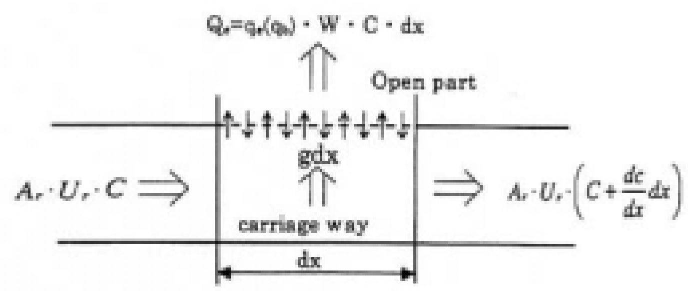


Figure 2.6 Diffusion of vehicle exhaust gas by the respiration action

$$A_r U_r \frac{dc}{dx} = -q_b WC \tag{2.2}$$

If equation 2.2 is solved with the boundary conditions x=0, $C=C_1$, x=L, the unit respiration volume q_b can be obtained with equation 2.3.

$$q_b = \frac{A_r \cdot U_r}{WL} \ln(C_1 / C_2) \tag{2.3}$$

where q_b : unit respiration volume ($m^3/(s \cdot m)$)
W : width of open ceiling section (m)

The unit respiration volumes (q_b, q_e) are the converted values from the natural ventilation air volumes (per unit area of the open section) into the open air. The dimension can be indicated by $m^3/s{\cdot}m^2$ (m/s). In case a trenched structure of infinite length is represented, $q_b=q_e$. According to previous experiments [1)] in Japan, the values are generally between 0.10 and 0.15m/s, but depending on the road structure and the traffic conditions these values may differ considerably.

The unit respiration volume can controlled by the intensity of air velocity and air turbulence. The intensity of the air velocity is bigger for uni-directional traffic than for bi-directional traffic. On the other hand, the intensity of the air turbulence is bigger for bi-directional traffic than for uni-directional traffic. Both of these are of effect to the respiration volume.

In case the bi-directional traffic conditions are the same as the uni-directional traffic conditions, this means that the air flow conditions are controlled by the absence or existence of a central wall in the carriage way.

The unit respiration volumes for uni-directional traffic can be compared with those for bi-directional traffic: in the latter case the unit respiration volume is slightly bigger than for the former case. On the other hand, for the estimation of the gaseous concentration in the carriage way, there is no difference between uni-directional traffic uni-directional traffic.

The respiration volume (q_b, q_e) is the multiplied value of the unit respiration volumes and the width of the open part W. In most cases this value is used as the air volume per unit tunnel length.

The breathing effect in the open part of the trenched structure is more properly treated as a fluctuation depending on the air velocity in the carriage way (U_r)[1), 2)].

The air velocity in the carriage way (U_r) is a more significant driving force to the respiration effect than the traffic velocity, because the air velocity is determined in relation to the road structure, traffic conditions and aerodynamic characteristics. Therefore a non-dimensional respiration volume can be expressed as a unit respiration volume at unit air velocity. In the case of a wind velocity U_r in the adjoining tunnel structure, the value is as follows:

$$q_0 = \frac{q_b}{U_r} \tag{2.4}$$

Figure 2.7 shows the relation between the width proportion and the height of the open part. Figures 2.8a.[1)] and 2.8b.[1)] show the relation between the width proportion (W/B) and the non-dimensional respiration volume (q_0). Figures 2.9a.[1)] and 2.9b.[1)] show the relation between the height of the side wall (H1) and the non-dimensional respiration volume. These relations are based on the results of a large number of experiments, and have a very high degree of accuracy causing almost no scatter in the diagrams.

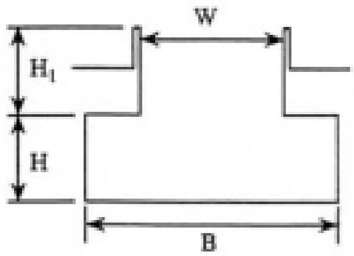
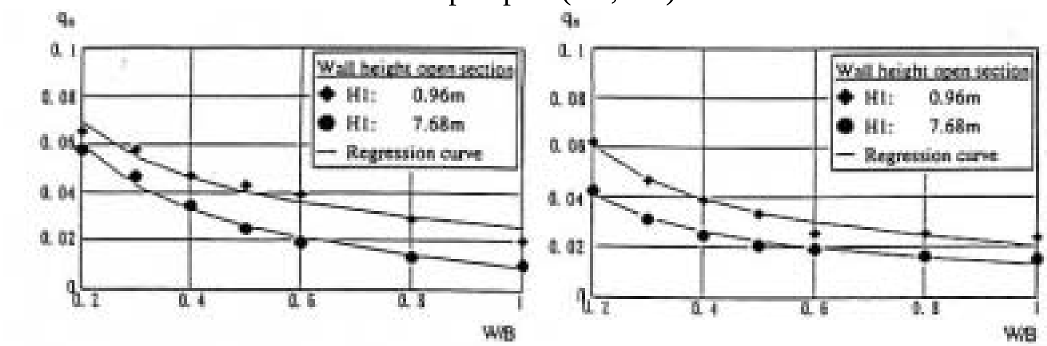
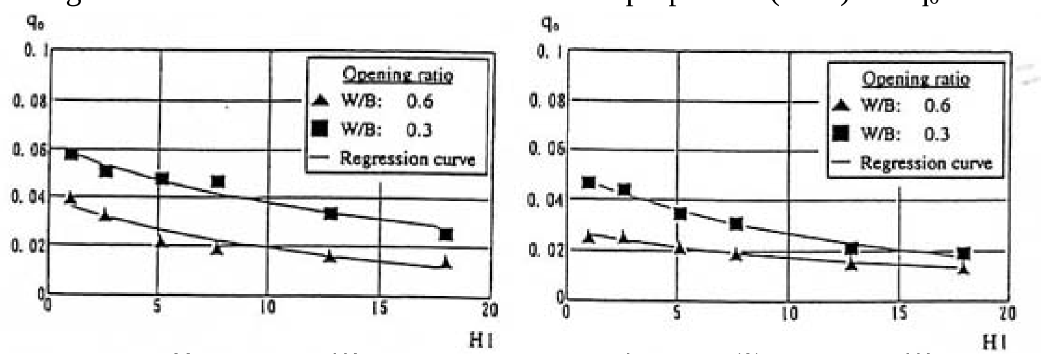


Figure 2.7 Relation between the width proportion (W/B) and height of the side wall at the open part (H1, H2)



a. One-way traffic b. Two-way traffic

Figure 2.8 Relation between the width proportion (W/B) and q_0 [1)]



a. One-way traffic b. Two-way traffic

Figure 2.9 Relation between the height of the side wall (H1) and q_0 [1)]

It is well known that for general road tunnels, the vehicle aerodynamic characteristics value (aerodynamic drag coefficient: CD) depends largely on the blockage ratio A_t/A_r between the tunnel cross sectional area (A_r) and the projected front area of the vehicles (A_t). According to the scale model experiment results shown in figure 2.8a. and 2.9a., in case the width proportion of the open part is narrow, which means that the efficiency of the piston action increases (depending on the decrease of the dynamics of the vehicle drag), the non-dimensional respiration volume tends to increase. On the other hand, if the width proportion is large, which means that the efficiency of the piston action decreases, the volume tends to decrease.

Consequently, the dilution gets accelerated and the concentration decreases in the carriage way. In reality, however, the air volumes differ according to the road structure and the traffic and natural wind conditions, and accurate calculations have until now been restricted to a certain degree. Therefore, in case a trenched structure tends to have characteristics that might lead to an insufficient setting of the respiration volumes during the planning stage of that structure, a scale model experiment or the development of an accurate calculation method depending on measurements in a similar road structure will have to be carried out.

The underlying calculation method consists of calculations for wind velocity and concentration distribution. Both are discussed separately in section 3.2 and 3.3, respectively.

3. CALCULATION METHOD FOR GASEOUS CONCENTRATION

3.1 Procedure

The process of the concentration distribution calculation is given in figure 3.1.

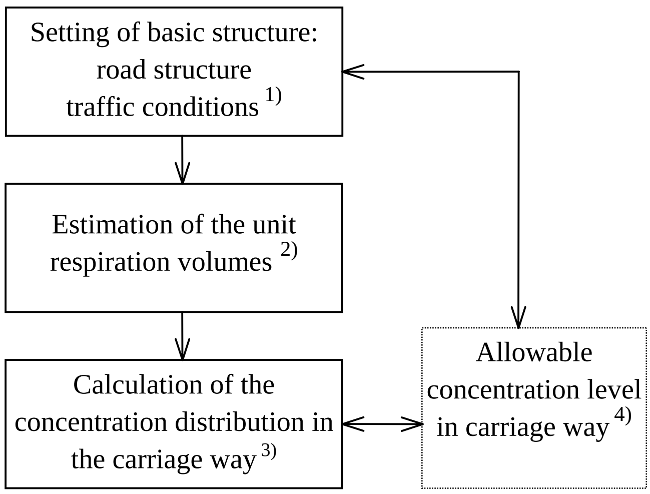


Figure 3.1 Process of the calculation method of air quality for depressed structures

1) Shape of the road structure, structure of the open part, land use of the surrounding area, etc. Traffic volume, number of traffic lanes and content of large size vehicles for different time periods.

2) Setting of the respiration volumes based on the road structure, previous knowledge on the traffic conditions (uni- or bi-directional, etc.), experiment and investigation.

3) Calculation of wind velocity in the carriage way by the use of ventilated air pressure calculation for tunnels, and estimation of concentration distribution with the use of the emission coefficient.

4) Design concentration based on tunnel ventilation design.

3.2 Calculation method concerning wind velocity

This calculation method concerns the wind velocity in the carriage way of trenched structures including tunnel parts with natural ventilation.

Figure 3.2 gives a schematic representation of an intermittent tunnel structure.

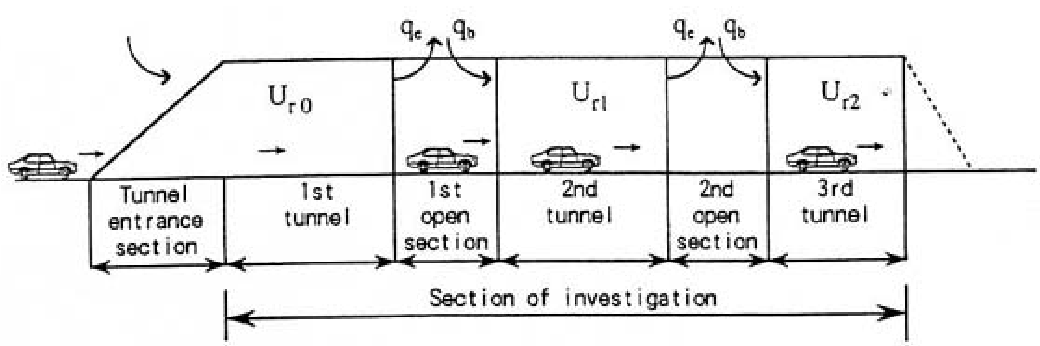


Figure 3.2 Schematic representation of an intermittent tunnel structure

There are different wind velocity calculation methods [3), 4)], based on the pressure balance equation, for simple trenched structures and intermittent tunnel structures, in which trenched structures and tunnel structures alternate. We have here chosen the calculation method based on the full transverse ventilation method to calculate the wind velocity in the carriage way, because the respiration action is as phenomenon similar to full transverse ventilation and the basic principles of full transverse ventilation are widely known. This wind velocity is used for the calculation of the concentration in the carriage way and the diffusion from the open part.

The method calculates the wind velocity in the carriage way, where the whole section of discussion is taken as a single tunnel structure and with a transverse ventilation system only in the first and the second opening as is shown in figure 3.2. If in this situation the respiration volumes of the first and the second opening are such that the supplied and extracted air volumes are equal, the flow velocity in the direction of the road axis is equal at all places of the section. In this case, U_r is calculated with equation (3.1).

$$\left\{\left(1+\zeta_{in}+\lambda_1\frac{L_{r1}}{D_r}\right)\frac{\rho}{2}U_{r1}^2+\rho\frac{q_e(q_b)W\ \ U_{r1}}{A_r}\right\}=\frac{\rho}{2}\frac{A_m}{A_r}n\left(U_t-U_{r1}\right)^2 \tag{3.1}$$

where 1 : This value stands for the dynamic pressure which is thrown away at the final end of the tunnel (exit).

ζ_{in} : This coefficient is only used in the first opening and is zero from the second.

$L_{r1} \sim L_{rn}$: If the cross sectional area of the carriage way is constant over the whole section of investigation, L_r can be taken as the length of the whole tunnel.

D_r : If the representative diameter of the carriage way is constant over the whole section of investigation, the same value for D_r can be used over the whole tunnel length.

λ_1 : Friction loss between air and structural surface in carriage way

U_{r1} : Air velocity at first tunnel (unknown factor)

n : Number of vehicles at unit length of tunnel

The second item in the left lid of this equation expresses the air curtain effect. In general, this air curtain effect influences the inducing air flow in the carriage way: if the respiration volume increases, meaning that the ceiling openings become wider, the induced air velocity becomes smaller. The extreme case of this tendency is the open air, for which the traffic induced air flow in the traffic space is not considered.

In case of a continuous slit (either central or lateral) over the total trenched structure, the calculation method based on transverse ventilation can be applied, provided that the respiration volumes are set appropriately in accordance with the shape of the ceiling openings.

3.3 Calculation method concerning concentration distribution

This calculation method concerns the estimation of the concentration distribution along the road axis and the dispersion factor from the open part (for unidirectional traffic).

Based on the estimation results of the unit respiration volumes and the wind velocity in the carriage way, the dispersion factor from the open part of trenched structures is decided.

The unit volume Q_e (ml/s) of the dispersed matter emitted from the open part of trenched structures is the multiplied value of the ventilated wind volume influenced by the respiration

action and the concentration of polluted matter (ppm), as shown in figure 2.5.
Next, setting the fractional length dx within the slit part, as shown in figure 2.6, equation (3.2) can be obtained from the law of constancy of mass.

$$A_r \cdot U_r \cdot \frac{dc}{dx} = g - q_b \cdot W \cdot C \tag{3.2}$$

If we solve this equation with boundary conditions x=0 and C=C_0, the concentration C(x) can be calculated with equation (3.3).

$$C(x) = \frac{g}{q_b \cdot W} + \left(C_0 - \frac{g}{q_b \cdot W} \right) \exp\left(- \frac{q_b \cdot W}{A_r \cdot U_r} x \right) \tag{3.3}$$

The emission volume qd (ml/s/m) from the open part can be obtained from equation (3.4).

$$qd(x) = q_b \cdot W \cdot C(x) = g + (q_b \cdot W \cdot C_0 - g) \exp\left(- \frac{q_b \cdot W}{A_r \cdot U_r} x \right) \tag{3.4}$$

Therefore, the total volume of emitted polluted matter from the open part can be obtained from equation (3.5), after integrating equation (3.4) from x=0 to x=L.

$$Q_d = \int qd(x) d = g \cdot L + \frac{A_r \cdot U_r \cdot (q_b \cdot W \cdot C_0 - g)}{q_b \cdot W} \cdot \left\{ 1 - \exp\left(- \frac{q_b \cdot W}{A_r \cdot U_r} L \right) \right\} \tag{3.5}$$

4. CONCLUSIONS

1) The prediction method for air velocity and gaseous concentration in the carriage way can be applied for the case of full transverse ventilation. The setting of the respiration volumes, however, must be carried out case by case.
2) The determination of the respiration air volume by theoretical method without any experiment is very difficult.
3) The opening ratio (area of ceiling openings) can be controlled to fulfill the standards of air quality for the carriage way and its surroundings.
4) Trenched road structures with natural ventilation could reduce the mechanical ventilation installation and the operation costs.
5) It is necessary to investigate safety systems with smoke behaviour in case of fire.
6) The visual environment and the traffic conditions are different from ordinary motorways on various aspects, and the effects to the driving tasks of this structure must be considered.

5. REFERENCES

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