Research Article

Optimization Method for Twin-Tunnel Complementary Ventilation Design and Its Energy Saving Effect

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Received 18 December 2018; Revised 18 March 2019; Accepted 25 March 2019; Published 22 May 2019

Academic Editor: Eusebio Valero

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Based on the compensation principle and optimization theory, an energy conservation optimization mode for twin-tunnels complementary ventilation design was proposed. And, compensation concept utilization in energy conservation of long tunnels ventilation was discussed. The energy consumption for long tunnels can be reduced significantly by remoulding longitudinal ventilation to complementary ventilation of single U-type mode or normal mode. The short-term and long-term ventilation systems of the Qingniling Tunnel, Dabieshan Tunnel, and Lianghekou Tunnel were redesigned using the optimization method, and the new scheme was compared to the original design in terms of ventilation effects, and energy consumption. In redesign, the energy consumption of short-term ventilation systems decreased 240 kW, 150 kW, and 390 kW, and energy efficiency increased by 40%, 50%, and 68.4%, respectively. In the long term, the numbers of those were 1185 kW, 1185kW, and 540 kW, and 42.5%, 58.09%, and 45%, while the pollutants concentration increased a little. The study can provide a reference for the energy efficient design of ventilation systems in long and extra-long highway tunnels.

1. Introduction

To provide adequate air quality during normal operational period, support self-evacuation and rescue efforts during emergency incidents, mechanical ventilation systems are often employed in vehicular tunnels [1–3]. Longitudinal, semi-transverse, and transverse ventilation systems are the traditional mechanical approaches employed in the design of vehicular tunnel ventilation systems [4, 5]. Among these ventilation systems, longitudinal tunnel ventilation systems have been most widely adopted owing to the effective utilization of the piston wind [6–20]. And, ventilation shafts are often placed to divide tunnels into separate ventilation sections suitable for longitudinal tunnel ventilation in the extra-long tunnels (longer than 3.00 km), because the pollution concentration, increasing along the tunnel in the airflow direction, may exceed the admissible threshold. However, ventilation shafts bring about increase of ventilation system initial investment and operation energy consumption [21]. Twin-tunnel complementary ventilation system can solve this problem to some extent [22]. The system has two interchange

channels between uphill tunnel and downhill tunnel, which allows the ample fresh air in the downhill tunnel to be used to complement the insufficient fresh air volume in the uphill tunnel. Compared with traditional ventilation systems, 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 pollutants concentration, and good visibility.

The concept of “twin-tunnel complementary” ventilation system was proposed by Bemer et al. for the first time in 1991 to solve the imbalance of ventilation requirement between uphill tunnel and downhill tunnel in some large single-slope twin tunnels, considering twin tunnels as a single unit rather than as two separated tunnels [23]. The concept came into practice for the first time in Ping-Lin tunnel in Taiwan, and the investment and operation cost of the tunnel are reduced largely [7]. Then, Zhang et al. 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 [24]. Wang et al. further developed the ventilation scheme and applied it in the Dabieshan Highway Tunnel [25–27], Qingniling Highway Tunnel, Lianghekou Tunnel, and Jiuling Tunnel, and obtained economic and ecological benefits. Ren et al. investigated the effectiveness of twin-tunnel complementary ventilation by the numerical simulation. The results showed that the distance from air interchange channels to the uphill-tunnel inlet is the most important factor involved in influencing the ventilation efficiency rather than the flow volume of air interchange channel and the jet fan thrust in tunnel on the ventilation efficiency [22].

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 [26]. Although Chai et al. proposed an improved method, which considered differences in key pollutants in the uphill and downhill tunnels and a larger design of air volume is allocated to the uphill tunnel to reduce the energy consumption of the interchange channel and total energy consumption [28], the key factors are determined by repeatedly calculations, which are often complex with heavy computing burden, and easily to be error; meanwhile, the result may not the best for energy-saving. Therefore, a simplified design method is needed.

Additionally, in the above researches, the twin-tunnel complementary ventilation systems were all investigated under the employment in the extra-long double-line tunnels to instead the longitudinal ventilation with a ventilation shaft or inclined shaft. The energy-saving of remoulding longitudinal ventilation into complementary ventilation was ignored. In this paper, the energy-saving optimization model for twin-tunnel complementary ventilation system was proposed, and the twin-tunnel complementary ventilation system utilization in energy-saving of remoulding longitudinal ventilation was discussed. The results can help engineers better understand the twin-tunnel complementary ventilation system, to design an effective ventilation system for double-line tunnel.

2. Energy-Saving Optimization Model for Complementary Ventilation

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 [26]. Although Chai et al.

FIGURE 1: A complementary ventilation network.

proposed an improved method, which considered differences in key pollutants in the uphill and downhill tunnels and a larger design of air volume is allocated to the uphill tunnel to reduce the energy consumption of the interchange channel and total energy consumption, and the key factors are determined by repeatedly calculations. The calculations are often complex with heavy computing burden, and easily to be error; meanwhile, the result may not the best for energy-saving. Therefore, a simplified design method is needed. The energy-saving optimization model is proposed to solve this problem.

2.1. Energy Consumption Function. In complementary ventilation systems, the uphill and downhill tunnels were divided into 6 sections by the two interchange channels, as shown in Figure 1. The high concentrated polluted air in branch 1 passes through branch 7 (1st interchange channel) into branch 4, while the low concentrated polluted air in branch 6 passes through branch 8 (2nd interchange channel) into branch 3. Owing to the concentration difference between the exchange flow, the pollutants exceeding the dilution capacity of design air volume in uphill tunnel are transferred to the downhill tunnel and diluted by the increased design air volume.

In airway j , the pressure losses, P_{Rj} (Pa), can be related to the square of the volume flow through the airway Q_j (m³/s), with a constant of proportionality being the resistance, R (Ns²/m⁸ or kg/m⁷) of the airway by the Atkinson's equation [29]:

$$P_{Rj} = R_j Q_j^2 \quad (1)$$

where airway resistance (R_j) consists of resistance caused by friction between airflow and tunnel wall, roof, and floor (frictional resistance) plus resistance caused by bends, changes in tunnel cross sectional dimension, and branches (shock loss). It is calculated using this equation:

$$\begin{aligned} R_j &= \left(\frac{\lambda_j L_j}{D_j} + \xi_j \right) \cdot \frac{\rho}{2} \cdot \frac{1}{A_j^2} \\ &= \left(\lambda_j L_j \frac{U_j}{4A_j} + \xi_j \right) \cdot \frac{\rho}{2} \cdot \frac{1}{A_j^2} \end{aligned} \quad (2)$$

where λ_j is the frictional coefficient (dimensionless), ξ_j is the shock loss factor (dimensionless), L_j is length of the airway (dimensionless), $D_j = 4A_j/U_j$ is hydraulic diameter of the airway (m), U_j is the airway cross sectional perimeter (m), A_j is airway cross section area (m²), and ρ is density of airflow inside the airway (kg/m³).

According to the law of conservation of energy, and the network of complementary system as shown in Figure 1, the required fans thrust P_{Fj} can be calculated as

$$\begin{aligned}
 P_{F1} + P_{T1} - P_{N1} + P_{F2} + P_{T2} - P_{N2} + P_{F3} + P_{T3} - P_{N3} \\
 &= P_{R1} + P_{R2} + P_{R3} \\
 P_{F1} + P_{T1} - P_{N1} + P_{F7} + P_{T7} - P_{N7} + P_{F4} + P_{T4} - P_{N4} \\
 &= P_{R1} + P_{R7} + P_{R4} \\
 P_{F6} + P_{T6} - P_{N6} + P_{F5} + P_{T5} - P_{N5} + P_{F4} + P_{T4} - P_{N4} \\
 &= P_{R6} + P_{R5} + P_{R4} \quad (3) \\
 P_{F6} + P_{T6} - P_{N6} + P_{F8} + P_{T8} - P_{N8} + P_{F3} + P_{T3} - P_{N3} \\
 &= P_{R6} + P_{R8} + P_{R3} \\
 P_{F7} + P_{T7} - P_{N7} - P_{R7} + P_{F8} + P_{T8} - P_{N8} - P_{R8} \\
 &= P_{F5} + P_{T5} - P_{N5} - P_{R5} + P_{F2} + P_{T2} - P_{N2} - P_{R2}
 \end{aligned}$$

where the traffic force P_{Tj} (Pa) and nature wind pressure P_{Nj} (Pa) can be obtained from the geometrical cross-section of a car A_m (m^2), the traffic flow per hour n (veh/h), vehicle velocity v_T (m/s), the length of uphill and downhill tunnel L_U (m) and L_D (m), and the nature wind pressure of uphill and downhill tunnel P_{NU} (Pa) and P_{ND} (Pa). The calculation methods are

$$P_{Tj} = \frac{A_m \rho}{A_j} \frac{n L_j}{2 \cdot 3600 v_T} \left(v_T - \frac{Q_j}{A_j} \right) \left| v_T - \frac{Q_j}{A_j} \right| \quad (4)$$

$$P_{Nj} = \begin{cases} \frac{L_j}{L_U} P_{NU} & (j = 1, 2, 3) \\ \frac{L_j}{L_D} P_{ND} & (j = 4, 5, 6) \end{cases} \quad (5)$$

Then, the output power of fans N_j can be calculated as

$$\begin{aligned}
 N_j = P_{Fj} Q_j &= (P_{Rj} + P_{Tj} - P_{Nj}) Q_j \\
 &= k_j Q_j^3 + (P_{Tj} - P_{Nj}) Q_j \quad (6)
 \end{aligned}$$

Considering the fan motor efficiency η , the energy consumption of section branch j can be calculated as

$$N'_j = \frac{N_j}{\eta} \quad (7)$$

The total energy consumption of the network can be calculated as

$$N = \sum N'_j = \frac{\sum N_j}{\eta} \quad (8)$$

2.2. Decision Variables and Constraints. As the above analysis, the energy consumption of network is influenced by the length and the air volume of each branch. And the variables are subject to the follow constraints:

(1) Design air volumes. As the interchange channels connect the single tunnels as a combined system, the design air volumes of complementary ventilation system should meet:

$$Q_1 + Q_6 \geq \max(Q_{Di} + Q_{Ui}) \quad (9)$$

where Q_1 , and Q_6 are the design air volumes of the uphill and downhill tunnels for complementary ventilation, respectively; Q_{Ui} and Q_{Di} ($i = 1, 2, 3$, or 4) are the required air volumes for diluting CO (Carbon monoxide) and smoke (VI) and the minimum air exchange rate and smoke extraction during a fire in the double-line tunnels, respectively, which can be calculated by Eq. (10).

$$\begin{aligned}
 Q_{D1}, Q_{U1} &= \frac{1}{3.6} q_{CO} \cdot f_{a(CO)} \cdot f_d \cdot f_{h(CO)} \cdot f_{iv(CO)} \cdot f_t \\
 &\quad \cdot L \cdot \sum_{m=1}^n \frac{(N_m \cdot f_{m(CO)})}{\delta_{CO}} \\
 Q_{D2}, Q_{U2} &= \frac{1}{3.6 \times 10^6} q_{VI} \cdot f_{a(VI)} \cdot f_d \cdot f_{h(VI)} \cdot f_{iv(VI)} \\
 &\quad \cdot f_t \cdot L \cdot \sum_{m=1}^{n_D} \frac{(N_{Dm} \cdot f_{m(VI)})}{\delta_{VI}} \quad (10)
 \end{aligned}$$

$$Q_{D3}, Q_{U3} = \max \left(\frac{A_r \cdot L \cdot n_s}{3600}, A_r \cdot v_{ac} \right)$$

$$Q_{D4}, Q_{U4} = 3 \cdot A_r$$

where q_{CO}, q_{VI} base emission of CO [$m^3/(\text{veh} \cdot \text{km})$], smoke [$m^2/(\text{veh} \cdot \text{km})$] for base year 2000; $f_{a(CO)}, f_{a(VI)}$ influence factors for road on CO, smoke emission (-); f_d influence factors for traffic density (-); $f_{h(CO)}, f_{h(VI)}$ influence factors for altitude of tunnels on CO, smoke emission (-); $f_{iv(CO)}, f_{iv(VI)}$ influence factors depended on average speed and road gradient (-); f_t influence factors for years differing from the base year (-); L length of uphill or downhill tunnel (m); n , n_D the number of vehicle type and diesel vehicle type; N_m , N_{Dm} traffic volume for each vehicle type; $f_{m(CO)}, f_{m(VI)}$ factor depended on vehicle type; δ_{CO}, δ_{VI} admissible values for CO (ppm), smoke (m^{-1}). A_r cross-section of uphill or downhill tunnel (m^2), n_s the minimum frequency of air exchange; v_{ac} the minimum air velocity in longitudinal ventilation (m/s).

As Eq. (10) shows, the required air volumes for minimum air exchange and smoke extraction during a fire are determined by the length and cross-section of tunnels, so the required air volumes for the uphill and downhill tunnel are similar, while the required air volumes for diluting CO and smoke are influenced by tunnels altitude, and road gradient. Although altitudes of uphill and downhill tunnel are similar and gradient changes do not greatly affect the vehicle's CO emissions, the high smoke emissions of diesel engines create different ventilation flow requirements. As Table 1 shows, under 80km/h, the value of $f_{iv(CO)}$ is 1.0 for a -3% gradient and 1.2 for one of 3%, the increasing ratio is only 20%, but the value of $f_{iv(VI)}$ increases from 0.4 to 4.4, and a 10 times increase is gotten. This means that the required air volume for

the uphill tunnel must be far higher than that for the downhill tunnel.

(2) Continuity of airflow. The ventilation system works in incompressible condition, so the air volumes should meet:

$$\begin{aligned} Q_3 &= Q_2 + Q_8 \\ Q_1 &= Q_2 + Q_7 \\ Q_4 &= Q_5 + Q_7 \\ Q_6 &= Q_5 + Q_8 \end{aligned} \quad (11)$$

And if $Q_7 = 0, Q_8 \neq 0$, the ventilation is the single U-type mode; if $Q_7 = Q_8 = 0$, the ventilation is normal longitudinal ventilation. In this situation, the ventilation system for uphill or downhill tunnel is independent, and the pollution by air exchange between the uphill tunnel and downhill tunnel is increasing. The pollutant concentration gets the maximum value at the outlet of uphill and downhill tunnels. So the design air volumes Q_1 and Q_6 should meet: $Q_1 \geq \max(Q_{Uj})$, $Q_6 \geq \max(Q_{Dj})$ to ensure the pollutants concentration under the admissible values.

(3) Air velocity limit. The air velocity in tunnel should not exceed the maximum allowable air velocity $v_{\max}$, and the minimum air velocity for air exchange is 1.5m/s [30]. So, the air volumes of branch j should meet:

$$\begin{aligned} Q_j &\geq 1.5 \cdot A_j \\ Q_j &\leq v_{\max} \cdot A_j \end{aligned} \quad (12)$$

($j = 1, 2, \dots, 6$)

(4) Admissible concentration. The pollutants concentration should not exceed the admissible values. In the ventilation network, there are four key points, the outlet of branch 2,3,4,5, where the concentration of pollutions is greater than the upstream sections. So, the constraints of admissible concentration can be taken as

$$\begin{aligned} \frac{q_U L_1}{L_U Q_1} + \frac{q_U L_2}{L_U Q_2} &\leq \delta \\ \frac{(q_U - q_U L_1 Q_7 / L_U Q_1 + q_D L_6 Q_8 / L_D Q_6)}{Q_3} &\leq \delta \\ \frac{q_D L_6}{L_D Q_6} + \frac{q_D L_5}{L_D Q_5} &\leq \delta \\ \frac{(q_D + q_U L_1 Q_7 / L_U Q_1 - q_D L_6 Q_8 / L_D Q_6)}{Q_4} &\leq \delta \end{aligned} \quad (13)$$

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

$$\begin{aligned} \frac{Q_U L_1}{L_U Q_1} + \frac{Q_U L_2}{L_U Q_2} &\leq 1 \\ \frac{(Q_U - Q_U L_1 Q_7 / L_U Q_1 + Q_D L_6 Q_8 / L_D Q_6)}{Q_3} &\leq 1 \\ \frac{Q_D L_6}{L_D Q_6} + \frac{Q_D L_5}{L_D Q_5} &\leq 1 \\ \frac{(Q_D + Q_U L_1 Q_7 / L_U Q_1 - Q_D L_6 Q_8 / L_D Q_6)}{Q_4} &\leq 1 \end{aligned} \quad (14)$$

where the q_U, q_D, Q_U , and Q_D are the vehicular emission pollutants (CO and smoke) and the required air volume for diluting those in uphill and downhill tunnels, respectively.

(5) Geometric constraints. As branch 1, branch 2, and branch 3 are in the uphill tunnel and branch 4, branch 5, and branch 6 are in the downhill tunnel, the lengths of branches should meet:

$$\begin{aligned} L_U &= L_1 + L_2 + L_3 \\ L_D &= L_4 + L_5 + L_6 \end{aligned} \quad (15)$$

As the Figure 1 shown, the channels are often parallel and perpendicular to the tunnels, so the lengths of branches 2 and 5 should meet:

$$L_2 = L_5 \quad (16)$$

And there is often a distance L_s between the inlet of uphill tunnel and the outlet of downhill tunnel, so the lengths of branches 1 and 4 should meet:

$$L_4 = L_1 + L_s \quad (17)$$

where the sign of L_s is determined by the relative location of uphill inlet and downhill outlet.

In complementary ventilation system, air flow near interchange channels should be as Figure 2(b). But if the lengths of branches 2 and 5 are too short to eliminate the backflow from one air interchange channel outlet to the other's inlet, the air would flow as Figure 2(a). [22, 28] So L_2 and L_5 should meet:

$$L_2 = L_5 \geq l_{\min} \quad (18)$$

(6) Mathematical constraints. All the variables should be nonnegative. Additionally, in order to reduce the solve time of this model and provide the convenience for construction, L_1 and L_2 can be taken as the multiple of INT_1 and INT_2 , as Eq. (19), where INT_1, INT_2 can be set as 50m, 20m, 10m 5m, 1m et al, and determined by the design precision.x

$$\begin{aligned} \frac{L_1}{INT_1}, \frac{L_2}{INT_2} &= \text{integer} \\ L_j, Q_j &\geq 0 \end{aligned} \quad (19)$$

2.3. Optimization Model. Based on the above analysis, the energy saving optimization model is built up and may be written as

$$\begin{aligned}
\min \quad & N = \sum N'_j = \frac{\sum N_j}{\eta} \\
\text{Subject to (s.t.)} \quad & Q_1 + Q_6 \geq \max(Q_{Di} + Q_{Ui}) \\
& Q_3 = Q_2 + Q_8 \\
& Q_1 = Q_2 + Q_7 \\
& Q_4 = Q_5 + Q_7 \\
& Q_6 = Q_5 + Q_8 \\
& 1.5 \cdot A_j \leq Q_j \leq v_{\max} \cdot A_j \\
& L_U = L_1 + L_2 + L_3 \\
& L_D = L_4 + L_5 + L_6 \\
& L_4 = L_1 + L_s \\
& L_2 = L_5 \geq l_{\min} \\
& \frac{Q_U L_1}{L_U Q_1} + \frac{Q_U L_2}{L_U Q_2} \leq 1 \\
& \frac{(Q_U - Q_U L_1 Q_7 / L_U Q_1 + Q_D L_6 Q_8 / L_D Q_6)}{Q_3} \leq 1 \\
& \frac{Q_D L_6}{L_D Q_6} + \frac{Q_D L_5}{L_D Q_5} \leq 1 \\
& \frac{(Q_D + Q_U L_1 Q_7 / L_U Q_1 - Q_D L_6 Q_8 / L_D Q_6)}{Q_4} \leq 1 \\
& \frac{L_1}{INT_1}, \frac{L_2}{INT_2} = \text{integer} \\
& L_j, Q_j \geq 0
\end{aligned} \tag{20}$$

3. Utilization in Energy Conservation of Long Tunnels

The flow of fresh air needed to maintain the air quality in a road tunnel is determined by the tunnel's length and the amount of pollutants emitted by the vehicles travelling through it. This is a function of the amount of traffic, its speed, and the gradient and altitude of the road [23, 30]. Especially, gradient often leads to the fact that the design ventilation flow for the uphill tunnel must be far higher than that for the downhill tunnel. Table 2 shows some long and extra-long twin tunnels' design ventilation flow for the uphill and downhill tunnels. The design ventilation flow ratio of uphill and downhill tunnel can reach 2.59. As the maximum allowable flow velocity limit, the uphill tunnels are usually divided into separate ventilation sections and exchange polluted air with fresh air via a ventilation shaft at the end of each section. And the complementary ventilation system is employed in some extra-long tunnels whose design ventilation flow of the uphill tunnel exceeds the maximum allowable flow velocity limit, but the sum of the uphill and downhill tunnels is lower than the double of the limits. Great economic and ecological benefits have been obtained for its low energy consumption by decreasing the flow velocity in the uphill tunnel.

However, this advantage has not been developed for the long-tunnel energy saving, in which longitudinal ventilation is often applied. Even though the energy consumption of single long tunnel often is lower than that of extra-long tunnel for its lower required air volume and resistance, but its number is huge, there are 3841 long tunnels (length 1000~3000m), but only 902 extra-long tunnels (length ≥ 3000 m) in Chinese highway end of 2017. The accumulative effect of energy saving is considerable.

The energy consumption can be reduced significantly by remoulding the longitudinal ventilation to the complementary ventilation, either the single U-type ventilation mode or the normal mode.

In the single U-type mode, the fresh air volume that gets from the uphill inlet is insufficient and is complemented with the fresh air getting from the downhill inlet via the air interchange channel near the uphill outlet and the downhill outlet so that the flow velocity can be reduced in most sections to reduce the frictional resistance and the required fans thrust, as shown in Figure 3(a).

In normal complementary mode, the design air volume of the uphill tunnel is decreased, while that of the downhill tunnel is increased, but the total required fans thrust is decreased because the required fans thrust of single tunnel is directly proportional to the cube of the air volume.

TABLE 1: Values of $f_{iv(CO)}, f_{iv(VI)}$ under different gradient at 80km/h.

Gradients (%)	-4	-3	-2	-1	0	1	2	3	4
$f_{iv(CO)}$	1.0	1.0	1.0	1.0	1.0	1.0	1.2	1.2	1.2
$f_{iv(VI)}$	0.3	0.4	0.55	0.8	1.3	2.6	3.7	4.4	-

TABLE 2: Design ventilation flow of some long and extra-long twin tunnels.

	Length (m)	Tunnel type	Design ventilation flow			Ventilation type
			Uphill (m ³ /s)	Downhill (m ³ /s)	U/D	
Diefushan Tunnel	1657	Long	467.16	230.15	2.03	Transverse ventilation
Wutongshan Tunnel	2270	Long	491.02	313.68	1.57	Transverse ventilation
Huangcaoshan Tunnel	2505	Long	512.25	281.00	1.82	Longitudinal ventilation
Jianshanzi Tunnel	4020	Extra-long	512.86	337.51	1.52	Longitudinal ventilation
Liangfengya Tunnel	4085	Extra-long	544.64	278.59	1.95	Longitudinal ventilation
Jinyunshan Tunnel	2528	Long	412.00	247.63	1.66	Longitudinal ventilation with shafts
Zhongliangshan Tunnel	3165	Extra-long	547.00	304.48	1.80	Longitudinal ventilation with shafts
Yanmenguan Tunnel	5235	Extra-long	839.78	415.52	2.02	Longitudinal ventilation with shafts
Jiahuoyan Tunnel	5228	Extra-long	835.80	350.09	2.39	Longitudinal ventilation with shafts
Lianghekou Tunnel	4130	Extra-long	772.6	298.38	2.59	Complementary ventilation
Dabieshan Tunnel	4900	Extra-long	595.47	279.37	2.13	Complementary ventilation
Jiuling Tunnel	5456	Extra-long	628.51	260.22	2.42	Complementary ventilation
Qingning Tunnel	5700	Extra-long	598.18	381.21	1.57	Complementary ventilation

FIGURE 2: Air flow near the interchange channels.

Meanwhile, if the design air volume of the downhill tunnel is determined by the minimum air exchange, the total design air volume can be reduced so that the flow velocity can be reduced in both uphill and downhill tunnels, as shown in Figure 3(b). The frictional resistance and the required fans thrust can be reduced further.

Because the pollutants transfer is not necessary, the distance between the two air interchange channels can be extended. When the first channel is located at the upstream of uphill and the second channel is located at downstream of uphill, the pressure difference between the channel inlet

and outlet can induce the flow into the channel, and the axis fans installed in channels are not necessary. And cross-passageways for vehicle and people passing can be used as air interchange channels to reduce the construction cost.

4. Case Study

4.1. Project Overview. The Qingning Tunnel is one of the main highway tunnels linking Shiyan with Tianshui. It is designed as a separated four-lane double-line tunnel, the

FIGURE 3: Pressure and velocity profile for complementary remoulding of longitudinal ventilation.

downhill tunnel is 5464 m with slope of -2% , and the uphill tunnel is 5700 m, which consists of 5060 m with slope of 1.99% and 640 m with slope of 1.385% , as shown in Figure 4. The average designed elevations of the uphill and downhill tunnel are 877.4 and 876.6 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 velocity for the two tunnels is defined as 8 m/s. The predicted peak traffic is 1082 vehicles/h in 2025 and 2032 vehicles/h in 2033. The nature wind pressures of the uphill and downhill tunnel are 78.68 Pa and 75.22 Pa, respectively. The required air volumes under different conditions in the left (downhill) and right tunnels (uphill) are summarised in Table 3. In original design, the longitudinal ventilation is employed for the short term (2025), the complementary ventilation is employed for the long term (2033), and the ventilation system layout is shown in Figure 5 [26]. But the required air flow ratio of the uphill and downhill tunnel is 1.32 when the longitudinal ventilation

is employed for the short term, and the ratio of diluting smoke is 3.52 as great as that value for long term. The complementary ventilation employed for short time may get an improvement in energy efficiency.

The data in Table 3 show that the design air volume in the uphill tunnel is determined by dilution smoke, while that in downhill tunnel is determined by the minimum air exchange, both the short term and the long term, when the ventilation system was designed with the longitudinal ventilation. In the design, the total required air volume is $663.32 \text{ m}^3/\text{s}$ of the short term, and $979.39 \text{ m}^3/\text{s}$ of the long term. However, the design air volume is determined by minimum air exchange in redesign with the complementary ventilation, in which the total required air volume for short term is $597.55 \text{ m}^3/\text{s}$, with a decrease rate of 9.92% , and $796.74 \text{ m}^3/\text{s}$ with a decrease rate of 18.6% , for the long term. The smoke control U/D value is 3.52, which makes the sum air demand of diluting smoke ($484.52 \text{ m}^3/\text{s}$ and $767.92 \text{ m}^3/\text{s}$) is lower than that of the minimum exchange ($597.55 \text{ m}^3/\text{s}$ and $796.74 \text{ m}^3/\text{s}$). Compared with the

FIGURE 4: Qingningling Tunnel.

FIGURE 5: Original ventilation system design for the Qingningling Tunnel.

design air volume of original complementary scheme, the reduction of design air volume is $121.39 \text{ m}^3/\text{s}$, and the decrease rate is still 10.4%.

4.2. Redesign for Short Term. The short-term ventilation system was redesigned with complementary ventilation system by using the optimization method, and the normal complementary mode was adopted. Then, the constraints of $Q_7 = 0, P_{F7} = 0$ were added, and the optimal single U-type

scheme for energy saving was worked out. These schemes were compared to the original design in terms of the energy consumption, and ventilation effects, as shown in Table 4.

The data in Table 4 show that the complementary ventilation scheme is more efficient than the longitudinal ventilation scheme, and the normal complementary mode is more efficient than the single U-type mode. As the total required thrust decreases from 222.38 Pa to 129.15 Pa, the gross power of the normal complementary mode decreases from 600 kW to 360 kW, which is a decrease of 240 kW, corresponding to a

TABLE 3: Required air volumes (m^3/s).

Design conditions		Short term (2025)				Long term (2033)			
		Uphill	Downhill	Sum	U/ D	Uphill	Downhill	Sum	U/ D
Pollutants dilution	CO	181.47	176.05	357.52	1.03	300.10	291.13	591.23	1.03
	Smoke	377.42*	107.1	484.52	3.52	598.18*	169.74	767.92	3.52
Fire emergency		188.37	188.37	376.74	1	188.37	188.37	376.74	1
Minimum air exchange		311.65	285.9*	597.55*	1.09	415.53	381.21*	796.74*	1.09
Maximum value		377.42	285.9	663.32	1.32	598.18	381.21	979.39	1.57

Note: the item marked with * indicates the maximum required air volume for tunnels; "U/D" indicates the required air flow ratio of the uphill and downhill tunnel.

FIGURE 6: Comparison of pressure and flow velocity distribution in tunnels.

realised energy conservation of 40%. Assuming the working time of the fans is 10 h/d, and the annual energy consumption cost can be reduced by 146 thousand dollars on average, which demonstrates great economic and ecological benefits. While the energy saving of the optimal single U-type scheme is only 60 kW, it is equal to 25% of the normal complementary

mode. The total air volume and the required thrust also increase to $631 \text{ m}^3/\text{s}$ and 207.08 Pa, respectively.

The pressure and velocity profile of different schemes are shown in Figure 6. In original design, longitudinal ventilation is adopted, and 10 jet fans are installed in the inlet and outlet section of the uphill tunnel, while the number of the

TABLE 4: Comparison of ventilation schemes in energy consumption.

Section	Original design			Redesign			Single U-type mode				
	Air volume (m ³ /s)	Required thrust (Pa)	Gross power (kW)	Length (m)	Air volume (m ³ /s)	Required thrust (Pa)	Gross power (kW)	Length (m)	Air volume (m ³ /s)	Required thrust (Pa)	Gross power (kW)
Uphill	1		30×10	2750	300	46.85	30×4	0	0	0	0
	2	377.42	222.38	1250	212	0.00	0	3300	312	6.51	30×1
	3		30×10	1700	336	29.90	30×3	2400	424	200.57	30×17
Downhill	4		0	2750	262	0.00	0	0	0	0	0
	5	285.9	0	1250	174	0.00	0	3300	207	0	0
	6		0	1464	298	0.00	0	2164	319	0	0
Channels	7	—	—	0	88	0.00	—	0	0	0	—
	8	—	—	0	124	52.40	150	0	112	0	0
Total	663.32	222.38	600	—	598	129.15	360	—	631	207.08	540

FIGURE 7: Comparison of short-term pollutants concentration distribution in tunnels.

downhill tunnel is 0, and the traffic force and nature wind pressure provided the thrust. In the redesign, there are 4 jet fans installed in the inlet section and 3 jet fans in the outlet section of the uphill tunnel for the decrease of ventilation resistance resulting from the air volume decreasing. Fans are also installed in the second air interchange channel to induce the air from the inlet of downhill tunnel into the outlet section of uphill tunnel through the channel. While no fan is installed in the first channel, the air flow in that is induced by the pressure difference between the inlet and outlet of the channel. In single U-type mode scheme, most fans of the uphill tunnel are installed in the outlet section, and the air is induced from the uphill and downhill tunnels. The traffic force provides the most thrust in other sections. Additionally, the flow in the interchange channel is induced by the pressure difference between the inlet and outlet of it.

Figure 7 shows the pollutants concentrations (smoke and CO) profile of different schemes. The figures show that the smoke and CO concentrations in the uphill tunnel of the redesign scheme increase faster than that of original scheme, and the difference between the two schemes reaches the maximum at the second air interchange channel. Then the difference between two schemes keeps steady, after a sudden decrease at the second air interchange channel. While in the downhill tunnel, the smoke and CO concentrations of the redesign are a little lower than those of the original design at the inlet section. Then the concentrations of the redesign increase fast and surpass the original design in the middle section. At the outlet section, the difference between the two schemes keeps steady, after a sudden change at the second air interchange channel.

Because the design air volume of single U-type mode is greater than that of the normal complementary mode, the smoke and CO concentrations with normal complementary mode are higher than those of the single U-type mode, except for the CO concentration in the outlet section of downhill tunnel.

Additionally, only the maximum smoke concentration of the uphill tunnel reaches the maximum allowable value in the original design and redesign, and the maximum smoke concentration of the downhill tunnel and the maximum CO concentration of twin tunnels are far below the maximum allowable value. However, the concentration of redesign is higher than that of the original design at the most range of length, which means that fresh air is utilised more efficiently in the redesign complementary ventilation.

4.3. Redesign for Long Term. The long-term ventilation system was redesigned with normal complementary ventilation mode, and the scheme was compared to that designed with original design in terms of the ventilation effects, and energy consumption.

The data in Table 5 show that the redesign scheme is significantly different from the original scheme. The location of the first air interchange channel moves from 3700m to 3650m away from the uphill inlet. The design air volumes of twin tunnels are not equal, and the air volumes of two air interchange channels are also not equal. The data also reveal that the redesign scheme is more efficient than the original scheme. While the total required thrust decreases from 920.1 Pa to 568 Pa, the gross power decreases from 2790

TABLE 5: Comparison of two ventilation schemes in energy consumption.

	Length (m)	Original design[26]			Improved method [28]			Redesign				
		Volume (m ³ /s)	Thrust (Pa)	Power (kW)	Length (m)	Volume (m ³ /s)	Thrust (Pa)	Power (kW)	Length (m)	Volume (m ³ /s)	Thrust (Pa)	Power (kW)
Jet fan	1	3700	450	250.1	3700	480	306.9	30×27	3650	402	54.1	30×5
	2	100	232	6.76	100	305	11.68	0	100	223	0	0
	3	1900	450	183.8	1900	480	150.8	30×17	1950	460	283.5	30×24
	4	3700	450	269.7	3700	320	126.5	30×8	3650	337	166.0	30×14
	5	100	232	6.76	100	145	2.64	0	100	158	0	0
	6	1664	450	132.5	1664	320	92.9	30×6	1714	395	0	0
Axial fan	7	—	218	42	—	175	27.1	162.95	0	179	64.4	315
	8	—	218	42	—	175	27.1	162.95	0	237	0	0
Total	—	900	920.1	2790	—	800	731.3	2065.9	—	797	568.0	1605

Note: “Volume”, “Thrust” and “Power” indicate the air volume, required thrust and gross power, respectively. Integrated values for the jet fan power are based on a value of 30 kW for a single jet fan.

FIGURE 8: Comparison of long-term pollutant concentration distribution in tunnels.

kW to 1605kW, which is a decrease of 1185 kW, corresponding to a realised energy conservation of 42.5%. Assuming the working time of the fans is 10 h/d, the annual energy consumption cost can be reduced by 720.9 thousand dollars on average. Even compared with the improved method proposed by Chai et al., the gross power is 2065.9 kW, the decrease is still 460.9 kW, and the energy conservation is 22.3%; therefore, 280.4 thousand dollars energy cost can be saved. Great economic and ecological benefits can be obtained.

Figure 8 shows the pollutants concentrations (smoke and CO) profile of redesign complementary and original complementary ventilation for long term; the pollutants concentrations of redesign and the improved method are greater than the original method at most range, but it does not exceed the maximum allowable, which means that the fresh air is utilised more efficiently with the improved method. Because the redesign air volume of single tunnel is lower than that of the original scheme, the pollutants concentration of redesign is higher than that of the original scheme at the most range of length and increases faster, in the uphill and downhill tunnels. Compared to the improved method by Chai et al., the redesign air volume of the uphill tunnel is lower than the improved method, while that of the downhill tunnel is inverse. So, the pollutants concentration of the uphill tunnel is greater than that of the improved method at most range and increases faster, while that of the downhill tunnel is lower than that of the improved method and increases slower. And, owing to the flexible scheme for air volume, a

better energy efficiency is obtained. The energy consumption of optimization method is lower than that of the improved method, as shown in Figure 9, although the total design air volumes of them are approximately equal (shown in Table 5).

The pressure and velocity profile of original and redesign schemes are shown in Figure 9. In the original design, 22 jet fans are installed in the section of uphill-tunnel inlet and downhill-tunnel outlet, 14 jet fans are installed in downhill-tunnel inlet and uphill-tunnel outlet section, and 2 axial fans are installed in two air interchange channels, respectively. In the redesign scheme, owing to the flow velocity reducing in the uphill and downhill tunnels except the outlet section of uphill tunnel, most jet fans are installed in the outlet section of the uphill tunnel. 24 jet fans in the outlet section of the uphill tunnel and 14 jet fans in the outlet section of the downhill tunnel, only 5 jet fans in the inlet section of the uphill tunnel, no jet fan in the outlet section of downhill tunnel, and only 1 axial fan in the first air interchange channel to induce the air from the inlet of the uphill tunnel into the outlet section of the downhill tunnel through the channel are installed. While no fan is installed in the second channel, the air flow in that is induced by the pressure difference between the inlet and outlet of the channel.

As shown in Figure 9, the flow velocity in uphill tunnel of redesign is lower than that of the improved method by Chai et al., while that in the downhill tunnel is inversed. So, the fans installed in uphill tunnel of redesign are less than those of the improved method, while those in the downhill tunnel are also inversed.

FIGURE 9: Comparison of pressure and flow velocity distribution in tunnels.

4.4. Comparison. The ventilation systems of the two additional highway tunnels, Dabieshan Tunnel (shown in Figure 10) and Lianghekou Tunnel (shown in Figure 11), were redesigned, and the normal complementary mode was adopted in these tunnels. The energy savings achieved in these tunnels are listed in Table 6. 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.

In longitudinal ventilation remoulding, the air interchange channel of Dabieshan Tunnel is 4100 m away from the uphill-tunnel, and the distance of Lianghekou Tunnel is 2650 m. Even though the reduction of total design air volume is very little, in fact the total air volume of Lianghekou Tunnel increases $6 \text{ m}^3/\text{s}$, and the gross power is reduced more than 50%, which is benefited from the short distance of great air volume, while the smoke concentration is not greater than the threshold value, as shown in Figure 12.

In complementary ventilation redesign, the air interchange channel location of Dabieshan Tunnel is 3400 m, the same as the original complementary design scheme, while the location of Lianghekou Tunnel is 2300m away from the uphill-tunnel inlet, 175m away from the original design location. The reduction of total design air volume is $41 \text{ m}^3/\text{s}$ in Dabieshan Tunnel, the gross power is reduced 1185 kW, the energy conservation is 58.1%, and 720.88 thousand of dollars for ventilation operation is saved every year. And the smoke concentration is greater than the original design but lower than the threshold value, as shown in Figure 13(a). Even though the total design air volume of Lianghekou Tunnel is nearly equal to that of the original design, the gross power is still reduced 540 kW, the energy conservation reaches 45%, and 328.5 thousand of dollars for ventilation operation is saved every year, while the smoke concentration is similar to that of the original design and lower than the threshold value, as shown in Figure 13(b).

FIGURE 10: Dabieshan Tunnel.

FIGURE 11: Lianghekou Tunnel.

FIGURE 12: Smoke concentration distribution in Dabieshan Tunnel and Lianghekou Tunnel for short term.

FIGURE 13: Smoke concentration distribution in Dabieshan Tunnel and Lianghekou Tunnel for long term.

TABLE 6: Energy savings for ventilation achieved in tunnel operation period with the optimization method.

Tunnel	Period	Design Volume (m ³ /s)		Interchange volume (m ³ /s)		Total power (kW)		Energy Saving (%)	Saving cost (thousand dollars)
		O.	R.	O.	R.	O.	R.		
Dabieshan Tunnel	short-term	368.9	319	0	78	300	150	50	91.25
		278.97	299		56				
	long-term	420	432	240	150	2040	855	58.09	720.88
Lianghekou Tunnel	short-term	420	367		202				
		450	375	0	186	570	180	68.42	237.25
	long-term	300	381		196				
		480	497	380	357	1200	660	45	328.5
		480	462		362				

Note: "O." indicates the original design, and "R." indicates the redesign.

5. Conclusion

This paper proposed an optimization model for twin-tunnels complementary ventilation design. And the complementary ventilation system utilization in energy conservation of longitudinal ventilation remoulding was discussed. The effectiveness of the optimization method and the energy saving in longitudinal ventilation remoulding was verified by redesigning three tunnels where the original design longitudinal ventilation was adopted in the short term and the complementary ventilation was adopted in the long term, with the optimization method. The main results were drawn as follows:

(1) Optimization design method can significantly increase the energy saving of the complementary ventilation. In the redesign of long-term ventilation systems, the energy consumption is reduced by 42.5~58%; therefore hundreds of thousands of dollars for ventilation operation is saved every year.

(2) Remoulding ventilation schemes, longitudinal ventilation to complementary ventilation, benefits the energy conservation greatly. In the short-term ventilation systems remoulding, the energy consumption is reduced by 40~68.4%; therefore, hundreds of thousands of dollars for ventilation operation is saved every year.

(3) The normal mode is more effective than the single U-type mode in remolding longitudinal ventilation system for energy saving. For the air exchange between uphill and downhill tunnels is bidirectional in the normal mode; the air volume can be reduced more significantly, while that of the single U-type mode is unidirectional; the downhill tunnel provides fresh air for the uphill tunnel.

(4) It is not necessary to install fans in each air interchange channel for inducing the air into the channel, for the pressure difference between the inlet and outlet of the channel is enough.

Data Availability

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

Conflicts of Interest

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

Acknowledgments

This research was supported by the Key Research Program of Henan Provincial Department of Transportation (2017Z4). The authors would also like to express special thanks to Phd. Junling Qiu and Xing Liang from Chang'an University for their assistance during the revision of works.

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