Research Article

Complementary Ventilation Design Method for a Highway Twin-Tunnel Based on the Compensation Concept

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Based on the compensation concept, an improved method for twin-tunnel complementary ventilation design considering differences in key pollutants in the uphill and downhill tunnels was proposed. The results demonstrate that the scheme developed using the improved method is more energy efficient when the energy consumption of the interchange channel is included. Here, a larger design of air volume is allocated to the uphill tunnel, and the admissible pollutant concentration for its exits. The complementary ventilation system of the Qingniling Tunnel, Dabieshan Tunnel, and Lianghekou Tunnel was redesigned for long-term performance using the improved method, and the resulting scheme was compared to that designed using the current method in terms of the total required air volume, interchange air volume, ventilation effects, and energy consumption. The results show that these factors in improved method are significantly smaller than that of the current method with an allowable reduction of ventilation effects. Moreover, the total airflow required in the Qingniling Tunnel was reduced from 889.31 to 796.74 m³/s, with a decrease rate of 10.4%; the interchange air volume was reduced from 203 to 175 m³/s, and the estimated energy consumption was decreased from 2760 to 2065.9 kW. This represents a 26% improvement in energy efficiency. The proposed method can provide a reference for the energy efficient design of ventilation systems in extra-long highway tunnels.

1. Introduction

Tunnel ventilation systems must be able to provide adequate air quality during normal operation, in addition to supporting self-evacuation and rescue efforts during emergency incidents [1]. In short tunnels, the nature ventilation and the piston effect of moving vehicles are usually sufficient to drive fresh air in and discharge polluted air out [2]. However, in long vehicle tunnels, the mechanical ventilation system is required to dilute pollutions emitted by vehicles [3–7]. Longitudinal, semitransverse, and transverse ventilation systems are the traditional approaches employed in the design of vehicular tunnel ventilation systems [8]. Among these ventilation systems, longitudinal tunnel ventilation systems have been applied in many highway tunnels owing to their lower construction and operation costs and effectiveness of controlling smoke during fire emergencies [9–24]. However, the major constraints of longitudinal ventilation systems are excessive air volume and velocity. Additionally,

these systems cannot ventilate long unidirectional vehicular tunnels without a build-up of pollutant concentration levels in the direction of travel unless air exchange points are provided [25]. Typically, the maximum length of tunnels which can be ventilated by longitudinal ventilation systems is no longer than 3.00 km [26], and ventilation shafts are placed to divide longer tunnels into shorter ventilation sections suitable for longitudinal tunnel ventilation in the tunnel longer than 3.00 km, which bring about increase of ventilation system initial investment and operation energy consumption [27]. However, in some twin-tunnels with large slopes, the required air volume for uphill tunnel is greater than the maximum allowable airflow, but the sum of required air volume for the two tunnels is less than the total maximum allowable airflow; in such cases, ventilation shafts are not a necessity. Bemmer et al. (1991) proposed an alternative method [28], which dilutes the polluted air in uphill tunnel with fresh air in downhill tunnel through an interchange channel, thus requiring less airflow. This ventilation pattern

is able to dilute the concentration of pollutants to under admissible levels in separated extra-long highway tunnels with unequal airflow requirements without increasing the total ventilation volume, thus reducing the ventilation operating costs. However, this method had not been adopted in any actual projects until Zhang et al. (2011) applied such a ventilation scheme in the ancillary tunnel works of the Jinping Hydropower Station. Relevant calculation methods were also proposed through theoretical analysis, and the scheme was named the air interchange system for road tunnel longitudinal ventilation owing to its airflow exchange characteristics between the double-line tunnels [29]. After this, Wang et al. (2014) further developed the ventilation scheme and applied it in the Dabie Mountain Highway Tunnel [30], Qingniling Highway Tunnel, Lianghekou Tunnel, and Jiuling Mountains Tunnel. Compared with traditional ventilation system, the twin-tunnel complementary ventilation system is a relatively innovative method, which has a number of advantages including low consumption of energy and construction, multiplexing, more reasonable distribution of pollutant concentration, and good visibility [31].

However, in the complementary ventilation design of the above projects, the sum of the required air volume for dilution of key pollutants in the double-line tunnels is taken as the total design air volume, an equal design air volume for the uphill and downhill tunnels is taken as the most cost-optimal air distribution scheme, and the interchange air volume is defined to make the concentration of key pollutants at the exit of the downhill tunnel equal to that at the exit of the uphill tunnel [32]. Analysis of these cases reveals that the required air volume for the uphill tunnel is usually determined by the air volume necessary for smoke (VI) dilution, while required air volume for the downhill tunnel is determined by the minimum air exchange rate, and the air demand for diluting carbon monoxide (CO) is larger than that for smoke. In other words, the key pollutant for the two tunnels is different. Thus, the sum of the required air volume for dilution of key pollutants in double-line tunnel may be more than is necessary for the dilution of pollutants, which leads to wasted energy.

In terms of the design airflow distribution, because there is a directly proportional relationship between the fan power and the cube of the air volume [33], an equal design air volume for uphill and downhill tunnels enables minimum fan power for the main tunnel. However, this neglects a consideration of the power consumption of the axial flow ventilator in the interchange channel. With a decrease in the design air volume of the uphill tunnel, the capacity for pollutants dilution will also be reduced. As a result, the complementary air volume necessary through the interchange channel will be increased, as will the energy consumption of the ventilator in the interchange channel. Therefore, the most cost-optimal design air volume for the uphill and downhill tunnels should be further investigated.

In addition, it is unnecessary to make the concentration of key pollutants at the exits of the uphill tunnel equal to that of the downhill tunnel when the total required air volume is larger than the total demand for pollutants dilution. This

FIGURE 1: Schematic of a complementary ventilation system.

would increase the interchange air volume needlessly and result in wasted energy.

Based on the fundamental principle of complementary ventilation and the “compensation concept” for pollutants, this study analyses the above problems and establishes an improved complementary ventilation design method for energy conservation.

2. Fundamental Principle

A schematic of a complementary ventilation system is shown in Figure 1. The principle concept of complementary ventilation can be explained as follows: when the sum of the required air volume for the double-line tunnels is less than the total combined maximum allowable airflow for the two tunnels, the two ventilation systems can be connected with two interchange channels to form a combined system. This allows air interchange between the uphill and downhill tunnels to be realised, and the ample fresh air in the downhill tunnel can be used to complement the insufficient fresh air volume in the uphill tunnel [29].

3. Description of the Current Method

3.1. Determination of the Design Air Volume. The design air volume should be the minimum air volume required to provide adequate air quality during normal operation while also supporting self-evacuation and rescue efforts during fire emergencies. The maximum air requirement for CO and VI dilution and the minimum air exchange rate and smoke extraction during a fire in the double-line tunnels are taken as the design air volume for the longitudinal ventilation system. Because of the combination of two tunnels in complementary ventilation, the design air volume for the tunnels was defined as the following [29, 30, 32]:

$$Q'_U + Q'_D \geq Q_U + Q_D = \max(Q_{Ui}) + \max(Q_{Di}) \quad (1)$$

where Q'_U , Q'_D , Q_U , and Q_D are the design air volumes of the uphill and downhill tunnels for complementary and longitudinal ventilation, respectively; Q_{Ui} and Q_{Di} ($i = 1, 2, 3$, or 4) are the required air volume for diluting CO and VI and the minimum air exchange rate and smoke extraction during a fire in the double-line tunnels, respectively. If the maximum air flow volume for the downhill tunnel is equal to the required air volume for the minimum air exchange rate, then the second-highest value will replace the maximum value, as mentioned above, because the design air volume will be increased to provide adequate air quality for the uphill

FIGURE 2: Range of locations for the interchange channel.

tunnel. In the current method, the design air volume is often taken as

$$Q'_U = Q'_D = \frac{Q_U + Q_D}{2} \quad (2)$$

This results in the minimum value for $Q'^3_U + Q'^3_D$, which thus result in the minimum gross power required for the draught fan in the main tunnel, because the fan power is directly proportional to the cube of the air volume.

3.2. Location of the Interchange Channel. The concentration distribution of pollutants in a twin-tunnel complementary ventilation system is shown in Figure 2. The pollutant concentration in the uphill tunnel will exceed the threshold, as

shown by the extension line, if the design air volume for complementary ventilation is used for longitudinal ventilation. At the same time, the pollutant concentration in the downhill tunnel will be far below the threshold. As the airflow in one tunnel will be partially diverted to the other tunnel, before the diverted airflow from the first tunnel flows into the second tunnel the rate of increase in the pollutant concentration in the main tunnel between the two interchange channels will be faster than that in the other parts. The afflux of the split flow from the other tunnel then leads to a step change in the pollutant concentration.

The location of the interchange channel in a complementary ventilation system should be in the range of (L_m, L_n) to ensure the effectiveness of the interchange and that the pollutant concentration in the uphill tunnel does not exceed the admissible level, as shown in Figure 2. If the location exceeds the maximum length (L_n) for longitudinal ventilation with the design air volume (Q'_U) for complementary ventilation in the uphill tunnel, the pollutant concentration in that tunnel will exceed the threshold. Furthermore, if the location exceeds the point (L_m) where the pollutant concentration in the two tunnels is equal, the interchange cannot supply fresh air to the uphill tunnel.

$$L_n = \frac{Q'_U}{Q_U} L_U \quad (3)$$

$$L_m = \frac{q_D \cdot Q'_U \cdot L_U \cdot L_D}{q_U \cdot Q'_D \cdot L_D + q_D \cdot Q'_U \cdot L_U} \quad (4)$$

3.3. Interchange Air Volume. According to the fundamental theory of ventilation, the air volume of the interchange channels, Q_{h1} and Q_{h2} , must satisfy the following:

$$\begin{aligned} \frac{q_D - ((q_D \cdot L_{D3}) / (L_D \cdot Q'_D)) \cdot Q_{h1} + ((q_U \cdot L_{U1}) / (L_U \cdot Q'_U)) \cdot Q_{h2}}{Q'_D - Q_{h1} + Q_{h2}} &\leq \delta_{\lim} && \text{Exit of downhill tunnel} \\ \frac{q_D \cdot ((L_{D2} + L_{D3}) / L_D) - ((q_D \cdot L_{D3}) / (L_D \cdot Q'_D)) \cdot Q_{h1}}{Q'_D - Q_{h1}} &\leq \delta_{\lim} && \text{Interchange Channel exit in downhill tunnel} \\ \frac{q_U + ((q_D \cdot L_{D3}) / (L_D \cdot Q'_D)) \cdot Q_{h1} - ((q_U \cdot L_{U1}) / (L_U \cdot Q'_U)) \cdot Q_{h2}}{Q'_U + Q_{h1} - Q_{h2}} &\leq \delta_{\lim} && \text{Exit of uphill tunnel} \\ \frac{q_U \cdot ((L_{U1} + L_{U2}) / L_U) - ((q_U \cdot L_{U1}) / (L_U \cdot Q'_U)) \cdot Q_{h2}}{Q'_U - Q_{h2}} &\leq \delta_{\lim} && \text{Interchange Channel exit in uphill tunnel} \end{aligned} \quad (5)$$

Considering the equality of the ventilation system before and after airflow interchange, $Q_{h1} = Q_{h2}$, then according to the current calculation method, the pollutant concentrations

at the exits of the double-line tunnels are equal to each other, i.e., $(q_D + q_U) / (Q'_D + Q'_U)$. Thus, the interchange air volume can be calculated as follows:

$$Q_{h1} = Q_{h2} = \frac{q_U \cdot Q'_D - q_D \cdot Q'_U}{(Q'_D + Q'_U) \cdot (((q_U \cdot L_{U1}) / (L_U \cdot Q'_U)) - ((q_D \cdot L_{D3}) / (L_D \cdot Q'_D)))} \quad (6)$$

4. Proposed Improved Method Based on Compensation

4.1. Compensation Theory of Complementary Ventilation. From the perspective of required air volume, complementary ventilation connects the ventilation systems of two tunnels as an integrated system through an interchange channel. This system complements the insufficient fresh air volume in the uphill tunnel with the ample fresh air volume in the downhill tunnel. From the perspective of pollutant dilution, complementary ventilation transfers the pollutants above the ventilation load capacity in the uphill tunnel to the downhill tunnel for dilution through the interchange channel by increasing the fresh air supply in the downhill tunnel. In other words, the downhill tunnel is used to compensate a portion of the load of the uphill tunnel, ensuring that the standard is met overall. Therefore, the total design air volume of the tunnel is defined as follows:

$$Q'_U + Q'_D \geq \max(Q_{Ui} + Q_{Di}) \quad (7)$$

Because $\max(Q_{Ui}) + \max(Q_{Di}) \geq \max(Q_{Ui} + Q_{Di})$, the total required air volume for the compensation method will be less than that for the current method, which will increase the utilisation efficiency of fresh air in the tunnels and be beneficial for conserving energy in the ventilation system.

4.2. Design Air Volume for a Single Tunnel considering Energy Consumption of the Axial Flow Ventilator. In previous studies, because fan power and the cube of the air volume are directly proportional, the most economic and energy efficient method is to assign half of the total required air volume as the design air volumes for the double-line tunnels [29]. However, the energy consumption of the axial flow ventilator in the interchange channel was not taken into consideration. As previously mentioned, with a decrease in the design air volume for the uphill tunnel, the interchange air volume will increase, which will result in increased energy consumption in the two interchange channels. Meanwhile, the air volume increase in the downhill tunnel will also cause an increase in energy consumption. Therefore, when considering energy conservation, the design air volume for the uphill tunnel should have an appropriately larger value.

4.3. Location and Air Volume of the Interchange Channel. In the determination of the total required air volume, consideration of the unbalanced load for the same pollutant in two tunnels will make the calculation more complex, particularly for the determination of the location of the interchange channel and interchange air volume. In this case, the location of the interchange channel should be at the intersection of the ranges determined based on removal of CO and VI, as follows:

$$\begin{aligned} L_m &= \max(L_{mCO}, L_{mVI}) \\ L_n &= \min(L_{nCO}, L_{nVI}) \end{aligned} \quad (8)$$

The design of equal pollutant concentrations at the exits of the double-line tunnels is undoubtedly economical and

rational if the total required air volume is calculated based on the pollutant (CO or VI). However, in the case that the total required air volume is not determined by CO or VI, i.e., the total required design air volume is larger than total required air volume for pollutant dilution, this method will increase the interchange air volume to reduce the pollutant concentration at the exit of the uphill tunnel to an unnecessarily low level (meanwhile, the pollutant concentration at the other exit will be increased unnecessarily). The interchange air volume should be sufficient for the tunnel ventilation to ensure that the pollutant concentration does not exceed the threshold values. Thus, the interchange air volume ($Q_{h1} = Q_{h2}$) can be taken as the ratio of pollutant overload $((1 - Q'_U/Q_U) \cdot q_U)$ in the uphill tunnel to the difference in pollutant concentration of the two interchange channels $((Q_U \cdot L_{U1})/(L_U \cdot Q'_U)) - ((Q_D \cdot L_{D3})/(L_D \cdot Q'_D))$, as follows:

$$\begin{aligned} Q_{h1} &= Q_{h2} \\ &= \frac{q_U \cdot Q_U - q_U \cdot Q'_U}{Q_U (((Q_U \cdot L_{U1})/(L_U \cdot Q'_U)) - ((Q_D \cdot L_{D3})/(L_D \cdot Q'_D)))} \end{aligned} \quad (9)$$

As $q_U/Q_U = q_D/Q_D = \delta$, the following is obtained:

$$\begin{aligned} Q_{h1} &= Q_{h2} \\ &= \frac{Q_U - Q'_U}{(((Q_U \cdot L_{U1})/(L_U \cdot Q'_U)) - ((Q_D \cdot L_{D3})/(L_D \cdot Q'_D)))} \end{aligned} \quad (10)$$

According to the pollutant distribution characteristics in longitudinal ventilation, the pollutant concentration is higher downstream of the airflow. Therefore, the location of the interchange channel should be as near the exit of the uphill tunnel as possible to reduce the interchange air volume; furthermore, if the distance between interchange channels is determined, the minimum interchange air volume (which meets the requirements) is also determined and unique. With a decrease in the design air volume for the uphill tunnel, the pollutant overload quantity will increase, as will the corresponding minimum air exchange volume.

5. Ventilation Mode Analysis

In the ventilation design of highway tunnels, the required air volume is determined from a combination of the most unfavourable conditions. However, in reality, the most unfavourable conditions rarely occur in both the double-line tunnels at the same time. Thus, operation according to the most unfavourable conditions will inevitably result in wasted air volume and energy [34, 35].

Xia et al. (2014) proposed the use of full jet longitudinal ventilation with a single U-type ventilation mode and a double U-type ventilation mode, according the real conditions of the Dabieshan Tunnel. It is difficult to explain the single U-type ventilation mode from the perspective of air volume, but easy to explain from the perspective of the compensation concept [36].

According to complementary ventilation design, the design air volume and installed power for the uphill tunnel

TABLE 1: Long-term required air volumes (m^3/s).

Design conditions	Right line		Left line	
	CO	Smoke	CO	Smoke
30km/h	288.70	349.93	221.40	152.47
40km/h	216.53	345.96	207.56	125.79
50km/h	173.22	503.90	166.05	120.76
60km/h	144.35	419.92	138.37	100.63
70km/h	122.70	538.87	117.62	91.65
80km/h	129.92	598.18*	103.78	80.87
Traffic block	300.10*	427.58	291.13*	169.74*
Fire		188.37		188.37
Minimum Air exchange		415.53		381.21

Note: the item marked with * indicates the maximum required air volume for pollutant dilution.

are less than those in longitudinal ventilation with the maximum allowable air volume. Thus, the maximum allowable traffic volume under the full jet longitudinal ventilation mode of complementary ventilation is also less than that under the full jet longitudinal ventilation of a single tunnel. The maximum allowable traffic volume can be calculated from predicted traffic volume compositions and the pollutant concentration at the tunnel exit.

If the traffic volume of the uphill tunnel is greater than the maximum traffic volume for full jet longitudinal ventilation mode of complementary ventilation (but not greater than the maximum traffic volume for full jet ventilation of a single tunnel), a single U-type ventilation mode can be adopted. This increases the fresh air supply to the uphill tunnel by conveying air with low pollutant concentration at the tunnel exit through the downhill tunnel. In other words, the fresh air in downhill tunnel will “compensate” part of the air, which should have been obtained from the entrance of the uphill tunnel. Because the air passing through the interchange channel contains a certain concentration of pollutants, and the maximum air discharge volume is limited by the maximum allowable air speed in the uphill tunnel after convergence, the maximum allowable traffic volume for the single U-type ventilation mode is also less than that for the full jet longitudinal ventilation of a single tunnel. In fact, this ventilation mode can also be applied to the longitudinal ventilation of jet fans with uneven ventilation quantities, which can decrease energy consumption by reducing the length of sections with large air volumes.

If the traffic volume in the uphill tunnel increases further, a double U-type ventilation mode should be adopted to transfer a portion of the pollutants to the left tunnel. This is the normal conventional complementary ventilation mode.

6. Case Study

6.1. Project Overview. The Qingniling Tunnel is a key engineering feature on the Gansu section of the Shiyan–Tianshui Expressway. It is designed as a separated four-lane double-line tunnel, with the left line having a total length of 5464 m (road gradient: -2%) and the right line having a length

FIGURE 3: Qingniling Tunnel.

of 5700 m (5060 m at 1.99% and 640 m at 1.385%), shown in Figure 3. The average designed elevations of the left and right lines are 876.6 and 877.4 m, respectively. In the twin-tunnel with unidirectional traffic, the design driving speed is 80 km/h, and the cross-sectional area is 62.79 m^2 . The maximum ventilation airflow for the two tunnels is $502.32 \text{ m}^3/\text{s}$. The predicted peak traffic is 1082 vehicles/h in 2025 and 2032 vehicles/h in 2033. Because longitudinal ventilation can meet the predicted demands for 2025, the complementary ventilation design is only considered for ventilation in 2033. The required air volumes under different conditions in the left (downhill) and right tunnels (uphill) in 2033 are summarised in Table 1. Xia et al. (2015) designed a complementary ventilation scheme using the current method, and the ventilation system layout is shown in Figure 4 [32].

FIGURE 4: Current ventilation system layout in the Qingning Tunnel.

FIGURE 5: Comparison of required air volumes calculated for two design methods (m^3/s).

The ventilation system of the Qingning Tunnel has been redesigned with the improved method, and the scheme was compared to that designed with the current method in terms of the total required air volume, air volume of the interchange channel, ventilation effects, and energy consumption.

6.2. Total Required Air Volume Analysis. Based on the data in Table 1, the total required air volumes calculated from the improved design method and the current design method are shown in Figure 5.

Figure 5 shows that the total required air volume over the long term in the Qingning Tunnel under the most unfavourable conditions is determined by the minimum air exchange. The total required air volume decreases from $889.31 \text{ m}^3/\text{s}$ to $796.74 \text{ m}^3/\text{s}$ with the improved design method, representing a decrease of 10.4%.

6.3. Location of the Interchange Channel and Interchange Air Volume. The total required design air volume of the double-line tunnels in the long term is defined as $800 \text{ m}^3/\text{s}$. For design air volumes of the left line and right line of $500+300$, $480+320$,

$460+340$, $440+360$, $420+380$, and $400+300$, the relevant installation ranges for the interchange channel are calculated. The interchange air volume is calculated with equal pollutant concentrations at the exits of the double-line tunnels (shown in s2) and by maintaining the pollutant concentration at the exit of the uphill tunnel under the threshold value (shown in s1). The location and distance of the interchange channels (3800 m to the entrance of the uphill tunnel, with a distance of 100 m) were the same as in the design of Xia et al. The gross power of the ventilation system is estimated according to the directly proportional relationship between the fan power and the cube of the air volume. The calculation results are summarised in Table 2.

The data in Table 2 shows that, with an increase in the design air volume for the uphill tunnel, the installation range for the interchange channels increases, and the air volume of the interchange channels decreases gradually. When the design air volume of the right tunnel is increased from $400 \text{ m}^3/\text{s}$ to $500 \text{ m}^3/\text{s}$, the range for the interchange channels extends from 2564 m to 2959 m, with a rate of 15.4%; the interchange air volume concurrently decreases by $72 \text{ m}^3/\text{s}$, with a rate of 31.7%.

Determining the air volume of the interchange channel by maintaining the pollutant concentration at the exit of the uphill tunnel within admissible values, compared to the air volume determined for equal pollutant concentrations at the exits of the two tunnels, could greatly decrease the interchange air volume and gross power of the ventilation system. For the Qingning Tunnel, the maximum decreases in the interchange air volume and gross power are 17.1% and 8.6%, respectively.

With an increase in the design air volume of the uphill tunnel, the gross power of the ventilation system decreases gradually. In the calculations, the decrease in the air volume of the interchange channel caused by increasing the design air volume of the uphill tunnel has not been realised to the maximum extent, because the location of the interchange channel is fixed at 3800 m. Thus, the gross power for a required air volume of the right tunnel of $500 \text{ m}^3/\text{s}$ is larger than that for a required air volume of $480 \text{ m}^3/\text{s}$. Hence, if the location of the interchange channel is at 3800 m to the

FIGURE 6: Smoke concentration distribution in tunnels calculated for two design methods.

TABLE 2: Calculation results for different tunnel design air volume combinations.

Q'_R (m^3/s)	L_n	L_m	$Q_{h1} = Q_{h2}$				Gross power			
			s1 (m^3/s)	s2 (m^3/s)	Δs (m^3/s)	$\Delta s/s2$ (%)	s1 (kW)	s2 (kW)	Δs (kW)	$\Delta s/s2$ (%)
500	4764	1805	155	187	32	17.11	2116.4	2287.6	171.2	7.48
480	4574	1680	175	203	28	13.79	2065.9	2248.7	182.8	8.13
460	4383	1563	191	217	26	11.98	2103.7	2301.4	197.7	8.59
440	4193	1452	206	228	22	9.65	2181.6	2370.7	189.1	7.98
420	4002	1347	217	238	21	8.82	2211.4	2409.8	198.4	8.23
400	3812	1248	227	245	18	7.35	2271.3	2454.3	183	7.46

Note: when the design air volume of the right tunnel is taken as $400 \text{ m}^3/\text{s}$, L_n is close to 3800 m ; if the ventilation layout is designed according to the data in the table, the pollutant concentration of the second interchange channel in the uphill tunnel would exceed the specified admissible values.

entrance of the uphill tunnel, the rational air distribution scheme will be a design air volume of $480 \text{ m}^3/\text{s}$ for the uphill tunnel and $320 \text{ m}^3/\text{s}$ for the downhill tunnel.

6.4. Comparison of Ventilation Effects. Figures 6 and 7 show the pollutant concentrations (VI and CO) for the scheme designed using the current method and that designed with the improved method; the design air volumes for

the right and left tunnels are $480 \text{ m}^3/\text{s}$ and $320 \text{ m}^3/\text{s}$, respectively.

The figures show that the concentration of smoke and CO calculated for the current method are far below the admissible values, and the pollutant concentrations at the exits of the two tunnels are not equal. This is because, in the current method, the total required air volume is determined by “grafting” the required air volume for diluting CO in one tunnel to

FIGURE 7: CO concentration distribution in tunnels calculated for different design methods.

that for diluting smoke in the other tunnel. Thus, the total design air volume is greater than the minimum total required air volume; additionally, the dislocation resulting from this “grafting” also leads to unequal pollutant concentrations at the tunnel exits.

The pollutant concentrations at the exits of the interchange channel and tunnel calculated for the improved method are all slightly higher than that calculated for the current method, but are still below the admissible values. This means that fresh air is utilised more efficiently with the improved method.

It is noteworthy that the CO concentration at the exit of the left tunnel is close to the admissible threshold and even exceeds it when the interchange air volume is increased (the pollutant concentrations at the exits of both tunnels are taken as being equal). This is because the given design air volume for the left tunnel ($320 \text{ m}^3/\text{s}$) is close to the required air volume for diluting CO ($291.13 \text{ m}^3/\text{s}$). Further, with an increase in interchange air volume, the quantity of CO transferred from the right tunnel to the left tunnel increases accordingly and exceeds the dilution capacity of the designed

air volume in the left tunnel. Therefore, in the calculation of complementary ventilation design, it is necessary to check the CO concentrations when the smoke concentration is used to calculate the design air volume, location of the interchange channel, and air exchange volume.

6.5. Comparison of Energy Consumption. According to the law of airflow resistance, ventilation resistance is directly proportional to the square of the air volume, and power consumption of a draught fan is directly proportional to the cube of the air volume. Based on the calculation of Xia et al. (2015), the required pressure and gross power of the ventilator were estimated, as summarised in Table 3.

The data in Table 3 indicates that the required pressure increase and total installed power calculated for the improved method are significantly smaller compared to those with the current method. The total pressure required decreases from 920.1 to 731.3 Pa, which is a decrease of 20.5%; the total installed power decreases from 2790 to 2065.9 kW, which is a decrease of 724.1 kW, corresponding to a realised energy conservation of 26%. Assuming the working time of the

FIGURE 8: Dabieshan Tunnel.

FIGURE 9: Lianghekou Tunnel.

FIGURE 10: Smoke concentration distribution in Dabieshan Tunnels calculated for two design methods.

TABLE 3: Comparison of draught fan configurations for two design methods.

		Current method [32]			The Improved Method		
		Air volume	Require pressure	Gross power	Air volume	Require pressure	Gross power
		(m ³ /s)	(Pa)	(kW)	(m ³ /s)	(Pa)	(kW)
Jet fan	L	450	250.1	660	320	126.5	240
		450	183.8	420	320	92.9	180
	R	450	269.7	660	480	306.9	810
		450	132.5	420	480	150.8	510
Axial fan		218	42	630	175	27.1	325.9
Total		—	920.1	2790	—	731.3	2065.9

Note: integrated values for the jet fan power are based on a value of 30 kW for a single jet fan.

draught fan is 10 h/d, the annual energy consumption cost can be reduced by 396 thousand dollars on average, which demonstrates great economic and ecological benefits.

6.6. Case Comparison. The ventilation systems of two additional highway tunnels, Dabieshan Tunnel (shown in Figure 8 and Table 4) and Lianghekou Tunnel (shown in Figure 9 and Table 4), were redesigned. And the energy savings achieved

in these tunnels are listed in Table 4. With a decrease in the total design volume and interchange volume, the energy cost is significantly reduced, and the annual cost of ventilation operation is decreased by hundreds of thousands of dollars.

Figures 10 and 11 show the smoke concentrations for Dabieshan tunnel and Lianghekou Tunnel designed using the current method and that designed using the improved

FIGURE 11: Smoke concentration distribution in Lianghekou Tunnels calculated for two design methods.

TABLE 4: Energy savings in tunnel operation ventilation achieved with the improved method.

	length (m)		Total design air (m ³ /s)	Design Volume (m ³ /s)		Interchange volume (m ³ /s)		Total power (kW)		Energy saving (%)	Saving cost (thousand dollars)
	uphill	downhill		C.	I.	C.	I.	C.	I.		
Dabieshan Tunnel	2665 (1.47%)	2720 (-1.47%)	116.06+772.6 (VI)	420	350	240	200	2040	1800	11.76	140.2
	+2243 (1.97%)	+2181 (-1.97%)		+420	+450						
Lianghekou Tunnel	1260 (1.95%)	1262 (-1.95%)	196.23+595.5 (VI)	480	400	380	335	1200	900	25	175.2
	+2865 (2.49%)	+2870 (-2.49%)		+480	+510						

Note: "C." indicates the current method, and "I." indicates the improved method.

method, respectively. Owing to the design air volume of uphill tunnels designed using improved method is greater than that using current method and the design air volume of downhill tunnels using improved method is less than that design using current method. Thus, the concentration calculated by improved method is less than that calculated by current method at the upstream (between the entrance and the second transverse channel) of the uphill tunnel, while it is

inverse of the downhill tunnel. The concentration calculated by improved method is greater than that calculated by current method significantly downstream of the uphill tunnel, while the relationship of downhill tunnel is complex, but it is certain that the exit concentration calculated by improved method is higher than that calculated by current method.

It is noteworthy that the exit concentration of uphill and downhill tunnel calculated by current method is equal,

because the total design air volume is determined by the diluting smoke.

7. Conclusion

A complementary ventilation design for a twin-tunnel based on the compensation concept could effectively meet the ventilation requirements of the tunnels and reduce the total required air volume, while avoiding wasting air volume for ventilation. In the cases mentioned in this study, the total required air volume under the most unfavourable conditions could be reduced by 10.4%.

In terms of the design airflow distribution, the capacity of the uphill tunnel should be given priority; more volume should be allotted to it to reduce the energy consumption of the other tunnel due to “compensation” and that of the interchange channel due to air exchange.

The method of determining the interchange air volume according to maintaining the pollutant concentration at the exit of the uphill tunnel within admissible values could effectively reduce the interchange air volume compared to that determined according to equal pollutant concentrations at the exits of the two tunnels. In the cases mentioned in this study, this decrease in the interchange air volume reached 13.8%, boasting significant energy conservation in the ventilation.

Owing to the decrease in total required air volume and interchange air volume, the pollutant concentrations near the exits of the double tunnel designed using the improved method are greater than that designed using the current method, but could still meet the specifications. Compared to the current method, the improved method could significantly reduce the energy consumption of complementary ventilation and has clear advantages in terms of energy conservation for ventilation and favourable economic and social benefits.

Data Availability

The data used to support the findings of this study are included within the article.

Disclosure

The current address for Jing Song is Shandong Provincial Communications Planning and Design Institute, Jinan 250000, Shandong, China.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

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