#4350

Building Serv. Eng. Res. Technol. 9(4) 141–153 (1988) Printed in Great Britain

Summary The paper addresses the ventilation system design and analysis for the Limehouse Link Tunnel, a 1.6 km dual carriageway vehicular tunnel with an incoming slip road on the south carriageway and an outgoing slip road on the north carriageway. The road cross-section varies to accommodate speed change lanes. The tunnel complex is represented mathematically by a series of flow paths with nodes. The paper describes the design features, the major system components and the technique used in analysing the system.

Longitudinal ventilation analysis for the Limehouse Link Tunnel with slip roads

K M LEUNG† BSc CEng MIMechE MIEE MCIBSE MHKIE MIMarE and D W WOOD‡ BA CEng FIMechE FCIBSE MInstE MInstR MASHRAE

† Electrical & Mechanical Services Department, Hong Kong Government, Hong Kong
‡ Sir Alexander Gibb & Partners, Earley House, London Road, Earley, Reading RG6 1BL, UK

Received 18 April, in final form 15 June 1988§

List of symbols

A	Cross-sectional area (m^2)
A_J	Cross-sectional area of jet fan (m^2)
A_T	Cross sectional area of tunnel (m^2)
A_S	Average frontal area of a traffic sign (m^2)
A_V	Average frontal area of a vehicle; car or lorry (m^2)
C_D	Drag coefficient
C_{DV}	Drag coefficient of a vehicle; car or lorry
C_{DS}	Drag coefficient of a traffic sign
CO_{lim}	Maximum permissible CO concentration (ppm)
D_h	Hydraulic diameter of tunnel (m)
D_{VL}	Number of passenger vehicles per km per lane (veh km^{-1} lane^{-1})
D_{LW}	Number of commercial vehicles per km per lane (veh km^{-1} lane^{-1})
e	Internal energy per unit mass (J kg^{-1})
f_H	Altitude factor
f_I	Upgrade factor
f_{IV}	Upgrade/speed factor
f_V	Speed factor
g	Gravitational acceleration (m s^{-2})
K_{lim}	Admissible smoke concentration (m^{-1})
K_S	Traffic sign loss factor
K_W	Wind loss factor
L	Length of tunnel (m)
m	Mean commercial vehicle weight (tonne)
n	Number of jet fans between two nodes
N^-	Number of vehicles moving in the same direction as V_T
N^+	Number of vehicles moving in the opposite direction to V_T
N_C	Number of signs per km (km^{-1})
p	Static pressure (Pa)
P	Total pressure (Pa)
Q	Air flow volume (m^3 s^{-1})
Q_{CO}	Required fresh air quantity per second and per lane for reduction of CO concentration (m^3 s^{-1} lane^{-1})
Q_K	Required fresh air quantity per second per lane for smoke dilution (m^3 s^{-1} lane^{-1})
q^0_{CO}	Basic value of CO emission (m^3 h^{-1} veh^{-1})
q^0_T	Basic value of smoke emission (m^2 h^{-1} tonne^{-1})
Re	Reynolds number
V_J	Exit air velocity of jet fan (m s^{-1})
V_T	Mean tunnel air velocity (m s^{-1})
V_V	Mean velocity of a vehicle (m s^{-1})
V_W	Velocity of natural wind (m s^{-1})
u	Mean velocity of fluid (m s^{-1})
z	Elevation above a horizontal datum plane (m)
$\frac{\delta Q}{\delta M}$	Net heat transferred to the fluid per unit mass (J kg^{-1})
$\frac{\delta W}{\delta M}$	Net work done to the fluid per unit mass (J kg^{-1})
ρ	Air density (1.2 kg m^{-3})
λ	Tunnel skin friction loss factor
ζ_{EN}	Entry loss factor
ζ_{EX}	Exit loss factor
ΔP_F	Pressure loss due to wall friction, entry/exit, traffic signs and signals between two nodes (Pa)
ΔP_J	Pressure rise induced by the jet fans between two nodes (Pa)
ΔP_T	Difference in total pressure between two nodes, $P_2 - P_1$ (Pa)
ΔP_V	Pressure loss due to vehicular drag/piston effect
ΔP_W	Wind induced pressure difference between portals (Pa)
η	Installed fan efficiency
μ	Air viscosity (18 × 10^{-6} Pa s)

† Seconded to Sir Alexander Gibb & Partners.

§ This is a revised version of a paper presented at the BHRA Seminar *Tunnel Air Management*, Cranfield, 1 March 1988.

1 Introduction

Limehouse Link is being designed as a 'cut and cover' tunnel to traverse an urban area which includes existing roads, waterways and numerous underground services in London Docklands. Following a feasibility study by Mott, Hay & Anderson & Partners, the London Docklands Development Corporation appointed Sir Alexander Gibb & Partners in January 1987 as Consultants for design and supervision of construction.

Construction of the road tunnel, including the main civil works, services diversions and tunnel services installation, is programmed to be completed over four years. Detail design of the project is well advanced and construction is expected to commence early in 1989. It is anticipated that installation of mechanical and electrical equipment will begin in 1991.

The tunnel structure consists generally of a twin-cell reinforced concrete box providing two traffic lanes per cell for eastbound and westbound traffic respectively. The overall length of the tunnel is approximately 1600 m and carriageway widths are generally 7.3 m.

In the middle third of the tunnel, overall road width is increased to accommodate speed change lanes. Maximum road width is 17.6 m which includes slip road nosings. This is followed by a four-cell structure with the slip roads contained in separate cells. Paved verges are provided for vehicle clearance and to accommodate tunnel services (1.4 m wide on the nearside and 1.15 m wide on the offside of each carriageway). The vehicle gauge height allowance is 5.1 m with 0.25 m clearance above and a further 1.3 m for tunnel services.

The road alignment is heavily constrained by existing features to be retained and by the required terminal connections to the existing or planned road network. The two slip roads, one for exiting eastbound traffic and the other for incoming westbound traffic, are connected to a surface level junction on Westferry Road. The east end of the tunnel links to the future South Poplar Bypass and the west end links to the Highway. The tunnel alignment, typical cross-section and grade profile are shown in Figures 1, 2 and 3 respectively.

2 System description

2.1 General

After careful consideration of alternative ventilation systems for the tunnel, a longitudinal ventilation system was selected. It is the safest ventilation system for unidirectional traffic in the event of a fire and the length of the tunnel is within the limit for longitudinal ventilation. Positive control of the spread of smoke and heat is provided protecting the portion of the tunnel which will probably be occupied by trapped motorists. Vehicles travelling away from the fire can be driven out of the tunnel. Vehicles upstream of the fire will be protected from smoke and heat by the induced air flow. The longitudinal ventilation system will also provide the Fire Brigade with smoke-free access for fire fighting.

Longitudinal ventilation offers substantial savings in construction cost. If a transverse or semi-transverse system had been selected, then large supply and/or extract ducts running the full length of the tunnel would have been required, necessitating a considerable increase in structural dimensions.

2.2 Preliminary layout

The original studies included a layout of the tunnel with 950 m dual carriageway reducing to a single carriageway east of the underground junction. The single carriageway tunnel was originally intended to be ventilated with reversible jet fans normally operating in the direction of the main traffic flow. Large axial flow exhaust fans were to be provided close to the east and west exit portals of the dual carriageway to alleviate environmental pollution to residential developments adjacent to the portals, with the vitiated air discharged at high level. The ventilation plant at the east end of the dual carriageway was also intended to include a mid-tunnel ventilation plant for the single carriageway section. This plant was intended to supply air at the west end of the single carriageway section when the main traffic flow was travelling eastwards and exhaust air (reversible axial flow fans) when the main traffic flow was travelling westwards. Figure 4 shows the layout of the proposed ventilation system.

The prediction of the air flow at the point of bifurcation where the dual carriageway, the slip roads and the single

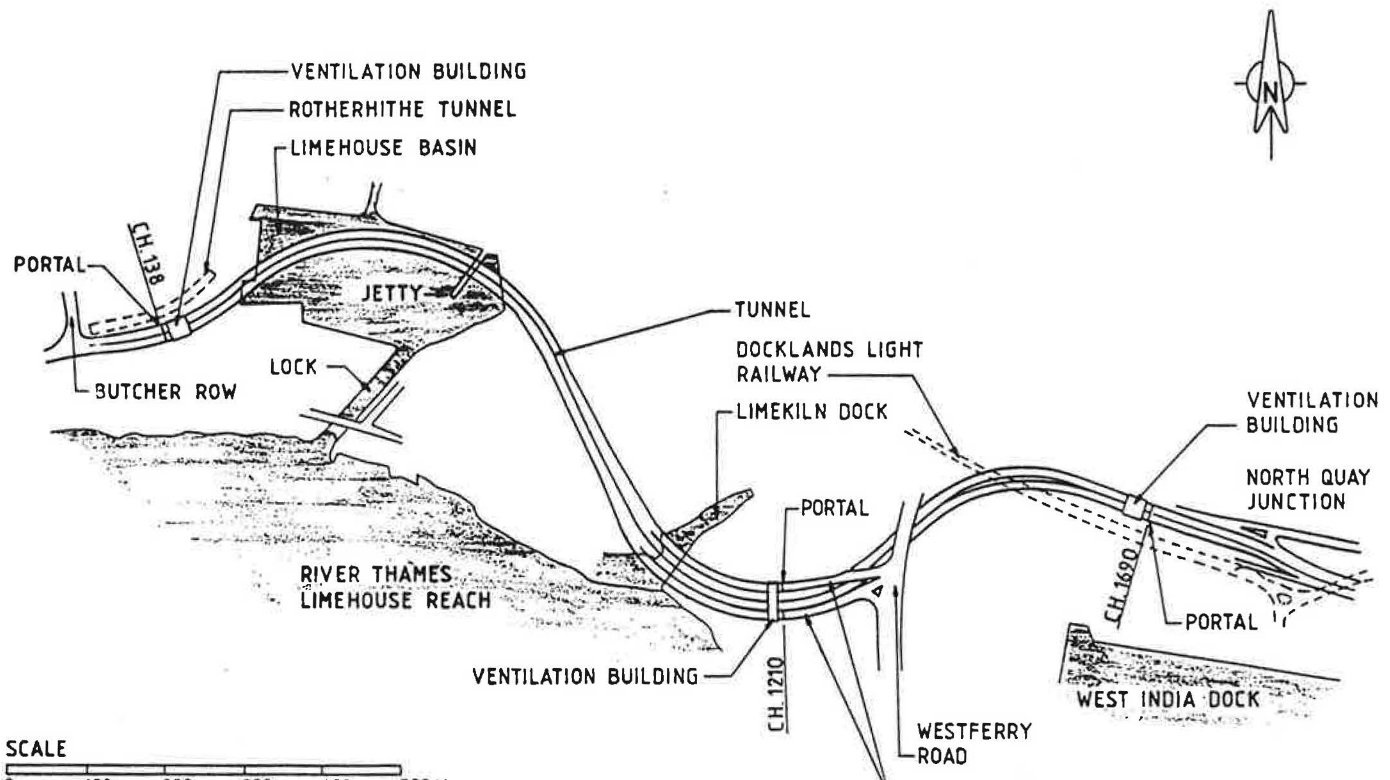

Figure 1 Location map

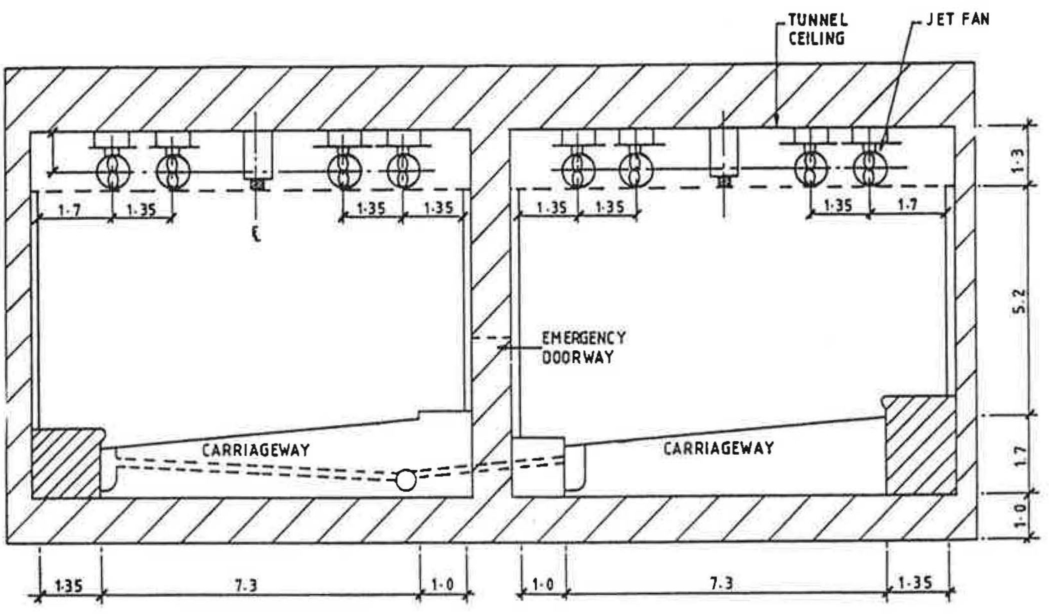

Figure 2 Tunnel cross-section

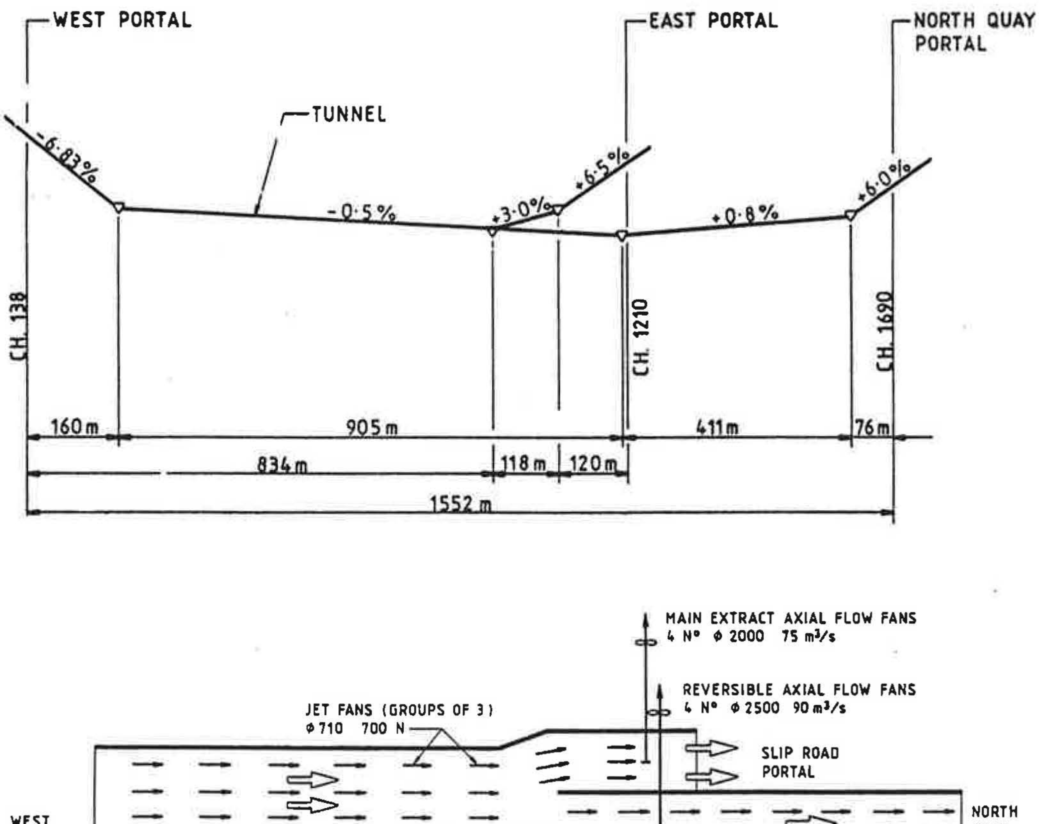

Figure 3 Grade profile

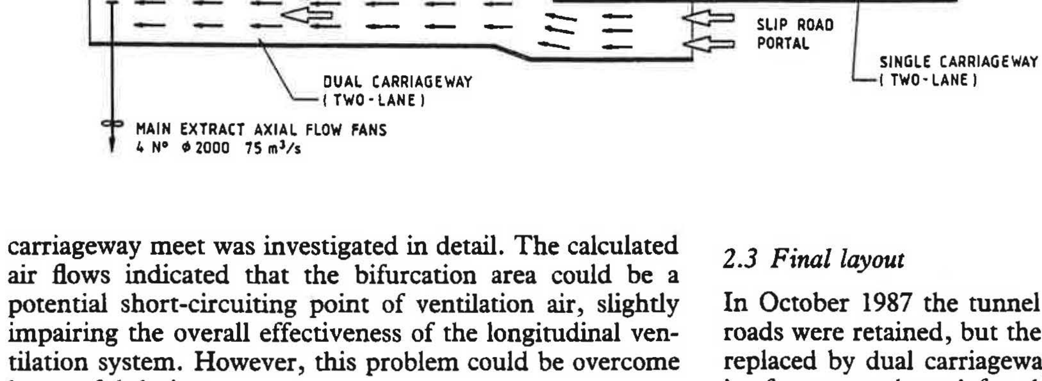

Figure 4 Initial ventilation scheme

carriageway meet was investigated in detail. The calculated air flows indicated that the bifurcation area could be a potential short-circuiting point of ventilation air, slightly impairing the overall effectiveness of the longitudinal ventilation system. However, this problem could be overcome by careful design.

2.3 Final layout

In October 1987 the tunnel layout was changed. The slip roads were retained, but the single carriageway section was replaced by dual carriageway. Longitudinal ventilation by jet fans was adopted for the revised layout. Jet fans are intended to be of the single direction type as this improves the fan operating efficiency and the thrust per motor input power ratio. Reversible fans are not considered to be necessary as, even with two-way traffic, single direction fans would handle the required air flows adequately. Because of structural limitations, 800 mm internal diameter jet fans are provisionally selected for the design. Extract fans will be installed over each exit portal as for the original scheme. The capital cost of the tunnel ventilation plant is expected to be around £1.7 M.

2.4 Ventilation fan sizes

Following preliminary investigations, the jet fan data given in Table 1 were chosen for the final design.

The noise criterion for each group of four jet fans will be NR90 at 1 m above the road surface.

Three main extract ventilation plants, each including four vertically mounted axial flow fans, will be located at the exit portals to remove the pollutants and disperse them to high level. A typical ventilation plant room layout is shown in Figure 5. The silencers will be designed to attenuate the noise levels to NR90 at 1 m above the road surface inside the tunnel when no traffic is running and to NR45 inside a building with open windows at a distance of 20 m from the top of the exhaust air shafts. These design noise criteria may have to be revised when the exact locations and heights of the adjacent buildings are known. The principal design data for the main extract fans are given in Table 2.

Figure 6 is a diagrammatic layout of the final ventilation system.

Table 1 Jet fan data

Volume flow rate ($m^3 s^{-1}$)	15.4
Jet exit velocity ($m s^{-1}$)	36.6
Impeller diameter (mm)	800
Measured thrust (N)	610
Motor rating (kW)	22
Rotational speed (rpm)	2950

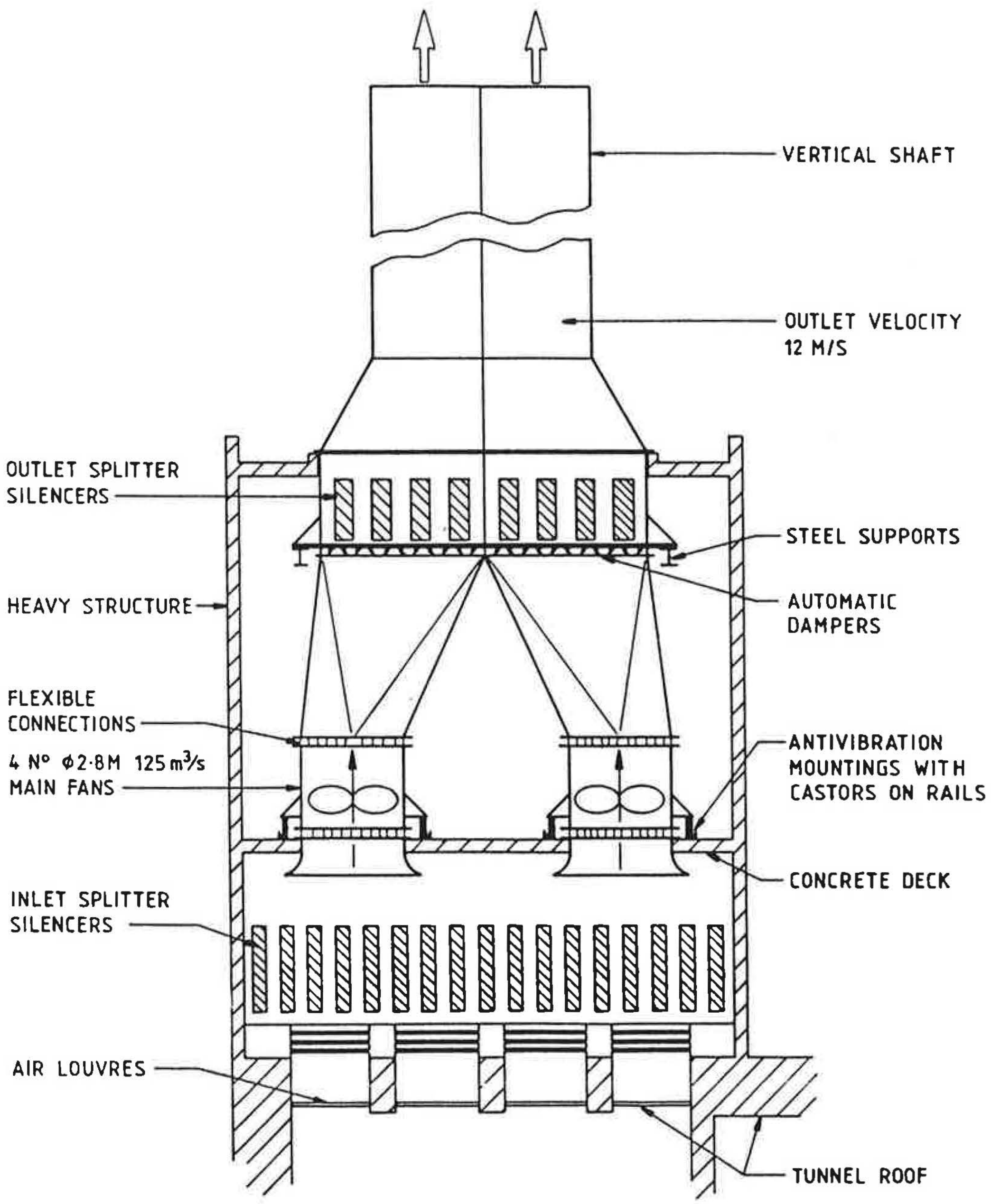

Figure 5 Typical layout for main axial fan ventilation plant room

Table 2 Principal design data for main extract fans

Parameter	Portal		
	FW	CE	BE
Volume flow rate ($m^3 s^{-1}$)	125	110	25
Impeller diameter (mm)	2800	2800	1500
Fan total pressure (Pa)	550	510	390
Fan absorbed power (kW)	90	71	13
Rotational speed (rpm)	590	590	975

Table 3 Definition of traffic conditions

Traffic condition	Vehicle speed	Status
1	Normal (50 km h^{-1})	Normal one-way
2	Congested (10 km h^{-1})	Normal one-way
3	Normal (50 km h^{-1})	Abnormal two-way
4	Congested (10 km h^{-1})	Abnormal two-way

3 Fresh air requirements

Suitable design parameters were adopted for the calculation of fresh air requirements, i.e. limits for carbon monoxide, diesel smoke, traffic flows and recirculation.

3.1 Carbon monoxide and diesel smoke

The fresh air requirements were calculated according to Reference 2. Following discussions with the Department of Transport, more stringent vehicle emission parameters were adopted due to the fact that there are no annual control checks on in-service vehicle emissions in the UK. The CO threshold limits are 250 ppm for congested traffic (15 km h^{-1} or below) and 150 ppm for free-flowing traffic (above 15 km h^{-1}).

Average CO emission values are 0.74 $m^3 h^{-1} veh^{-1}$ for all traffic speeds above 10 km h^{-1} and 0.40 $m^3 h^{-1} veh^{-1}$ for stationary traffic (using 140 vehicles per km).

The permissible visibility limit is $K_{lim} = 0.0075\ m^{-1}$. The basic diesel smoke emission values are 48 $m^2 h^{-1}$ $tonne^{-1}$ at 10 km h^{-1}, 27 $m^2 h^{-1}$ $tonne^{-1}$ at 20 km h^{-1}, and 18 $m^2 h^{-1}$ $tonne^{-1}$ at 60 km h^{-1}. Speed limits are 50 km h^{-1} for unidirectional flow and 50 km h^{-1} for bidirectional flow. The principal geometric dimensions of the tunnel are indicated in Figures 2 and 3. The mean altitude of the tunnel is 6 m below sea level.

3.2 Traffic data

The current and future traffic flow demands were assessed by LDDC traffic consultants using network modelling. The traffic data supplied included model assignment flows for the morning peak hour and the evening peak hour.

In order to provide a tunnel ventilation system capable of coping with the maximum traffic handling capacity, maximum working levels of 1 800 vehicles per hour per lane for free-flowing traffic at the design speed limit of 50 km h^{-1} and 1 000 vehicles per hour per lane for congested traffic at a vehicle speed of 10 km h^{-1} were adopted.

Four different traffic situations, each with morning (am) and evening (pm) peak flows, were considered for the calculation of the fresh air flows and the ventilation design (Table 3).

On the basis of the traffic analyses and the maximum working levels, the traffic flow patterns for each traffic situation are outlined in Figure 7.

With regard to the traffic composition, it is predicted that 85% of the traffic will be petrol-engined vehicles and the remaining 15% will be diesel-engined vehicles. The average weight of a commercial lorry is assumed to be 20 tonnes.

3.3 Recirculation

To minimise the recirculation of pollutants, the dividing central wall of the dual carriageway will be extended some 10 m outside the east and west end portals respectively. In addition, the exhaust fans at the exit portals will remove the vitiated air to a high level preventing recirculation. In these circumstances recirculation is assumed to be negligible.

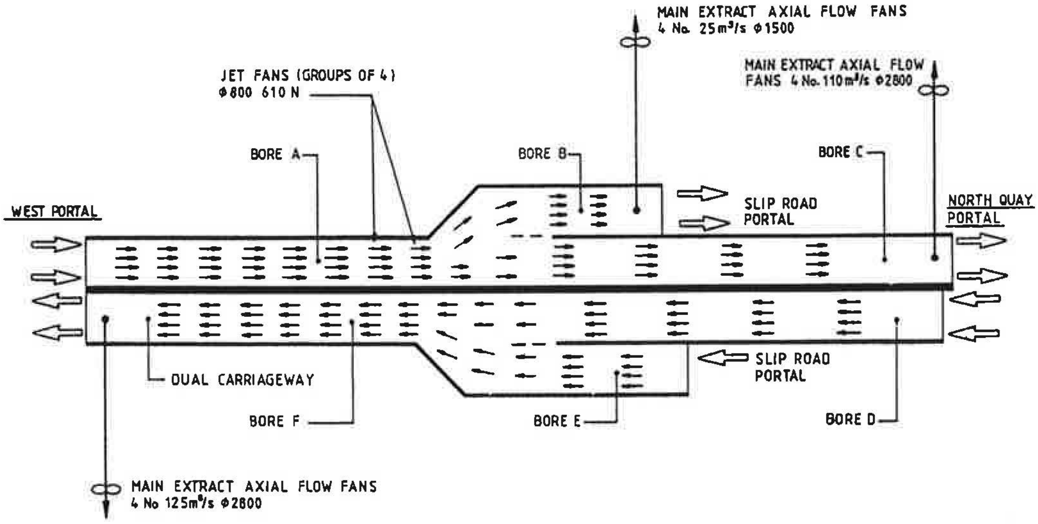

Figure 6 Final ventilation scheme

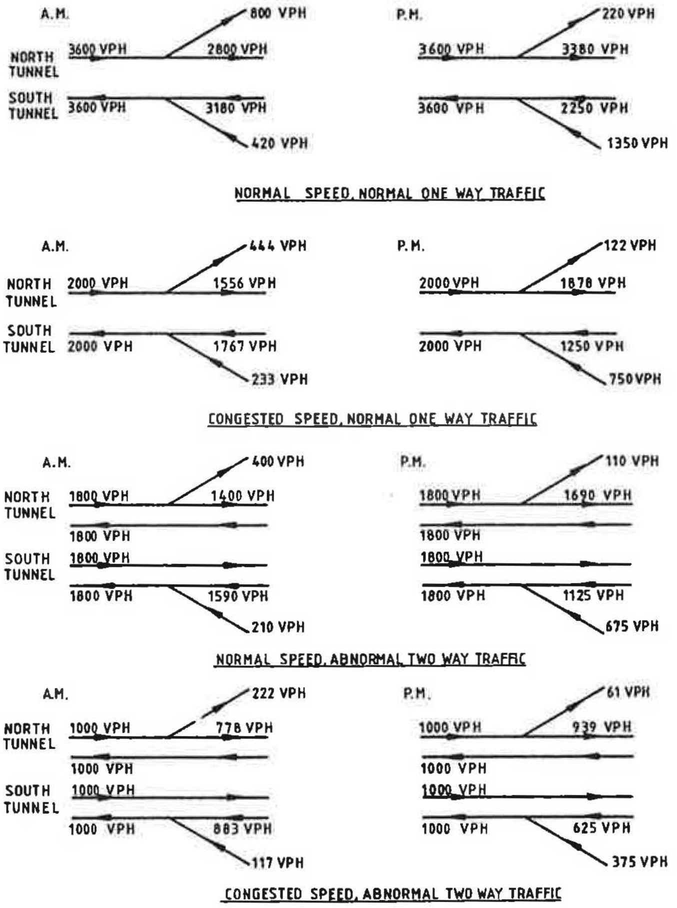

Figure 7 Peak traffic flow patterns

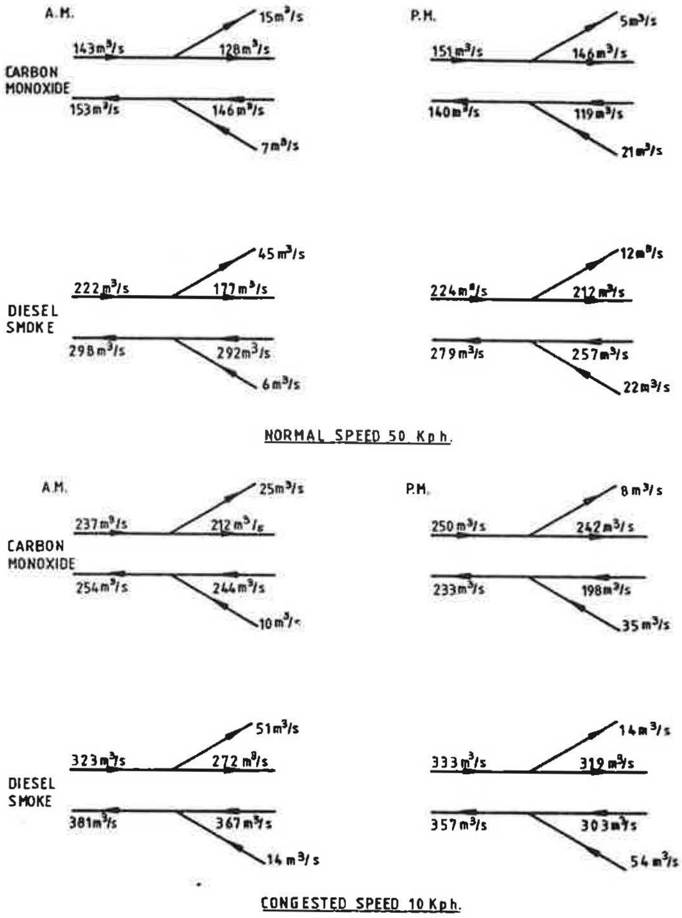

Figure 8 Maximum fresh air requirements for normal one-way traffic

3.4 Fresh air flows

The fresh air requirements for the dilution of carbon monoxide and diesel smoke were computed[2] as follows:

Carbon monoxide:

$$Q_{CO} = 10^{-3}\,\frac{q^0_{CO} f_V f_I f_H}{3600}\,D_{VL}\,\frac{10^6}{CO_{lim}}\,L$$

Diesel smoke:

$$Q_K = 10^{-3}\,\frac{q^0_T m f_{IV} f_H}{3600}\,D_{LW}\,\frac{1}{K_{lim}}\,L$$

In a tunnel with longitudinal ventilation, the pollution levels increase from ambient levels at the entry portal to maximum levels at the exit portal. With the slip road arrangement, the same principle still applies but the air flow through the bifurcation to the slip road has to be apportioned correctly to give the required dilution.

Figures 8 and 9 show the maximum fresh air flow requirements for the reduction of carbon monoxide and diesel smoke concentrations to the permissible limits respectively for the morning and evening peak traffic flows for the four different traffic conditions. It should be noted that the air flow rate required to meet the permissible visibility limit is generally higher than the air flow rate needed to meet the CO threshold limits. This is primarily due to the relatively high diesel smoke emission values given in section 3.1. The fresh air flows for the congested traffic are also higher than those for the free-flowing traffic. The maximum fresh air quantity entering the north tunnel is 364 $m^3\,s^{-1}$ during evening peak congested two-way traffic and that leaving the south

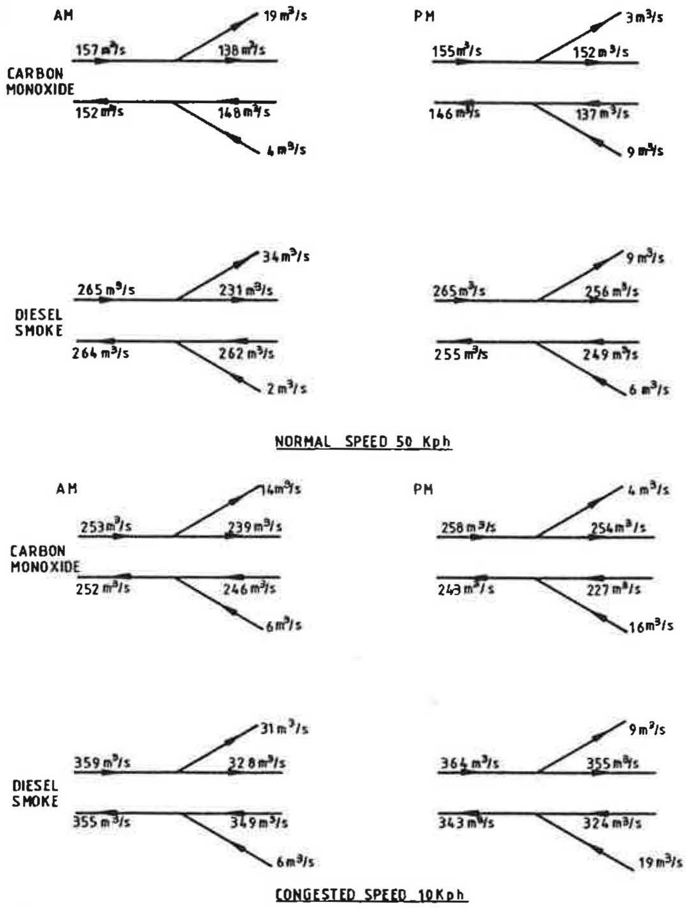

Figure 9 Maximum fresh air requirements for abnormal two-way traffic

tunnel is 381 $m^3 s^{-1}$ during morning peak congested one-way traffic.

Since these fresh air quantities are represented in terms of flow patterns which might not correspond exactly to the actual flows developed by the ventilation plant, these data are used for comparison with the results from the ventilation analysis to ensure compliance with the specified standards and as an environmental pollution assessment.

4 Ventilation analysis

The fundamental design criteria adopted for the design of the tunnel ventilation system are as follows:

(*a*) Provision of jet fans to ensure a fresh air intake sufficiently high to dilute the carbon monoxide and diesel smoke emissions from the vehicles to permissible limits.

(*b*) Provision of jet fans to develop a longitudinal tunnel air velocity of approximately 4 m s^{-1} along the carriageways and the slip roads to cope with smoke and heat generated by a substantial fire (50 MW) from a burning petrol tanker[5,12].

(*c*) Provision of exhaust fans to control the spread of fire smoke in fire emergency condition and to extract the pollutants from the exit portals through the vertical shaft and discharge them at high level for pollution control.

4.1 Design methodology

In view of the complexity of the tunnel configuration with an incoming slip road on the south carriageway and an outgoing slip road on the north carriageway, the layout was represented mathematically by a network of flow paths with designated nodes at strategic locations such as the entry and exit portals, the main change points of the tunnel cross-sectional area, the bifurcation and the exit extract point.

The steady-flow energy equation using one-dimensional flow theory with an incompressible fluid at constant environmental temperature was applied for each flow path. This gives a valuable insight into the behaviour of the mean tunnel air flow velocity.

$$\frac{\delta Q}{\delta M} = (e_2 - e_1) + \tfrac{1}{2}(u_2^2 - u_1^2) + g(z_2 - z_1) - \frac{\delta W}{\delta M} + \left(\frac{p_2}{\rho_2} - \frac{p_1}{\rho_1}\right) \quad (1)$$

For a constant-density real fluid having viscosity at constant temperature, the energy required to overcome the viscous friction is transformed into thermal energy which corresponds to a loss of useful energy, i.e. the frictional loss. The frictional loss is a function of the entry/exit loss and losses due to signs and tunnel wall resistances. Since there is assumed to be no external heat transfer, the work done to or by the fluid is due to the wind effect, the vehicular piston effect and the thrust of the jet fans. Equation 1 reduces to:

$$\Delta P_J = \Delta P_F + \Delta P_V + \Delta P_T \quad (2)$$

where

$$\Delta P_J = \frac{n\rho A_J V_J}{A_T}(V_J - V_T)\eta \quad (3)$$

$$\Delta P_F = \left(\rho_{EN} + \rho_{EX} + K_S + \frac{L}{D_h}\right)\frac{\rho V_T^2}{2} \quad (4)$$

$$\Delta P_V = \frac{\rho C_{DV} A_V}{2A_T}[N^-(V_V + V_T)^2 - N^+|V_V - N_T|(V_V - V_T)] \quad (5)$$

and

$$\Delta P_T = P_2 - P_1 \quad (6)$$

It has been suggested that η should lie between 0.5 and 0.9[8] and a value of 0.8 was used as a result of the specific location and the mutual interference of the groups of four jet fans with respect to the tunnel cross-secton (Figure 2). For the tunnel portal entry and exit loss factors, values of 0.6 and 1.0[4] were adopted respectively and the sign and signal loss factor was calculated as follows:

$$K_S = \frac{C_{DS} A_S N_S L}{A_T}$$

where $C_{DS} = 1.0$, $A_S = 0.06$ m^2 and $N_S = 100$ per km.

For the tunnel wall skin friction, an equivalent roughness of the airway wall of 16 mm was selected with a Reynolds number of 2.7×10^6 (turbulent flow where $R_e = \rho u Dh/\mu$) which gave a tunnel friction factor λ of 0.024 from the Moody diagram[7].

With regard to the vehicle piston effect, the mean resistance areas obtained were[6]:

Car:

$$C_{DV}A_V = 0.9 \text{ m}^2$$

Lorry:

$$C_{DV}A_V = 6.8 \text{ m}^2$$

The opposing wind induced pressure difference along a road tunnel is defined as:

$$\Delta P_W = K_W \frac{\rho V_W^2}{2} \quad (7)$$

Mean values of natural wind velocity of 5 m s^{-1} and 3.5 m s^{-1} were selected respectively for pollutant dilution and fire scenario calculations based on statistical meteorological data. The value of K_W was suggested to lie between 0 and 2[10] and a value of 1.0 was assumed.

To resolve the problem of bifurcation at the underground junction the equation of continuity was applied at each node:

$$\int \rho u \, dA = \text{constant} \quad (8)$$

A computerised mathematical model was developed to analyse the tunnel air flows. Figure 10 indicates the designed flow network.

4.2 Dilution of pollutants

Ventilation analysis was carried out for the four different traffic conditions and the tunnel air flow patterns were recorded in Tables 4 to 11. These flow figures were used for comparison with the fresh air requirements (Figures 8 and 9) to ensure the best selection of jet fans. It is considered that in the event of closure of one bore, the flow of traffic could be diverted to the surface road network. As alternative routes exist, the results of the analysis of the two-way traffic were only used as a reference.

Based on this analysis, it was decided that 16 and 32 jet fans in each main tunnel would be required to handle the vehicular emissions for the normal (50 km h^{-1} with opposing

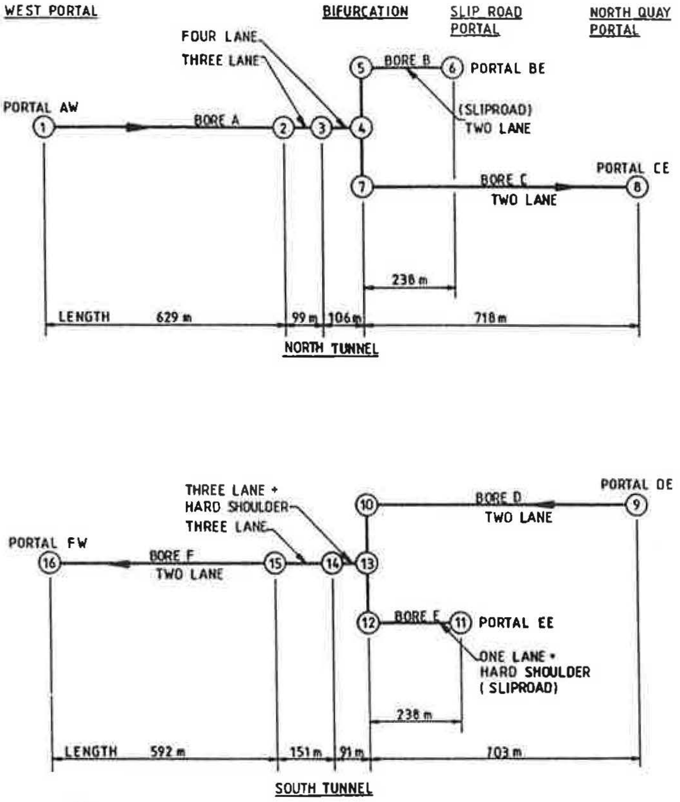

Figure 10 Flow paths and nodes

wind 5 m s^{-1}) and congested (10 km h^{-1} with opposing wind 5 m s^{-1}) one-way traffic. The normal (50 km h^{-1} with opposing wind 5 m s^{-1}) and congested (10 km h^{-1} with opposing wind 5 m s^{-1}) two-way traffic would require 44 and 56 jet fans respectively.

Prediction of external wind speed is based on available meteorological data. Adverse wind can have a considerable effect on the efficiency of a longitudinal ventilation system. For Limehouse Link, sufficient ventilation fans will be provided to generate an adequate air supply to deal with an adverse wind speed of 5 m s^{-1}.

Environmental pollution local to the tunnel portals has been carefully evaluated. The estimated annual average CO level will be around 25–30 ppm at the main exit portals without the main extract fans. It is anticipated that the CO level through the vertical exhaust shafts (slightly higher than the surrounding buildings), with a discharge velocity of 12 m s^{-1} and a wind velocity of 1.5 m s^{-1}, will drop from 25–30 ppm (annual average) at the shaft exit to 7 ppm (annual average) at 20 m from the exhaust shaft[13].

In this respect, the expected CO concentration at the exit portal and exhaust shaft areas will be well below the threshold long-term exposure limit (8 h TWA value) of 50 ppm[14]. A detailed study of the environmental impact at the portal areas is still in progress.

4.3 Fire scenarios

In the event of a fire in the tunnel, the ventilation system will control the direction of smoke and heat movement in order to facilitate both the safe evacuation of personnel and fire fighting access. Depending on where the emergency occurs, this will be accomplished by initiating selectively the appropriate fire emergency push button to override the normal automatic control and instantly activate the programmed pattern of ventilation fan operation. The emergency mimic display panel will be located at a central police control room to facilitate emergency operation.

Six different fire scenarios, each related to a 50 MW fire output, were examined. It is interesting to note that the calculation of critical velocities using the Froude number

Table 4 Ventilation analysis for traffic condition 1 (vehicle speed 50 km h^{-1}; one-way traffic; traffic volume 100%; opposing wind 5 m s^{-1})

Flow path	am					pm				
	n	Q (m^3 s^{-1})	V_T (m s^{-1})	CO (ppm)	K (10^{-3} m^{-1})	n	Q (m^3 s^{-1})	V_T (m s^{-1})	CO (ppm)	K (10^{-3} m^{-1})
1–2	8	446	7.1	18	0.9	8	452	6.9	19	1.0
2–3	0	466	5.2	20	1.1	0	452	5.0	21	1.2
3–4	0	466	3.4	24	1.3	0	452	3.3	26	1.4
5–6	0	52	0.8	43	5.3	0	12	0.2	48	6.2
7–8	8	414	6.3	16	3.3	8	440	6.7	49	3.6
9–10	8	410	6.2	22	1.3	8	376	5.7	17	1.0
11–12	0	82	1.2	4	0.1	0	127	1.9	9	2.5
13–14	0	492	3.8	22	1.5	0	503	3.9	17	1.2
14–15	0	492	5.4	26	2.0	0	503	5.5	21	1.7
15–16	8	492	7.5	47	4.5	8	503	7.6	41	4.2
Extract (m^3 s^{-1})										
Node 6				25					25	
Node 8				220					220	
Node 16				250					250	

Notes to Tables 4–11

† Inadequate fresh air supply.

The pollutant levels indicate concentrations at the end of the flow path.

See Table 3 for Traffic Conditions 1, 2, 3, and 4.

Table 5 Ventilation analysis for traffic condition 1 (vehicle speed 50 km h^{-1}; one-way traffic; traffic volume 100%; opposing wind 5 m s^{-1})

Flow path	am					pm				
	n	Q (m^3 s^{-1})	V_T (m s^{-1})	CO (ppm)	K (10^{-3} m^{-1})	n	Q (m^3 s^{-1})	V_T (m s^{-1})	CO (ppm)	K (10^{-3} m^{-1})
1–2	12	499	7.6	18	0.9	12	488	7.4	18	0.9
2–3	0	499	5.5	20	1.1	0	488	5.4	20	1.1
3–4	0	499	3.6	23	1.3	0	488	3.5	23	1.3
5–6	0	81	1.3	36	3.8	0	46	0.7	30	2.5
7–8	8	418	6.3	44	3.2	8	442	6.7	48	3.5
9–10	8	413	6.3	21	1.3	8	381	5.8	17	1.0
11–12	0	113	1.7	3	0.9	0	153	2.3	8	0.2
13–14	0	526	4.0	20	1.4	0	535	4.1	16	1.1
14–15	0	526	5.8	24	1.9	0	535	5.9	20	1.6
15–16	12	526	8.0	43	4.2	12	535	8.1	39	3.9
Extract (m^3 s^{-1})										
Node 6			50						50	
Node 8			220						220	
Node 16			250						250	

Table 6 Ventilation analysis for traffic condition 2 (vehicle speed 10 km h^{-1}; one-way traffic; traffic volume 100%; opposing wind 5 m s^{-1})

Flow path	am					pm				
	n	Q (m^3 s^{-1})	V_T (m s^{-1})	CO (ppm)	K (10^{-3} m^{-1})	n	Q (m^3 s^{-1})	V_T (m s^{-1})	CO (ppm)	K (10^{-3} m^{-1})
1–2	12	374	5.7	63	2.1	12	371	5.6	65	2.2
2–3	4	374	4.2	75	2.6	4	371	4.1	75	2.6
3–4	0	374	2.7	87	3.1	0	371	2.7	87	3.1
5–6	0	−31	−0.5	87	6.4	0	−29	−0.5	25	1.9
7–8	16	405	6.1	146	6.0	16	400	6.1	156	6.2
9–10	16	380	5.8	65	2.3	16	387	5.9	46	1.6
11–12	0	26	0.4	36	1.3	0	22	0.3	140	5.0
13–14	0	406	3.1	73	2.4	0	409	3.1	62	1.8
14–15	4	406	4.5	90	3.0	4	409	4.5	77	2.5
15–16	12	406	6.2	156	7.0	12	409	6.2	142	6.5
Extract (m^3 s^{-1})										
Node 6			50						50	
Node 8			440						440	
Node 16			500						500	

Table 7 Ventilation analysis for traffic condition 2 (vehicle speed 10 km h^{-1}; one-way traffic; traffic volume 100%; opposing wind 5 m s^{-1})

Flow path	am					pm				
	n	Q (m^3 s^{-1})	V_T (m s^{-1})	CO (ppm)	K (10^{-3} m^{-1})	n	Q (m^3 s^{-1})	V_T (m s^{-1})	CO (ppm)	K (10^{-3} m^{-1})
1–2	16	464	7.0	52	1.7	16	464	7.0	52	1.7
2–3	4	464	5.2	60	2.1	4	464	5.2	60	2.1
3–4	4	464	3.4	69	2.5	4	464	3.4	69	2.5
5–6	4	103	1.7	96	4.4	4	107	1.7	77	3.0
7–8	16	361	5.5	137	5.4	16	357	5.4	150	6.1
9–10	16	347	5.3	71	2.6	16	353	5.4	50	1.8
11–12	4	147	2.2	6	0.2	4	142	2.1	21	0.8
13–14	4	494	3.8	58	1.9	4	495	3.8	48	1.5
14–15	4	494	5.4	71	2.5	4	495	5.4	62	2.1
15–16	16	494	7.5	127	5.8	16	495	7.5	117	5.3
Extract (m^3 s^{-1})										
Node 6			75						75	
Node 8			330						330	
Node 16			375						3785	

Table 8 Ventilation analysis for traffic condition 3 (vehicle speed 50 km h^{-1}; two-way traffic; traffic volume 100%; opposing wind 5 m s^{-1})

Flow path	am					pm				
	n	*Q* ($m^3 s^{-1}$)	V_T (m s^{-1})	CO (ppm)	*K* ($10^{-3} m^{-1}$)	*n*	*Q* ($m^3 s^{-1}$)	V_T (m s^{-1})	CO (ppm)	*K* ($10^{-3} m^{-1}$)
1–2	16	291	4.4	32	2.6	16	290	4.4	32	2.6
2–3	4	291	3.2	39	3.3	4	290	3.2	39	3.3
3–4	4	291	2.1	43	4.0	4	290	2.1	43	4.0
5–6	4	130	2.1	52	4.8	4	112	1.8	44	4.2
7–8	16	161	2.4	102	8.4†	16	178	2.7	101	8.5†
9–10	16	170	2.6	58	4.8	16	143	2.2	60	5.2
11–12	4	140	2.1	1	0	4	169	2.6	3	0.1
13–14	4	310	2.4	37	2.7	4	312	2.4	33	2.4
14–15	4	310	3.4	44	3.5	4	312	3.4	40	3.2
15–16	16	310	4.7	73	6.4	16	312	4.7	69	6.1
Extract ($m^3 s^{-1}$)										
Node 6		75					75			
Node 8		330					330			
Node 16		375					375			

Table 9 Ventilation analysis for traffic condition 3 (vehicle speed 50 km h^{-1}; two-way traffic; traffic volume 100%; opposing wind 5 m s^{-1})

Flow path	am					pm				
	n	*Q* ($m^3 s^{-1}$)	V_T (m s^{-1})	CO (ppm)	*K* ($10^{-3} m^{-1}$)	*n*	*Q* ($m^3 s^{-1}$)	V_T (m s^{-1})	CO (ppm)	*K* ($10^{-3} m^{-1}$)
1–2	16	256	3.9	37	2.9	16	252	3.8	38	3.0
2–3	4	256	2.8	42	3.7	4	252	2.8	44	3.9
3–4	4	256	1.9	49	4.5	4	252	1.8	50	4.7
5–6	0	47	0.8	76	6.7	0	27	0.4	54	5.6
7–8	16	209	3.2	94	7.9†	16	225	3.4	95	8.1†
9–10	16	207	3.1	48	4.0	16	181	2.7	48	4.1
11–12	0	74	1.1	2	0.1	0	105	1.6	6	0.1
13–14	4	281	2.2	41	3.0	4	286	2.2	37	2.6
14–15	4	281	3.1	48	3.8	4	286	3.1	44	3.5
15–16	16	281	4.3	80	7.0	16	286	4.3	75	6.7
Extract ($m^3 s^{-1}$)										
Node 6		75					75			
Node 8		440					440			
Node 16		500					500			

Table 10 Ventilation analysis for traffic condition 4 (vehicle speed 10 km h^{-1}; two-way traffic; traffic volume 100%; opposing wind 5 m s^{-1})

Flow path	am					pm				
	n	*Q* ($m^3 s^{-1}$)	V_T (m s^{-1})	CO (ppm)	*K* ($10^{-3} m^{-1}$)	*n*	*Q* ($m^3 s^{-1}$)	V_T (m s^{-1})	CO (ppm)	*K* ($10^{-3} m^{-1}$)
1–2	32	450	6.8	58	2.5	32	450	6.8	58	2.5
2–3	4	450	5.0	67	2.9	4	450	5.0	67	2.9
3–4	4	450	3.3	77	3.4	4	450	3.3	77	3.4
5–6	4	186	3.0	85	4.0	4	187	3.0	79	3.6
7–8	16	264	4.0	177	7.4	16	263	4.0	187	7.8†
9–10	16	258	3.9	106	4.2	16	258	3.9	92	3.7
11–12	4	213	3.2	2	0.1	4	213	3.2	8	0.3
13–14	4	471	3.6	67	2.5	4	471	3.6	62	2.4
14–15	8	471	5.2	81	3.0	8	471	5.2	75	2.8
15–16	28	471	7.1	133	5.6	28	471	7.1	127	5.4
Extract ($m^3 s^{-1}$)										
Node 6		75					75			
Node 8		440					440			
Node 16		500					500			

Table 11 Ventilation analysis for traffic condition 4 (vehicle speed 10 km h^{-1}; two-way traffic; traffic volume 100%; opposing wind 5 m s^{-1})

Flow path	am					pm				
	n	Q (m^3 s^{-1})	V_T (m s^{-1})	CO (ppm)	K (10^{-3} m^{-1})	n	Q (m^3 s^{-1})	V_T (m s^{-1})	CO (ppm)	K (10^{-3} m^{-1})
1–2	32	427	6.5	62	2.7	32	427	6.5	62	2.7
2–3	4	427	4.7	71	3.2	4	427	4.7	71	3.2
3–4	4	427	3.1	81	3.6	4	427	3.1	81	3.6
5–6	0	128	2.1	92	4.4	0	129	2.1	85	3.8
7–8	16	299	4.5	169	7.1	16	298	4.5	179	7.5
9–10	16	289	4.4	94	3.8	16	290	4.4	83	3.3
11–12	0	160	2.4	4	0.1	0	159	2.4	10	0.3
13–14	4	449	3.5	71	2.6	4	449	3.5	63	2.5
14–15	8	449	4.9	85	3.2	8	449	4.9	79	3.0
15–16	28	449	6.8	140	5.9	28	449	6.8	135	5.7
Extract (m^3 s^{-1})										
Node 6			100					10		
Node 8			440					440		
Node 16			500					500		

criterion $N_{fr} = 4.5^{(11)}$ yielded values of 3.0 m s^{-1} for the two-lane section and 2.5 m s^{-1} for the four-lane section to prevent backlayering. However, the tunnel ventilation system has been provisionally designed to set up a minimum longitudinal velocity of approximately 4 m s^{-1} (References 5 and 12) immediately upon a fire outbreak to control the flow of the hot smoke layer in the same direction as the traffic flow. A simplified approach was adopted, assuming that the tunnel velocity will be developed rapidly after the start of a fire (a fire normally requires 10–20 min to develop to full capacity) when the fire output is small and the buoyancy effect is negligible. Two different values of stationary traffic behind the fire (70 and 35 vehicles per km per lane) with opposing and assisting wind of 3.5 m s^{-1} were considered in the analysis. It is interesting to note that a slight decrease in opposing wind speed usually makes no difference to the number of jet fans required. Near the fire, one group of four jet fans was assumed to be burnt out. The maximum design limit of longitudinal velocity was taken as 10 m s^{-1}. This was considered to be the velocity at which the motorist might encounter difficulty in walking against the direction of air flow.

The results of the fire scenario analysis are shown in Tables 12 to 17. The flow figures, which give a general insight into the magnitude of the initial fire emergency tunnel velocities, were used to determine the six emergency programmed control patterns of ventilation fan operation. In accordance with the analytical results, the selection of the number of jet fans was governed by the fire emergency situation.

5 Ventilation plant selected

As a result of the ventilation analyses for the four different traffic conditions and the six fire scenarios, the numbers of ventilation fans shown in Table 18 were provisionally selected.

Table 12 Fire scenario 1

Stationary traffic (veh km^{-1} $lane^{-1}$)	Wind condition (m s^{-1})	Analysis no.	Analysis results	Flow path 1–2	2–3	3–4	5–6	7–8
			n	32	4	0	8	12
70	3.5 (opposing)	A†	Q (m^3 s^{-1})	517	517	517	238	279
			V_T (m s^{-1})	7.8	5.7	3.7	3.8	4.2
			n	32	4	0	8	12
35	3.5 (assisting)	B	Q (m^3 s^{-1})	590	590	590	283	307
			V_T (m s^{-1})	8.9	6.6	4.3	4.6	4.7

Notes to Tables 12–17
† Selected jet fan operation arrangement for each fire scenario.
Fire scenario 1 refers to a fire in bore A.
Fire scenario 2 refers to a fire in bore B.
Fire scenario 3 refers to a fire in bore C.
Fire scenario 4 refers to a fire in bore D.
Fire scenario 5 refers to a fire in bore E.
Fire scenario 6 refers to a fire in bore F.
See Figure 6 for fire designation of tunnel bores.

Table 13 Fire scenario 2

Stationary traffic (veh km^{-1} $lane^{-1}$)	Wind condition ($m\ s^{-1}$)	Analysis no.	Analysis results	Flow path				
				1–2	2–3	3–4	5–6	7–8
			n	24	4	4	4	4
70	3.5 (opposing)	A†	Q ($m^3\ s^{-1}$)	562	562	562	285	277
			V_T ($m\ s^{-1}$)	8.5	6.2	4.1	4.6	4.2
			n	24	4	4	4	4
35	3.5 (assisting)	B	Q ($m^3\ s^{-1}$)	588	588	588	309	279
			V_T ($m\ s^{-1}$)	8.9	6.5	4.3	5.0	4.2

Table 14 Fire scenario 3

Stationary traffic (veh km^{-1} $lane^{-1}$)	Wind condition ($m\ s^{-1}$)	Analysis no.	Analysis results	Flow path				
				1–2	2–3	3–4	5–6	7–8
			n	24	4	4	4	12
70	3.5 (opposing)	A†	Q ($m^3\ s^{-1}$)	582	582	582	291	291
			V_T ($m\ s^{-1}$)	8.8	6.5	4.2	4.7	4.4
			n	24	4	4	4	12
35	3.5 (assisting)	B	Q ($m^3\ s^{-1}$)	610	610	610	287	323
			V_T ($m\ s^{-1}$)	9.2	6.8	4.4	4.6	4.9

Table 15 Fire scenario 4

Stationary traffic (veh km^{-1} $lane^{-1}$)	Wind condition ($m\ s^{-1}$)	Analysis no.	Analysis results	Flow path				
				9–10	11–12	13–14	14–15	15–16
			n	12	4	4	8	20
70	3.5 (opposing)	A†	Q ($m^3\ s^{-1}$)	291	293	584	584	584
			V_T ($m\ s^{-1}$)	4.4	4.4	4.5	6.4	8.8
			n	12	4	4	8	20
35	3.5 (assisting)	B	Q ($m^3\ s^{-1}$)	323	289	612	612	612
			V_T ($m\ s^{-1}$)	4.9	4.4	4.7	6.7	9.3

Table 16 Fire scenario 5

Stationary traffic (veh km^{-1} $lane^{-1}$)	Wind condition ($m\ s^{-1}$)	Analysis no.	Analysis results	Flow path				
				9–10	11–12	13–14	14–15	15–16
			n	4	4	4	4	20
70	3.5 (opposing)	A†	Q ($m^3\ s^{-1}$)	251	292	543	543	543
			V_T ($m\ s^{-1}$)	3.8	4.4	4.2	6.0	8.2
			n	4	4	4	4	20
35	3.5 (assisting)	B	Q ($m^3\ s^{-1}$)	257	312	569	569	569
			V_T ($m\ s^{-1}$)	3.9	4.7	4.4	6.3	8.6

Figure 6 is a diagram of the ventilation plant layout.

The basic ventilation fan control parameters are carbon monoxide concentration and visibility. Six air monitoring stations, each including a carbon monoxide analyser and a transmissometer, will be installed as shown in Figure 6. Two stations will be provided in each main tunnel to give continuous six-stage feedback control signals to control the operation of the jet fans in groups of four together with the main extract fans. One station will be provided for each slip road to control independently the On/Off operation of one group of jet fans for unusual traffic congestion.

Table 17 Fire scenario 6

Stationary traffic (veh km^{-1} $lane^{-1}$)	Wind condition ($m\ s^{-1}$)	Analysis no.	Analysis results	Flow path				
				9–10	11–12	13–14	14–15	15–16
			n	12	8	4	8	24
70	3.5	A†	Q ($m^3\ s^{-1}$)	278	231	509	509	509
	(opposing)		V_T ($m\ s^{-1}$)	4.2	3.5	3.9	5.6	7.7
			n	12	8	4	8	24
70	3.5	B	Q ($m^3\ s^{-1}$)	304	277	581	581	581
	(assisting)		V_T ($m\ s^{-1}$)	4.6	4.2	4.5	6.4	8.8

Table 18 Provisional fan selection

Bore	Jet fan configuration	Main extract fans
A	40 in 10 groups	
B	8 in 2 groups	4 at 25 $m^3\ s^{-1}$
C	16 in 4 groups	4 at 110 $m^3\ s^{-1}$
D	16 in 4 groups	
E	8 in 2 groups	
F	40 in 10 groups	4 at 125 $m^3\ s^{-1}$

Due to the lead time required to start the jet fans in groups and to develop the full tunnel air velocity, the switching levels of the ventilation fans will be set lower than the maximum permissible values. In principle, the control levels will fall within a CO concentration range from 50 to 150 ppm and a visibility range from 80 to 20%.

6 Conclusion

These calculations have demonstrated that the criteria for carbon monoxide, diesel smoke and fire control will be satisfactorily met. Computer modelling techniques have been used to check the air flows at the underground junctions using the Building Services Research and Information Association's air flow analysis program. The ventilation analyses gave the authors confidence that the ventilation system will comply with the relevant standards. The design features optimise construction cost, operating economy and driver safety during normal and emergency situations.

Acknowledgements

The authors thank Dr G E Whittle and Mrs K E Moreton-Smith of the Building Services Research and Information Association for their contributions with the mathematical computer modelling work and Mr G Fudger of the Department of Transport for helpful information and suggestions.

References

1 *Road Tunnels Technical Committee Report to the XV World Road Congress, Mexico City* pp 24–39 (1975)

2 *Road Tunnels Technical Committee Report to the XVII World Road Congress, Sydney* pp 57–82 (1983)

3 Haerter A Fresh air requirement for road tunnels *Proc. 1st Internat. Symp. Aerodynamics and Ventilation of Vehicle Tunnels, Canterbury UK*, Paper B1 pp B1-1–B1-16 (April 1973)

4 Guibilo M and Lacquaniti V Uncertainties in the design of longitudinal ventilation systems for bidirectional road tunnels *Proc. 4th Int. Symp. Aerodynamics and Ventilation of Vehicle Tunnels, York UK* Paper K3 pp 461–482 (March 1982)

5 Heselden A J M Studies of fire and smoke behaviour relevant to tunnels *Proc. 2nd Int. Symp. Aerodynamics and Ventilation of Vehicle Tunnels* Cambridge, UK Paper J2, pp J1-1–J1-18 (March 1976)

6 Pursall B R and West A Induced ventilation in road tunnels—A comparison betwen full-scale and model studies *Proc. 3rd Int. Symp. Aerodynamics and Ventilation of Vehicle Tunnels, Sheffield, UK* Paper J1 pp 377–398 (March 1979)

7 Massey B S *Mechanics of fluids* 5th edn pp 80–92 (London: Van Nostrand Reinhold) (1983)

8 Baba T and Ishida M Possibilities for the reduction of total costs of ventilation systems with low velocity jet fans *Proc. 5th Int. Symp. Aerodynamics and Ventilation of Vehicle Tunnels, Lille, France* Paper D2 pp 205–218 (May 1985)

9 Daly B B *Woods practical guide to fan engineering* pp 282–311 (Colchester: Woods of Colchester) (1978)

10 Pursall B R and West A Induced ventilation in road tunnels—A theoretical and practical analysis *Proc. 2nd Int. Symp. Aerodynamics and Ventilation of Vehicle Tunnels, Cambridge, UK* Paper A2, pp A2-1–A2-27 (March 1976)

11 Danziger N H and Kennedy W D Longitudinal ventilation analysis for the Glenwood Canyon Tunnels *Proc. 4th Int. Symp. Aerodynamics and Ventilation of Vehicle Tunnels, York, UK* Paper D3 pp 169–186 (March 1982)

12 *Road Tunnels Technical Commitee Report to the XVIII World Road Congress, Brussels* pp 53–76 (1987)

13 Pucher K and Sturm P Measurements of CO concentration in the vicinity of tunnel portals and exhaust air chimneys by model tests *Proc. 5th Int. Symp. Aerodynamics and Ventilation of Vehicle Tunnels, Lille, France* Paper H3 pp 461–470 (May 1985)

14 *Occupational Exposure Limits 1987* Guidance Note EH 40/87 pp 1–26 (London: Health and Safety Executive/HMSO) (1987)