Design of Ventilation for a Highway Tunnel in a Very Crowded Urban Area

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ABSTRACT

Resalat Tunnel is one of the widest twin-tube traffic tunnels of its kind, located in the heart of Tehran. Traffic volume passing through this tunnel is so that congestion exists in most hours of the days, particularly in rush hours time. Therefore the design of ventilation system for these tunnels is of paramount importance for all of tunnel users. All type of ventilation systems were technically and economically examined for these tunnels and finally the longitudinal type was selected as the best choice. The number and type of jet fans and arrangement of these fans in the tunnels were considered.

1. INTRODUCTION

High volume of traffic of Tehran in recent years has forced the traffic managers to design and construct new facilities in the city to overcome the problem among which some kilometers of urban tunnels are worthy to be mentioned. The principal purpose of the tunnels is to limit the environmental impact of noise and severance of motorway.

One of the most important affairs for these tunnels, with regard to the traffic and inevitable congestion, is ventilation without which use of the tunnels may encounter some difficulties. One of these tunnels that recently were opened to the traffic is Resalat tunnel. This tunnel is a 13.5m wide twin-tube three lanes tunnel, each tube consist of two parts with the lengths of 150m and 850m. The purpose of this paper is the design and proposing ventilation system of the latter parts. Design has been made with regard to the 2.7 % longitudinal gradient and the direction of headwind for both north and south tube.

2. BASIC CALCULATION DATA

2.1 Traffic

The first step for designing ventilation system of traffic tunnels is determination of traffic conditions through analysis of volume, increasing rate and peak point of traffic in both directions for whole life of the tunnels. For free-flowing conditions at 60 km/h, the maximum traffic volume lies between 1600 and 1800 cu/h (car unit per hour). In calculation of the traffic volume in terms of car unit, it should be mentioned that following coefficients have been assumed: coefficient of 2.5 for one four-axle truck, 2.2 for three-axle truck, 1.9 for two-axle truck, 1.7 for bus, 1.5 for minibus, 1 for normal cars and 0.7 for motorcycles. Congested traffic conditions will be frequent in this tunnel and it could occur at rush hours, weekend or before and after big sports events in the city stadiums.

The general urban tunnel design speed of 60 km/h will be maintained throughout the tunnels. It was considered that, since geometric standards to this speed are to be provided, the imposition of a lower permanent speed limit for the tunnel restrictions would be impossible to enforce, such limits being often more honoured in their breach than in their observance. The provision of gantry mounted signals before the tunnel will enable the police to impose temporary controls at times for dense traffic.

2.2 Tunnel

The principal geometrical data of the tunnel are the following:

- Length 850m each tube
- Cross sectional area 118m2
- Hydraulic diameter 13.5m
- Mean altitude above sea level 1220m.a.s.l
- Longitudinal gradient 2.7 %

2.3 Design parameters

The most important combustion products of petrol engine vehicles are carbon monoxide, carbon dioxide, sulphur dioxide and nitrogen oxides among which the first one prevails the others. Besides, smoke produced from imperfect combustion deteriorates visibility in the tunnel. Therefore, carbon monoxide, smoke and the volume of traffic are usual design parameters have been adopted for the calculation of the fresh air requirements.
Observations to date in the existing urban tunnels have not led to any doubt as to adequacy of the unit rates of vehicle emission.
The limited value for carbon monoxide is related to relatively short exposure time of the tunnel user and may be seen in the context of, although not derived from, the place of work. The current levels of threshold limit values based on various standards are 50ppm average for a 40 hour working week, 400ppm for 15 minutes exposure or 1500ppm for 30 minutes exposure. Also Russian standard suggests 160ppm and American standard determines 100ppm for this threshold.

3. CALCULATION METHOD AND RESULTS

3.1 Design of required fresh air

The calculation of the fresh air requirements was carried out according to (PIARC, 1995). Based on these regulations the admissible CO concentration for maximum free-flowing traffic was fixed at 250ppm, the one for congested traffic at 400ppm. The admissible value for diesel smoke and soot to ascertain sufficient visibility was fixed at 1.5 Dmg/m^3.
As mentioned earlier the extraction of air from the two tunnels is not equal and normally does not correspond to the equal requirements of the tunnels. This is due to the different longitudinal gradient, to the piston effect of the traffic and to the direction of headwind to the traffic.
In addition to PIARC, the amount of the pollutants and smoke, was determined by means of the equations recommended by various standards to compare the results. The standards of Britain, America, Norway, France and Japan were used for both cases of CO and smoke.
PIARC has suggested following equation for calculation the volume of required fresh air to dilute pollutants and smoke produced by the vehicles:

$$Q = q(v,i) \times f_h \times f_{cs} \times f_a \quad (1)$$

where, Q is the volume of required fresh air (m^3/h); f_h is the altitude factor; f_{cs} is the cold start factor; f_a is the ageing factor for catalysts; and $q(v,i)$ is the amount of pollutants produced by the vehicles. All these factors are determined from the PIARC suggested tables based on the longitudinal gradient and the vehicle velocities.
According to PIARC, the amount of required fresh air in each tube was designed based on the longitudinal gradient of $\pm 2.7\%$ and the vehicle velocities of 10, 20, 40, 60 and 80 km/h.

The amount of required fresh air was also determined for congestion and fire conditions according to PIARC recommendations. After considering the three types of situations i.e. congestion, normal traffic and fire conditions, finally the peak amount of Q was chosen to be 242.5 and 150 m^3/sec for northern and southern tubes respectively.

3.2 Various methods of ventilation in urban tunnels

Generally it is assumed that all medium and long traffic tunnels will need to be ventilated which may be performed in various methods. Some short tunnels may have natural ventilation, whilst medium and long tunnels should be ventilated mechanically. Mechanical ventilation may also be longitudinal, semi-transverse and fully transverse methods.

By this, one means the impact of the tunnels upon the neighbourhood and in particular the influence that this had upon the selection and design of the ventilation system. In essence, ventilation systems required space for their installation and the vitiated air must be discharged somehow. Each site will have specific features requiring different considerations although the low capital cost of the longitudinal jet fan system will be a considerable attraction every time.

At Resalat tunnel, when considering transverse and semi-transverse systems, any additional land take necessary to allow for ducts parallel to the carriageway would be difficult due to the proximity of the houses.

The construction of the plant rooms necessary for transverse systems with associated intake and discharge structures would raise similar objections if outside the boundary of the highway. Also they would be visually intrusive if on top as well as being an obstruction to the subsequent release of the roof surface for its future use. The remaining consideration in the selection of type of system was whether the discharge of the vitiated air from the tunnel portal would be of significance.

When simple longitudinal jet fan systems are proposed, a program was used to calculate the number of the fans required. For semi-transverse and other longitudinal methods of ventilation it may be used to verify the proposed design and to calculate the concentration of pollutants produced under design conditions. Much of the information used by the program is semi-empirical and depends on the particular conditions and design codes.

In addition to the foregoing reasons, economical consideration also resulted in choosing longitudinal method of ventilation as the most appropriate method for this tunnel. Therefore, the rest of the paper will dealt with this type of ventilation and the method of choosing the number of jet fans required for providing enough fresh air.

3.3 Longitudinal ventilation system

Normally the longitudinal ventilation system of a one-way road tunnel will be designed to meet with the worst possible traffic situation – most likely standing traffic on all lanes throughout the tunnel – together with a strong headwind.

Although the ventilation system seems to obtain some additional power we may wonder. If this approach is correct, the probability of such an extreme load on the ventilation system being rather low, especially in the case of 2x3 lanes tunnels.

As mentioned the type and condition of traffic may be as follows:

The normal traffic situations, e.g. free traffic flow and restricted traffic flow (v>= 30 km/h) – including rush hour densities, in combination with high headwinds.

Exceptional traffic situation, e.g. stagnating traffic flow (v= 5-10 km/h) for standing traffic, in combination with low headwinds, taking account of the actual duration of this situation.

The combination of headwind and traffic situation asks for a statistical approach to (exceptional) traffic situations, the wind being an important load on short and medium long tunnels and a statistical quantity as well.

When simple longitudinal jet fan systems are proposed, a program was used to calculate the number of the fans required. The first section of the program calculates the quantities of pollutants produced by

the vehicles. It has been assumed that carbon monoxide is the critical constituent from petrol combustion and that smoke is the critical factor in the emission from diesel engines.
As mentioned before, PIARC has suggested some equations for calculating the basic emission of carbon monoxide or diesel smoke for the vehicle under standard conditions is used. These equations are adjusted for the number and speed of vehicles, the gradient and the altitude to obtain the total volume of pollutants produced.
After the volume of pollutants has been obtained the second section of the program calculates the total quantity of air required and hence the velocity of airflow in each section of the tunnel. The pressures acting on the tunnel air are equated to obtain and equilibrium velocity to satisfy the continuity and momentum equations. Pressures induced by the motion of the traffic are calculated for each lane according to the local traffic speed and density as specified in the input data. Pressures due to the friction of the air flow on the tunnel walls, losses at the portals and the effects of the external winds and the impulses from the jet fans are included in the calculation.
The third section of the program calculates the number of jet fans needed for ventilation of the tunnel. PIARC has recommended the following equation for the design of longitudinal ventilation by means of jet fans:

$$n_j \times \Delta P_j = \Delta P_{veh} + \Delta P_{tu} + \Delta P_{MT} \tag{2}$$

where, n_j is the number of required jet fans; ΔP_j is the longitudinal pressure of fans; ΔP_{veh} is the pressure loss due to piston effect; ΔP_{tu} is the pressure loss due to friction of the tunnel walls; and ΔP_{MT} is the pressure loss due to the local wind.
The components of equation (2) may be found with the following equations:

$$\Delta P_j = \rho \times Q_j \times (V_F - V_T) \times \frac{1}{A_T} \times \eta_1 \times \eta_2 \times \eta_3 \tag{3}$$

$$\Delta P_{veh} = \frac{M.L}{V} \times \frac{C_\omega \times A_\omega}{A_T} \times \frac{\rho}{2} \times (V \pm V_T)^2 \tag{4}$$

$$\Delta P_{tu} = (1 + \Psi + \frac{\lambda.L}{D}) \times \frac{\rho}{2} \times u_T^2 \tag{5}$$

$$\Delta P_{MT} = \frac{1}{2} \times \rho \times v_w^2 \tag{6}$$

where parameters and coefficient existing in the equations may be found in (PIARC, 1995).
It should be mentioned that the following factors have also been taken into consideration in selecting the jet fans:

- the tunnel shape
- the vehicle load gauge
- the optimum longitudinal disposition of the jet fans.

It was necessary to assess the likely exposure to any toxic pollutants at the nearest habitation. This will be a function of the two random variables, traffic conditions upon which concentration and duration of pollutants in the vitiated air depend and wind which may divert, direct or dilute the pollutants.
Wind statistics were supplied from the nearest recording site of the Meteorological Office, the airport some 15 km away, a measurement made 10m above ground level and on an open airfield site. An upper limit of wind velocity of 2 m/s was chosen.
Calculation results showed that at slow traffic speeds the number of jet fans required is high. The highest figure being 29 fans with an opposing wind velocity and gradient and traffic speed of 5 to 10 km/h for the northern tube (East to West) and 18 fans with favourable wind velocity and gradient and the same traffic speed for the southern tube (West to East). The distance between the jet fans for the northern tube is 80 meters for middle ones and 60 meters for the jet fans near the portals (figure 1). While this distances are 100 meters and 70 meters for the middle and near portals jet fans of the Southern tube, respectively (figure 2).

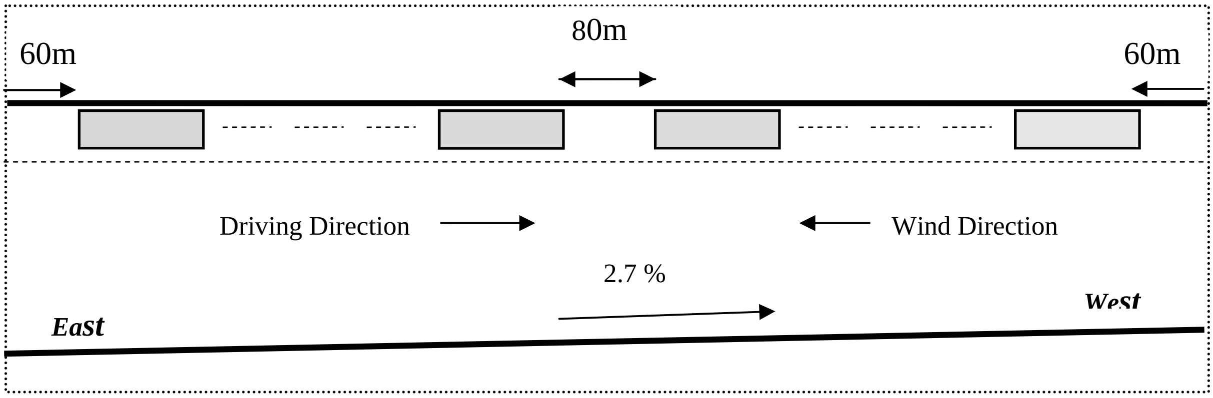

Fig. 1. Installation set up of jet fans in Northern tube (dimensions not in scale)

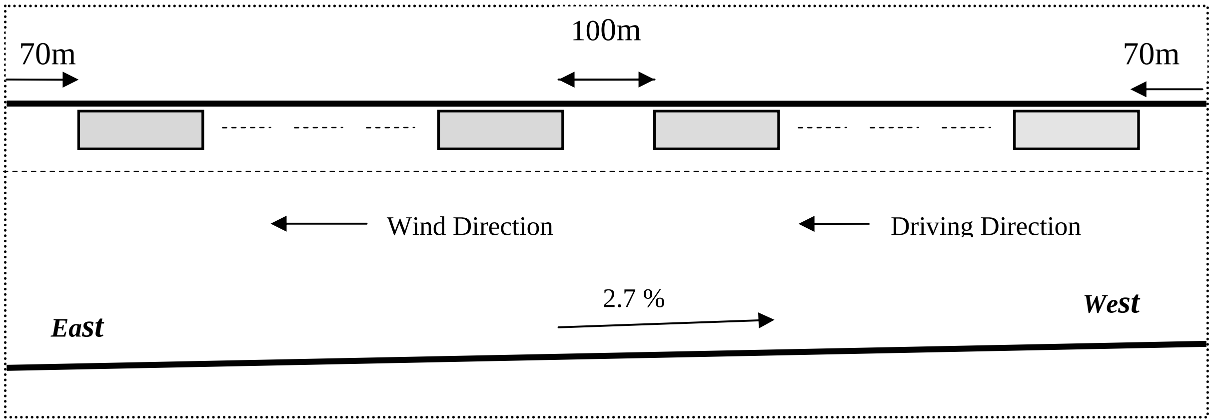

Fig. 2. Installation set up of jet fans in Southern tube (dimensions not in scale).

In order to satisfy these requirements the jet fans will be mounted in rows of 2, 3 and four, based on the matter that the row located in straight or curved part of the tunnel.
Now this design marginally exceeds the design parameter for diesel smoke as well. However examination of the curve of particulate pollution against visibility distance indicates that only a slight drop in visibility will occur.
At these low speeds this order of fall off in visibility will not adversely affect safety. Furthermore as previously stated the worst-case situation is unlikely to occur in practice.
Forty seven jet fans nominal internal and external diameters of 700mm and 900mm respectively will therefore be installed in both tubes to ensure that acceptable pollutant levels are maintained for all traffic conditions. The rated power of each fan will be in the order of 22kw.

4. CONCLUDING REMARKS

As the main products of the combustion of petrol are carbon monoxide and smoke, the control parameters for the design of ventilation will be these two materials based on which the calculation of required fresh air would be made. The design of ventilation of an urban tunnel must take into consideration air quality and environmental pollution issues in the vicinity of portals and exhaust areas. Ventilation capacity should be adequate for this, even a long time after opening the tunnel.
As mentioned in the previous sections, both tunnels would have been equipped with longitudinal ventilation. Having considered the other advantages mentioned in the main text, a cost comparison were also made between the longitudinal jet fan ventilation schemes proposed for Resalat tunnel and the other alternative methods of ventilation considered.

From the comparison it was concluded that the overall cost of providing a fully transverse ventilation system is approximately sixteen times greater than the proposed longitudinal scheme.
The main areas, which contribute towards this large increase in cost, are as follows:

- the additional capital and installation cost of the large centrifugal supply and extract fans and their associated control panels.
- the additional electrical power requirements and hence increased transformer and switchgear costs.
- the excavation and construction of large supply and extract ducts running the full length of each side of both the northern and southern tube tunnels.
- the excavation and construction of the underground supply fan ventilation stations.
- the construction of above ground extracts fan ventilation stations.

The overall cost of a semi-transverse ventilation system is approximately ten times greater than the proposed longitudinal scheme. The cost elements of a semi-transverse system are similar to those for the fully transverse system with the exception that the extract fans will be smaller, only supply ducts will be required and the extract fan buildings will be marginally smaller.
In case of longitudinal ventilation it is also important to have a certain amount of overcapacity so that even if some of the fans are incapacitated by a fire, and one or two are down for overhaul, the necessary capacity is still upheld.
Forty seven jet fans were designed to be installed in both tubes to ensure that acceptable pollutant levels are maintained for all traffic conditions. Twenty nine jet fans for the northern and eighteen for the southern tube were proposed based on the direction of driving, direction of headwind and the longitudinal gradient of the tunnels.
Since the tunnels will be unattended the automatic operation of the ventilation will depend upon the instruments. Therefore a high degree of reliability will be required. Stability over a long period in the tunnel environment is essential and frequent cleaning or recalibration is not wanted.
There will be one instrument of each type at each measurement location. These will be near the tunnel exit and at the centre. The output will be processed in a mini computer, the same one that will handle the traffic data and monitor the other equipment.

REFERENCES

PIARC, 1995. Ventilation systems: Vehicle emission, air demand, environment, longitudinal ventilation. PIARC Committee on Road Tunnels.