PROC. N.S. INST. SCI (1989)
Volume 38, pp. 169-187

VENTILATION OF A TUNNEL BENEATH NORTHUMBERLAND STRAIT

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After brief comparison of ventilation schemes used in three long European tunnels, several possible methods of ventilating a 13 km submarine vehicular tunnel are examined. Probably the most suitable is one supplying fresh air from a smaller ventilation tunnel parallel to that carrying the traffic.

Suivant une comparaison abrégée des schémas d'aération usagés dans trois longs tunnels européens, on a examiné les méthodes disponibles pour aérer un tunnel véhiculaire sous-marin, long de 13 km. Il est probable que la méthode la plus propice serait une qui fournirait de l'air frais provenant d'un petit tunnel parallèle à celui où la circulation prend place.

Introduction

The Order-in-Council of Queen Victoria that joined Prince Edward Island to Canada committed the Dominion government to a "steam service for the conveyance of mails and passengers...between the Island and the mainland..." This led to several generations of ice-breaking ferries. Although service is greatly improved over that of twenty years ago, they have proven to be an expensive bottle-neck requiring periodic replacement of an increasing number of ships and of their dock facilities, and they constantly operate at a substantial loss. Successive governments have agreed that satisfactory alternatives would be acceptable under this constitutional requirement.

Alternative Connections - A railway tunnel was proposed in 1890, and tunnels have been discussed casually from time to time since then. Development of large earth-moving machines made a causeway possible. In the 1950's, investigation showed that tidal flow, harbour installations, and the fishery in the Strait would be seriously affected by a causeway. In 1968, construction began on a combination bridge-causeway-tunnel as a cure for severe traffic delays. Tenders for the beginning of the actual crossing far exceeded estimates, however, and the project was abandoned.

In the last few years the problem has been examined again. A causeway was eliminated from consideration and proposals for a "fixed link", either bridge or tunnel, were invited from organizations prepared to bid on the construction of the "link" they proposed. Several such proposals were received, in 1987. Tunnel options I and II and their variants, discussed below, are from these preliminary proposals.

The current proposals for a complete bridge largely eliminate the unpredictable effects of a causeway upon plankton, and so upon the fisheries.

A tunnel is another possible alternative. The rocks beneath the Strait are sandstones and shales, in the irregular lenticular bodies characteristic of fluvial sediments. The sandstones are water bearing. The coefficient of premeability, k, ranges from 10^{-3} to 10^{-5} cm sec^{-1} and, in preliminary design work, water flows of 18 to 24 litres sec^{-1} were estimated (Golser, 1987). The rocks are very weak (unconfined uniaxial compressive strength 100 to 250 kg cm^{-2}), so modern tunnel-boring machines should be quite practical. This weakness, however, requires that the tunnel lining be substantial and installed close behind the face as the tunnel advances. The preliminary study by Golser, in 1987, assumed cover of about 30 metres of rock between the tunnel and the sea floor; practice in similar rocks in the Sydney coal field requires 200 feet (60 metres) of cover over the workings.

Tunnel Ventilation - In a vehicular tunnel, the ventilation system must guarantee that: (1) travellers are in safe air under all traffic conditions; (2) conditions are safe for operators and maintenance staff in the tunnel; (3) in case of accident, e.g. fire, the situation can be controlled and safe conditions provided for travellers and rescue services.

The major problem is carbon monoxide. Exhaust from a modern petrol engine is about 3% CO (Innes and Tsu, 1963); diesels produce strong odours, but CO content of the exhaust is low. Consequently, the problem depends upon traffic volume, composition, and speed; upon roadway grade and upon tunnel elevation. In addition, visibility is determined by particles from diesel exhaust and from tires and, perhaps, by fog. Also, very high longitudinal air velocity may influence steering. Comfort depends upon air temperature and humidity. (Fig 1)

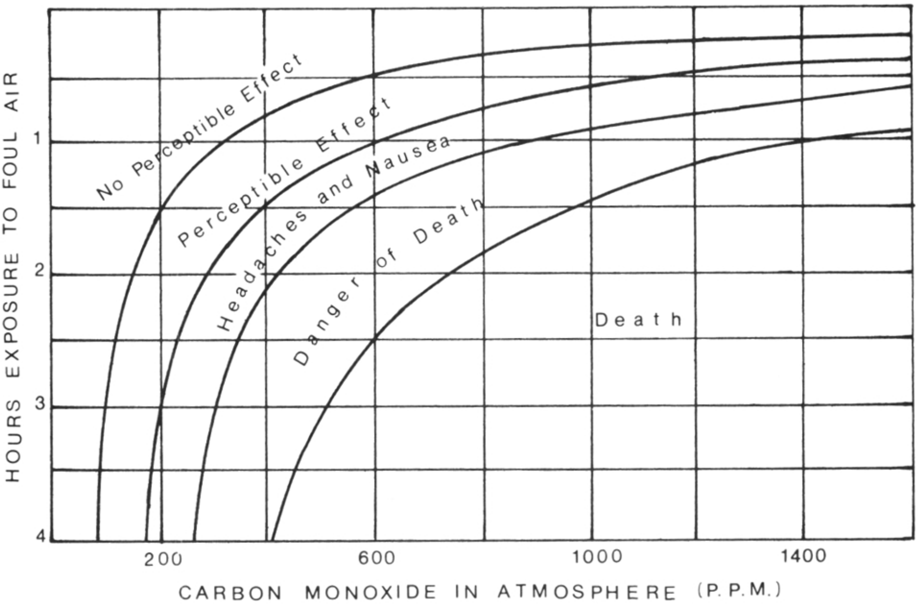


Fig 1 The effects caused by exposure to carbon monoxide.

Air Supply - Air sufficient to dilute CO to safe levels is usually sufficient to control the other factors. Common practice limits CO to $<$ 100 to 150 ppm for normal traffic, $<$ 200 to 250 ppm for congested traffic, and $<$ 50 ppm for workmen in the tunnel. Visibility is maintained by keeping particulate matter in the air to $<$ 2 to 4 mg m^{-3} for normal traffic, and $<$ 8 mg m^{-3} when congested. Longitudinal air velocity is commonly $<$ 4 m s^{-1}. (Thiéry, 1980)

In case of fire, current practice is: (1) to reduce longitudinal air movement to stop spreading of the fire and smoke; (2) to remove fumes via the exhaust airway in the roof, as immediately and completely as possible, while (3) keeping the lower part of the vehicle space free of fumes. This is done by manipulating the load on the fans. The example in Fig 2, from the Gotthard tunnel in Switzerland (Thiéry, 1980), shows the effect of stopping two sets of exhaust fans, but similar points of zero flow of fresh air result if the supply fans are suitably loaded, and the position of such points can be manipulated to some degree.

Tunnels are normally divided into ventilation zones. In the United States, the Federal Highway Administration requires that, in any zone, about 85% of total

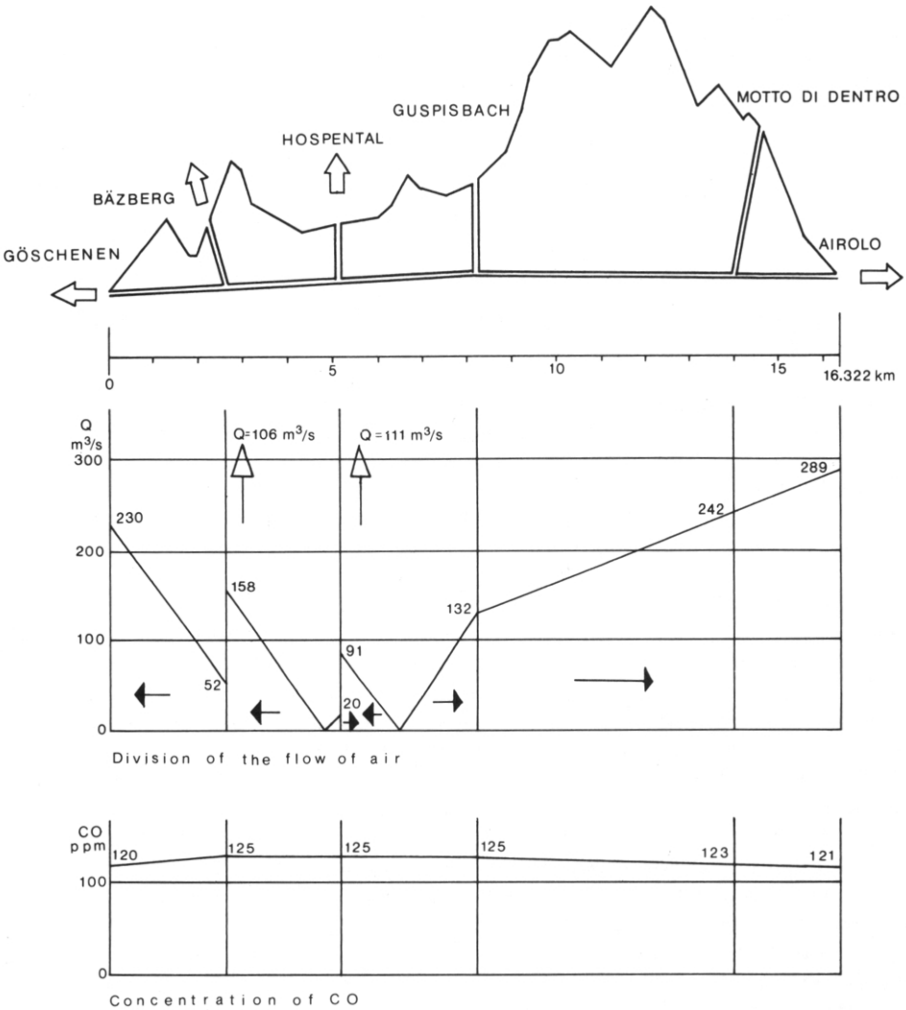


Fig 2 An example of control of air flow by manipulation of fans: the result of stopping two exhaust fans of the Gotthard tunnel. (Redrawn after Thiéry, 1980.)

capacity is maintained when one fan is out of operation (Bendelius, 1982). This can be done if four fans are employed in parallel (Fig 3).

Ventilation must be designed for extreme conditions, so size and location of airways are large factors in the design of the tunnel excavation. The pressure, P, necessary to move air in a duct of uniform cross section is

$$P = \frac{kSV^2}{A} = \frac{kSQ^2}{A^3}, \text{ because } V = \frac{Q}{A}$$

where P is in pascals, S is the internal surface of the airway in m^2, V is the air velocity in $m\,s^{-1}$, Q is the volume of air in $m^3\,s^{-1}$, A is the cross-sectional area of the airway in m^2, and k is a factor dependant upon the roughness of the airway surface, about 0.003 for smooth concrete. For a given Q, an airway of large area reduces the pressure and

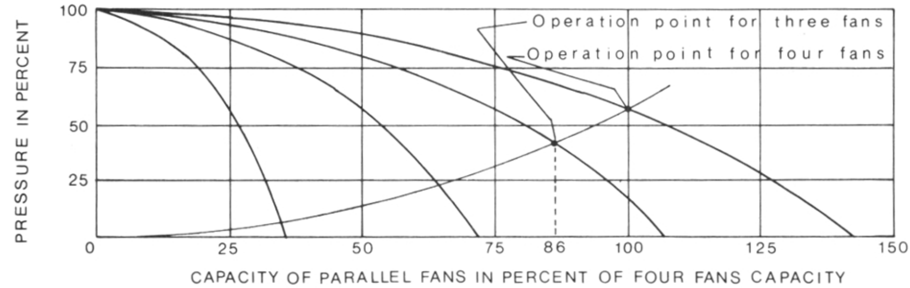


Fig 3 Operation of four fans in parallel in a ventilation zone. (After Bendelius, 1982.)

power requirements but, in a circular tunnel for example, lining costs increase as the radius, and excavation increases as the square of the radius. Therefore, although large airways produce savings in capital and operating costs for fans, the savings must be balanced against lining and excavation costs. In addition, the tunnel size, shape, and design of lining depend upon the stresses in the rocks. The inter-relations are not simple, but generally the minimum cross-sectional area is chosen.

Ventilation in Recent Long Tunnels

Arlberg, Austria (Lasser and Feizlmayr, 1978; Fig 4). At the bottom of each ventilating shaft, two fans drive fresh air about halfway to the next shaft, and two others extract foul air from the same intervals. Intake and discharge are through the same shafts, which are divided vertically. There are intake and discharge fans also at the portals. Primarily this is transverse ventilation, but some savings result from using the vehicle space as an airway, and 18% of the foul air is discharged through it. Fans are axial flow.

Gotthard, Switzerland (Diethelm *et al*, 1980; Fig 5). The mechanical arrangements follow the same system as at Arlberg, with two additional shafts. Intake and exhaust volumes are equal, i.e. fully transverse ventilation. Because of the shorter intervals between shafts, the airways in the northern part of the tunnel can be smaller than those in the southern. The fans are axial flow, and operating pressures are 1500 to 4900 pascals (Novenco Engineered Equipment). Both tunnels are divided into zones by the air shafts. In part, this provides control in emergencies but, primarily, it is to reduce the operating pressures required to move very large volumes of air. Large cross-sectional areas must be avoided because of stress from the rocks above the tunnels—up to 1000 metres of rock in both cases.

Mont Blanc, France-Italy (Ramel, 1963; Fig 6). At Mont Blanc, ventilation shafts are not possible because of permanent snowfields, glaciers and the height of the mountains above. The problem was solved by an ingenious use of supporting walls beneath the roadway to provide one exhaust channel and four inlet airways, each supplying one quarter of the north half of the tunnel. This arrangement was duplicated from the Italian portal. The scheme provides control zones, and the ingenuity lies in the increase in gallery area in each succeeding distant zone without increase in the tunnel dimensions. Half the foul air discharges through the vehicle space, with a maximum velocity of about 3.3 m s^{-1}.

All these tunnels cross mountain ranges, and differential barometric pressure between one side of the range and the other can be of concern. Longitudinal air velocity at Arlberg, for example, may be increased to 8 from the normal 4 m s^{-1}, in some circumstances.

The essential dimensions and features of the three tunnels are compared in Table I.

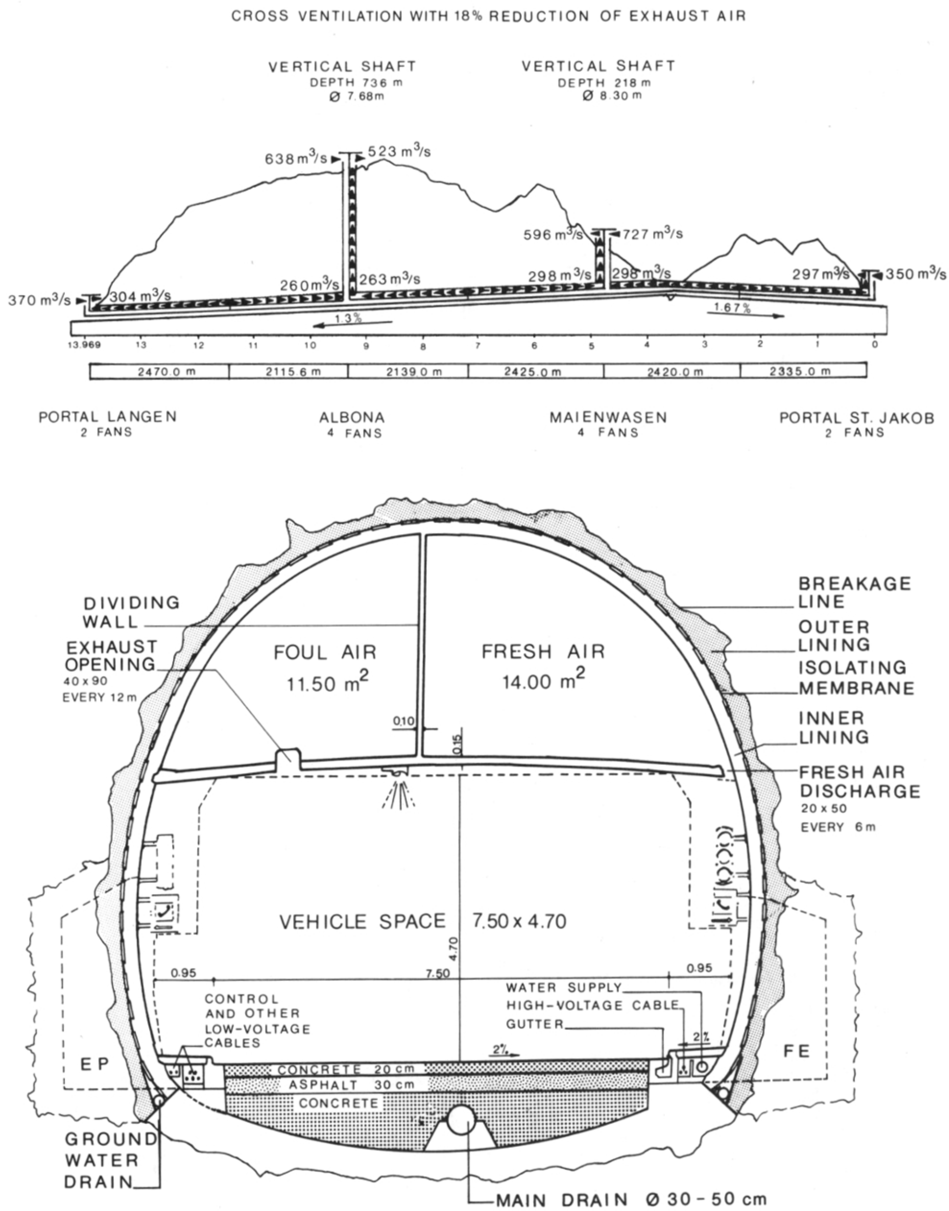
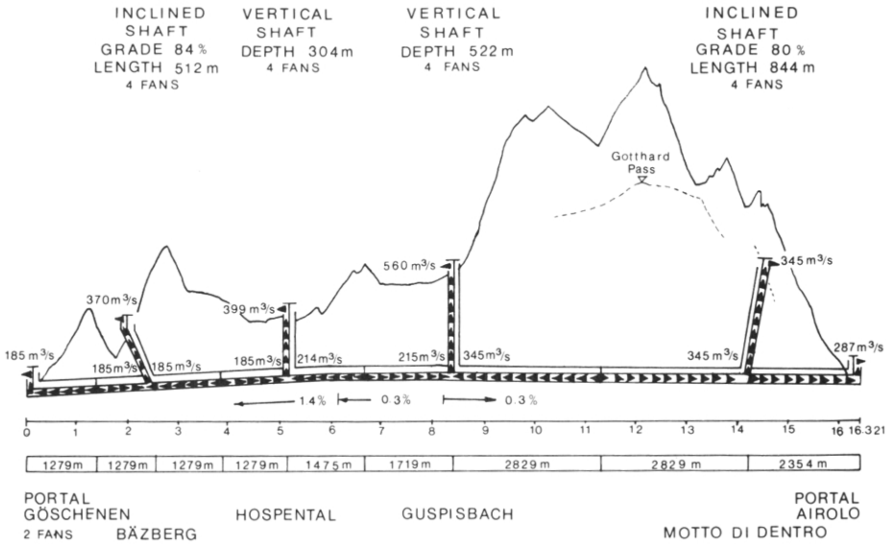


Fig 4 Ventilation scheme and typical cross-section, Arlberg tunnel, Austria. EP and FE are spaces for emergency phones and for firefighting equipment. (Redrawn after Lasser and Feizlmayr, 1988.)

Northumberland Strait

Obviously the ventilation is defined by the traffic a tunnel is required to carry. In 1927, the train ferry carried a few dozen cars each day, loaded upon railway flat cars. Probably no sensible engineer would then have predicted that, 60 years later, 145,000 vehicles would be ferried in one month. A tunnel is a very long-lasting structure,



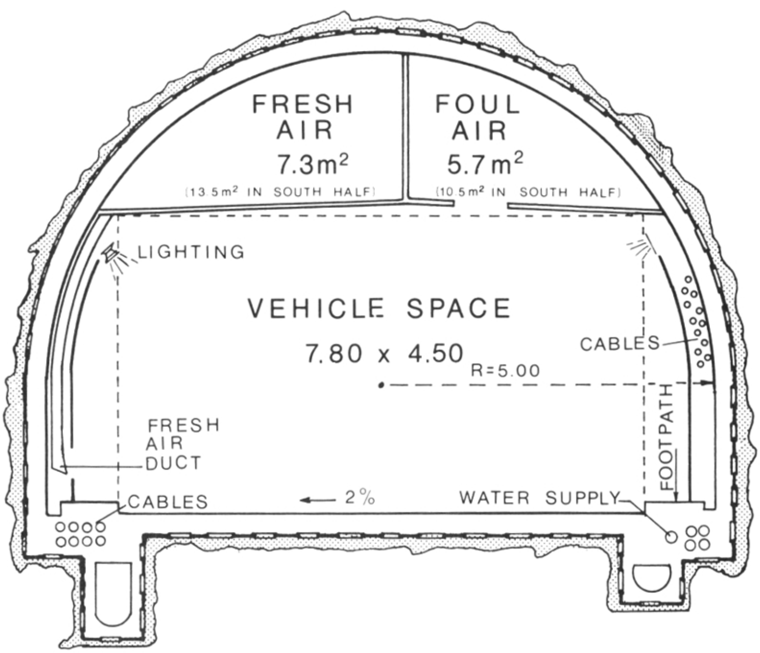


Fig 5 Ventilation scheme and typical cross-section of north part of Gotthard tunnel, Switzerland. (Redrawn after Diethelm et al., 1980.)

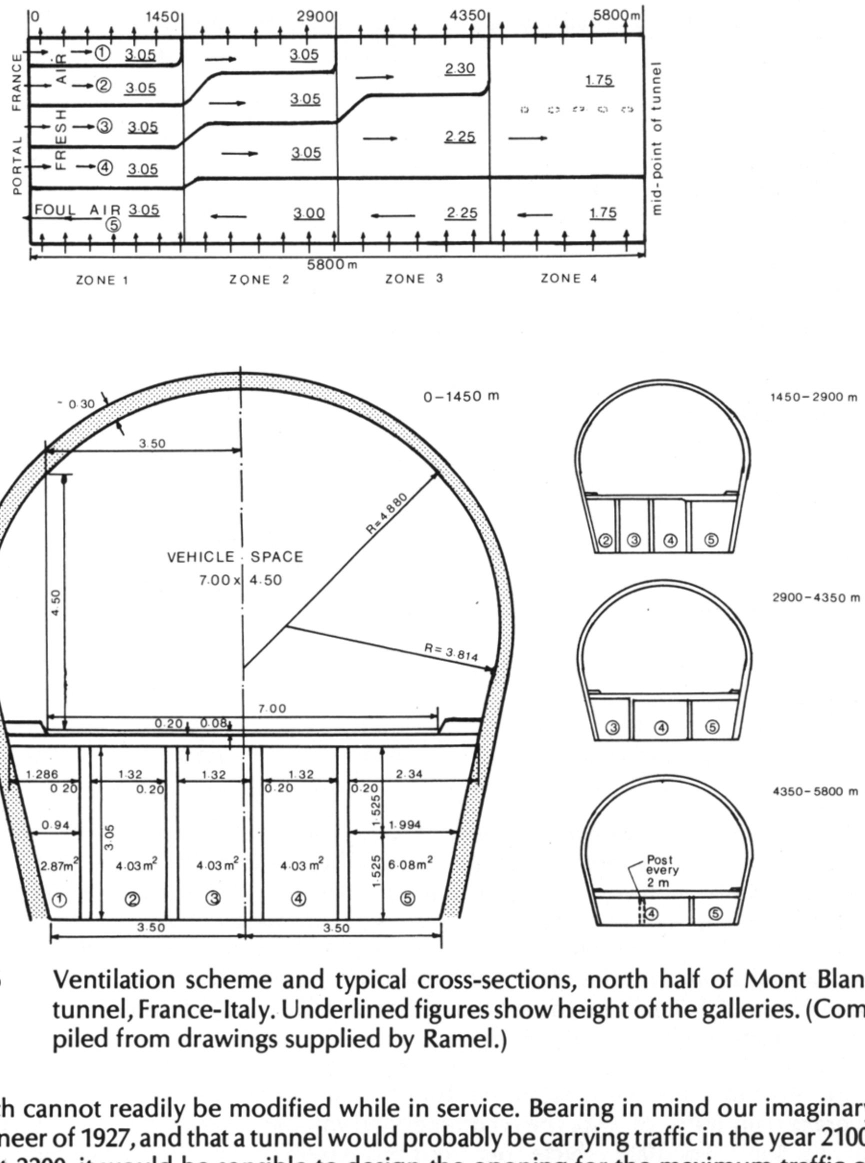


Fig 6 Ventilation scheme and typical cross-sections, north half of Mont Blanc tunnel, France-Italy. Underlined figures show height of the galleries. (Compiled from drawings supplied by Ramel.)

which cannot readily be modified while in service. Bearing in mind our imaginary engineer of 1927, and that a tunnel would probably be carrying traffic in the year 2100, if not 2200, it would be sensible to design the opening for the maximum traffic of which the roadway is capable, unless this makes the excavation and lining costs obviously ridiculous. Initial ventilation costs in "over-sized" airways would then be low, and fans could be changed later, as traffic required, without changing the tunnel itself.

Traffic Load - In the first three days of August, 1987, 26,600 vehicles were ferried across the Strait (*The Journal* newspaper, Summerside, quoting CN figures). This averages about 500 per hour for a 17-hour day.

The capacity of a 12-foot (3.66 m) traffic lane in a tunnel is approximately 2000 cars (no trucks) per hour (Bendelius, 1982). Reduction of lane width to 3.25 m reduces the capacity to 85%, and reducing lateral clearance to 0.95 m further reduces capacity to 88 percent of that figure, i.e. to about 75 percent or 1500 cars per hour. Because of trucks in the traffic stream, grades have an important effect.

Table I Comparison of Ventilation Data for Three Long European Tunnels

	Mont Blanc	Gotthard	Arlberg
Length, m	11,600	16,322	13,969
Elevation, m	~ 1200	1075-1150	850-1284
Capacity, car/hr.	450	1800	1800
heavy vehicles, %	?	10	11
Max. concentration, CO, %			
Normal	100	100	
Peak traffic		150	
Stationary traffic	200	230	
Max. grade and distance, km		1.4%-6.0	1.67%-4.0
Auxiliary shafts	0	4	2
diameter, m	-	5.60-6.65	7.68-8.30
Longest single ventilated section, m	1450	2829	2470
Area of air ducts, m^2			
Inlet	2.9 & 4.0 (min.)	7.3 & 13.5	14.0
Exhaust	6.0 (min.)	5.7 & 10.5	11.5
Longit. airflow in vehicle space, m/s	3.3	-	4 - 8
Number of fans	16	18	12
Type	centrif.	axial	axial
Operating pressure, mm H_2O	241-672	150-490	?
Total load, kW	6000	22,500	~ 11,200
Normal peak load	?	15,500	?
Total air supply, m^3/s	600	2,800	2,090
$m^3/s/km$	51.7	145	150
$m^3/s/km/veh/hr$	0.115	0.080	0.083

The Arlberg and Gotthard tunnels are designed for 1800 vehicles per hour. For comparison, the maximum traffic handled on the MacDonald Bridge, in Halifax, is 1000 cars per hour. It would be easy to jump to the conclusion that 1800 per hour is the appropriate maximum design load for Northumberland Strait, and provide the appropriate airways. A sense of proportion is needed, however: one must remember that, within a 600 km radius of the north end of the Gotthard is industrial Europe and a population of 152 million; there are another 57 million at its south end, and only a dozen major roads across the Alps.

The feasibility study released early in 1988, and prepared by Geoconsult, of Salzburg, Austria, mentions a maximum hourly traffic of 1975 vehicles and an annual average daily traffic of 9000. The recommended volume of ventilating air, however, is 80 $m^3s^{-1}km^{-1}$. For 1000 vehicles per hour this would be exactly the 0.08 $m^3s^{-1}km^{-1}veh^{-1}h^{-1}$ of the Arlberg and Gotthard tunnels (Table I), and other figures in the report are consistent. Although this figure is repeated many times in other reports, it would appear that the 1975 is probably a typographical error and that the traffic intended is about 1000 per hour—double the present maximum across the Strait. Because the Gotthard ventilation apparently has proven inadequate, one might reasonably increase the air supply to 0.10 $m^3s^{-1}km^{-1}veh^{-1}h^{-1}$, and use 100 $m^3 s^{-1}km^{-1}$ and 1000 veh h^{-1} as a reasonable figure for Northumberland Strait. Certainly this is sufficient to point out the problems and the options available.

Possible Ventilation Methods

For a number of reasons it is desirable to ventilate a submarine tunnel from the land, by means of ventilation shafts near the shore at either end. The situation at Northumberland Strait is shown in Fig 7. For the location considered in the feasibility

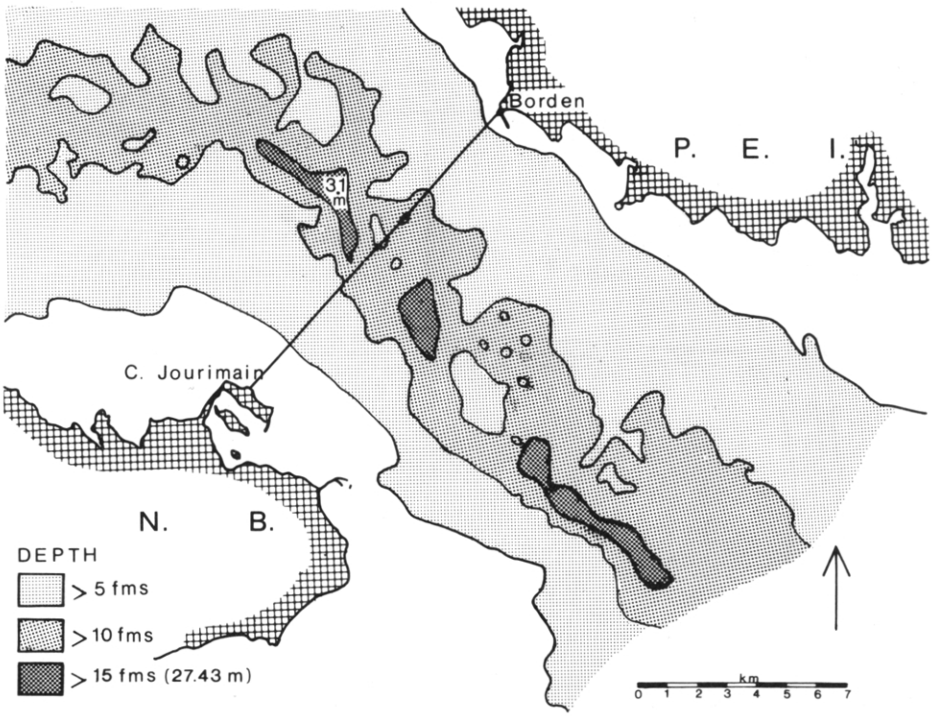


Fig 7 Water depths in Northumberland Strait, and line of proposed crossing. (Redrawn from hydrographic charts.)

study, the water gap is 13 km. At Borden, that study indicated an approach ramp 1320 m long, on 3% grade. This implies that the tunnel would cross the shore line at elevation -30 m.

The feasibility study considered a number of options. In all cases one can, for simplicity, consider that each shaft supplies air to its half of the submarine portion of the tunnel. The ramp portion, from shaft to portal at either end, is a separate and minor problem.

Option I (Golser, 1987; (Fig 8). Both intake and exhaust airways are above the vehicle space and have equal cross-sectional areas of about 18 m^2. The perimeter of each is about 17.1 m. Fresh air is discharged at regular intervals to the bottom of the vehicle space, and the foul air is extracted at intervals into the exhaust airway. If the 525 $m^3 s^{-1}$ of air required for one half (6.5 km) of the tunnel enters the fresh air channel then, after a distance of, say, 300 m an amount (300 x 525)/6500, or about 24.2 $m^3 s^{-1}$ will have been discharged into the roadway space, and about 500 $m^3 s^{-1}$ will continue into the next section of the airway, and so on. The cross-sectional area of the airway is constant, so the velocity of the air in it will decrease regularly along its length. Because the pressure required to move the air varies as V^2, however, the required pressure drops exponentially. These relations are shown in Fig 9. The total pressure required is 5200 pascals, or 520 mm, water gauge. The same situation obtains for the exhaust airway, except that the pressure is negative. The theoretical power requirement is 18,000 kW, at 60% efficiency. For this option the tunnel cross section is about 154 m^2, so the total excavation, shore to shore, is 13,000 x 154, or 2 x 10^6 m^3.

Option Ia. This differs from the above only in having the fresh air supply beneath the roadway. For the fresh air gallery the conditions are essentially as the same as in

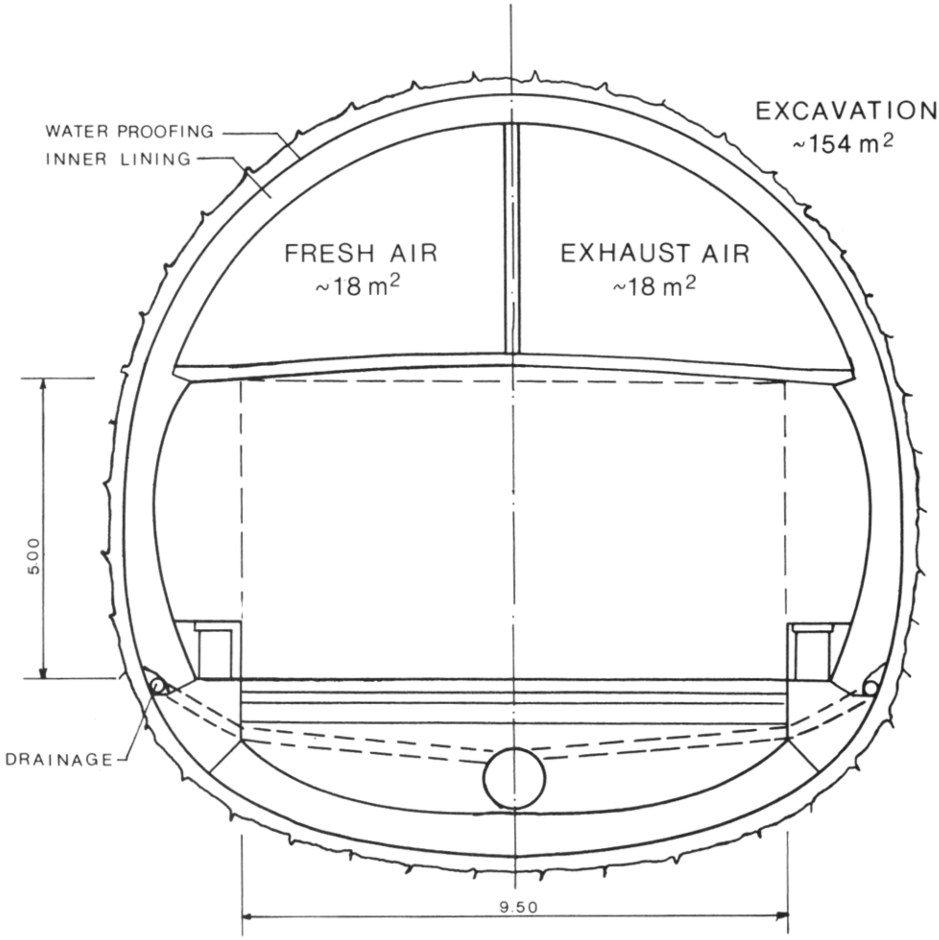


Fig 8 Typical cross-section, Option I.

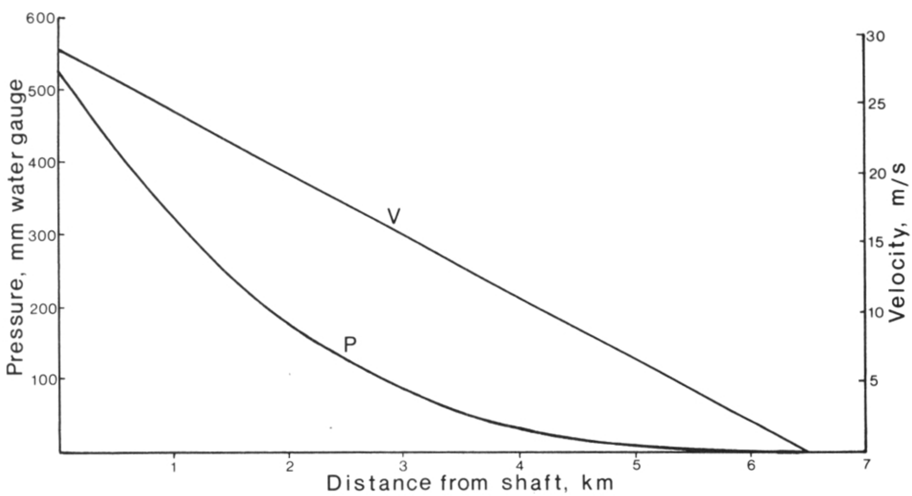


Fig 9 Pressure and velocity distribution in airways, Option I.

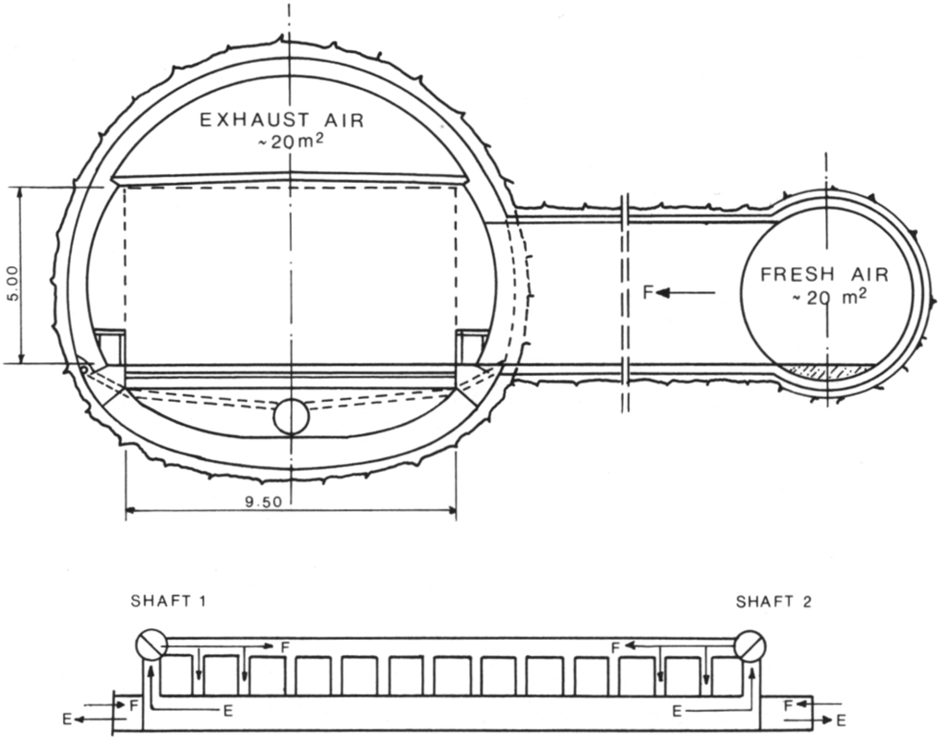


Fig 10 Ventilation scheme and typical cross-section, Option II.

Option I; the exhaust gallery, however, has a perimeter of about 21.5 m and this makes a substantial difference to the internal surface of the airway. The pressure required then becomes -620 mm, water gauge, which is a substantial change. The power requirement also increases to 20,000 kW. Because the excavated cross section is reduced to 137 m², the total excavation is about 1.78 x 10^6 m³.

Option II (Golser, 1987; Fig 10). In this variation the fresh air is supplied from a small parallel tunnel, through connecting channels regularly spaced, and is exhausted through an airway in the roof of the main tunnel. Each airway is about 20 m², the perimeter of the supply tunnel is about 15.5 m, and of the exhaust airway is about 23.5 m. The pressure necessary in the supply tunnel is about 340 mm, and in the exhaust airway is about -500 mm, water gauge. The lowered exhaust pressure results from the long perimeter caused by the shape of the airway. Theoretical power requirement is about 14,400 kW at 60% efficiency. If the supply and main tunnels are on 30 m centres, as in the Gotthard, and connected by airways 4 m in diameter, at 300 m intervals, the total excavation is 13,000 (133+20)+44 (12.6 x 22), or about 2 x 10^6 m³.

Option IIa (Fig 11). The *central* part of the tunnel has intake and exhaust airways above the vehicle space, as in Option I, but only 10 m² each. For the *end quarters* of the tunnel the whole volume above the vehicle space is used as the exhaust airway, area 20 m², and fresh air is supplied from a parallel ventilation tunnel, also 20 m² in area. This scheme avoids the problem of moving, within the main tunnel, the large volume of air that must pass through the end portions. The reduction in area of the channels beyond the end of the ventilation tunnel, however, produces an abrupt doubling of the air velocity and an attendant jump in the pressure needed to move the air. The net effect is a lowering of the exhaust pressure to -800 mm, water gauge, compared with -500 for option II, a problem for the fans. For the fresh air supply, the

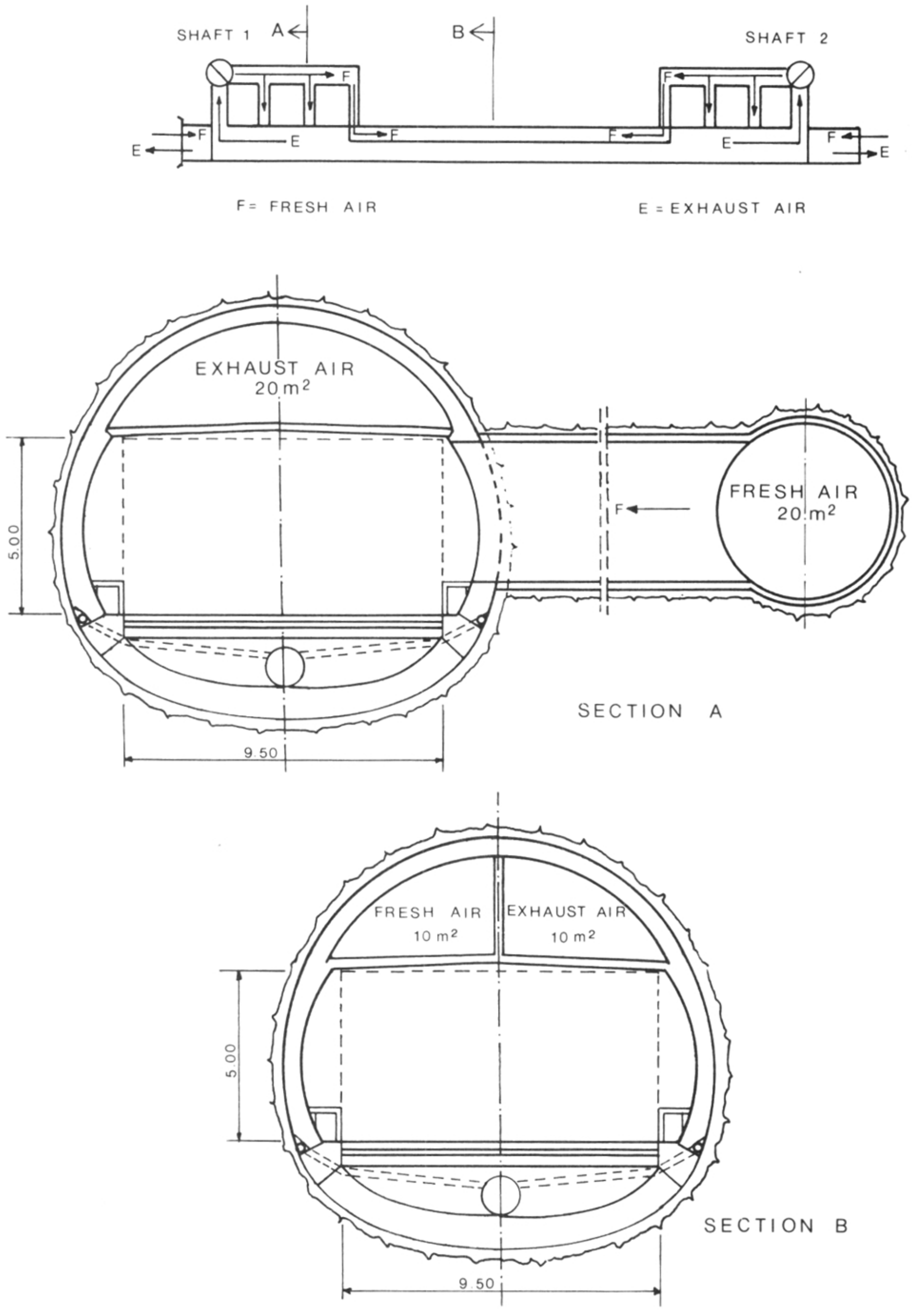


Fig 11 Ventilation scheme and typical cross-sections, Option IIa.

total pressure required is 620 mm. These features are shown in Fig 12. Theoretical power requirements are 5400 kW for the inlet and 6800 kW for the exhaust, for a total of 24,400 kW at 60% efficiency.

Option IIb (Fig 13). In this version, the air for the *central* half of the tunnel by-passes the end portion via a parallel ventilation tunnel of area 12 m². For 3250 m, then, about

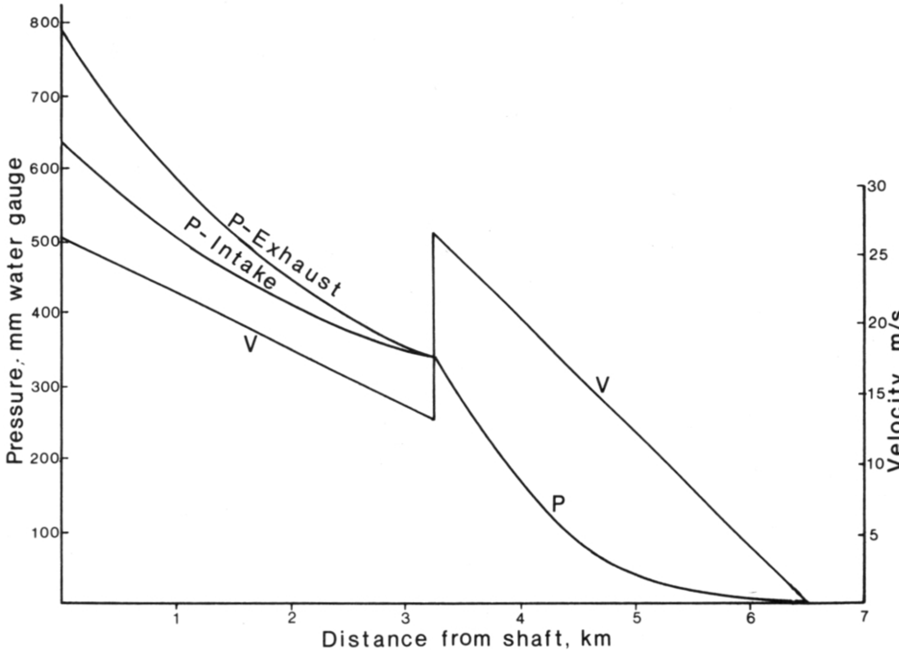


Fig 12 Pressure and velocity distribution in airways, Option IIa.

260 $m^3 s^{-1}$ moves at constant velocity in a uniform tunnel; the required pressure is 440 mm, water gauge. The air is then discharged into the vehicle space along the next 3250 m. The combined pressure requirement is 580 mm. The first 3250 m of the main tunnel is ventilated separately by a 10 m^2 duct beneath the roadway. The pressure required is 380 mm. Exhaust is by a 20 m^2 gallery in the roof, as in Option II. The pressure required is -500 mm. Theoretical power requirement is 1650 kW for the first quarter, 3000 for the 6.5 km of ventilation tunnel and 4300 for the exhaust gallery; a total of about 18,000 kW, shore to shore.

Option III (Fig 14). Although not mentioned in the recent feasibility study, it is interesting to see how the Mont Blanc system might be used under the Strait. We assume a minimum circular section to permit excavation by a tunnel boring machine. As at Mont Blanc, walls 20 cm thick support the roadway and divide the space into air galleries. Each of the four galleries supplies air to *one quarter of one-half* of the tunnel, thus generating four zones in each half of the tunnel; a fifth gallery is the exhaust airway.

As at Mont Blanc, it was found that evacuating all the foul air through the relatively small exhaust airway would cause excessively high velocities therein, and that true transverse ventilation is not practical. If one half of the foul air is discharged through the vehicle space, however, the maximum longitudinal air velocity (ca. 7.6 m s^{-1}) would be at the portals. This is just below the maximum 8 m s^{-1} allowed in the Arlberg tunnel but advantageously, at Borden, effects of barometric pressure are negligible.

It was found also that within a circular tunnel and a maximum fan pressure of 430 mm, as at Mont Blanc, the submarine part of the tunnel would require at least one "booster" fan in every gallery, each with the attendant special fan room. The problem, as is implied in Option IIa, above, arises from the large volume of air that must pass through the galleries in zone 1, the zone nearest the entrance.

By slashing out the bottom of the tunnel to a depth of 3.8 m below the roadway surface in the first two zones, however, and accepting the costs of fan pressures up to

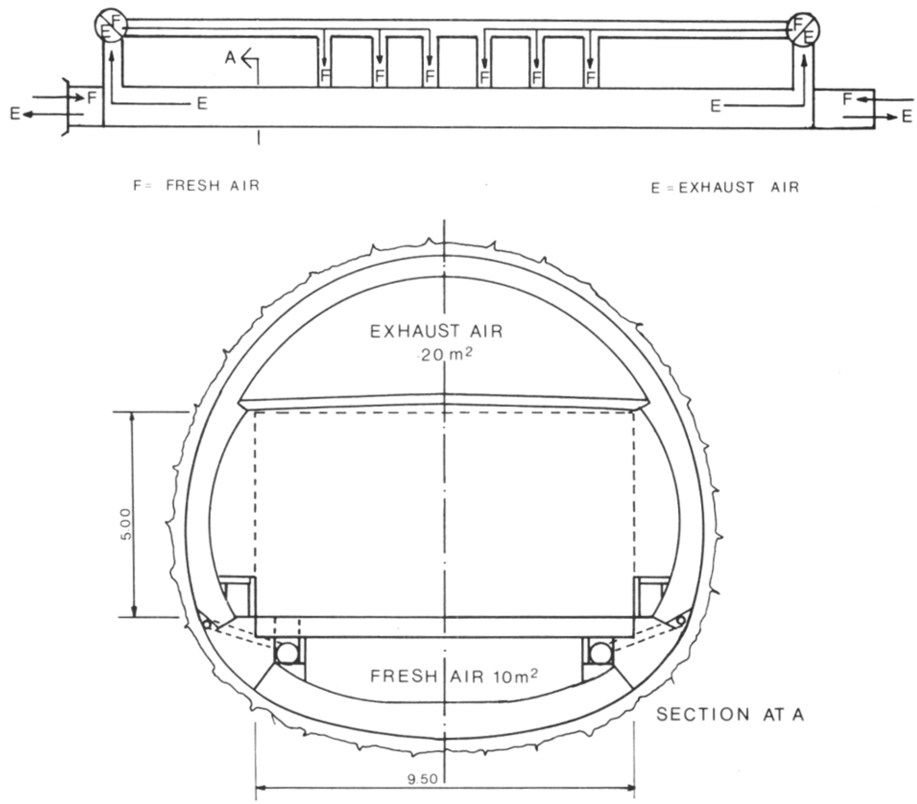


Fig 13 Ventilation scheme and cross-sections, Option IIb.

560 mm, the booster fans can be eliminated in the supply galleries. The area of individual galleries, of course, differs from zone to zone. The single exhaust gallery requires a pressure of -830 mm. The pressure and power requirements are shown in Table II. Air velocity is very high at the beginning of Gallery 1. Theoretical power requirement is 16,800 kW at 60% efficiency. Excavation amounts to about 1.5×10^6 m^3.

Option IV. The system of the Arlberg and Gotthard tunnels can be applied in Northumberland Strait, if ventilating shafts, protected by artificial islands, are acceptable in the Strait. A possible scheme is illustrated in Fig 15. The minimum circular tunnel is assumed, and 45 cm allowed for the thickness of the roadway. The inlet airway beneath the road would be about 15 m^2 and the exhaust airway above would be about 19 m^2. Because of the short length and corresponding low air volume in each section, the pressure and power requirements are markedly lower than for the other options considered.

Discussion

Except for the estimates of total excavation and total power, the data shown in Table II apply to *one half* (6,500 m) of the *submarine* portion of a Northumberland Strait tunnel. The five variants of Options I and II have the dimensions used in the feasibility study by Prof. Dr. J. Golser of Geoconsult, consulting engineers, of Salzburg, Austria, and air volume of 80 m^3 s^{-1} km^{-1} as in that study. Options III and IV assume 100 m^3 s^{-1} km^{-1}. The pressure and power requirements were calculated by a

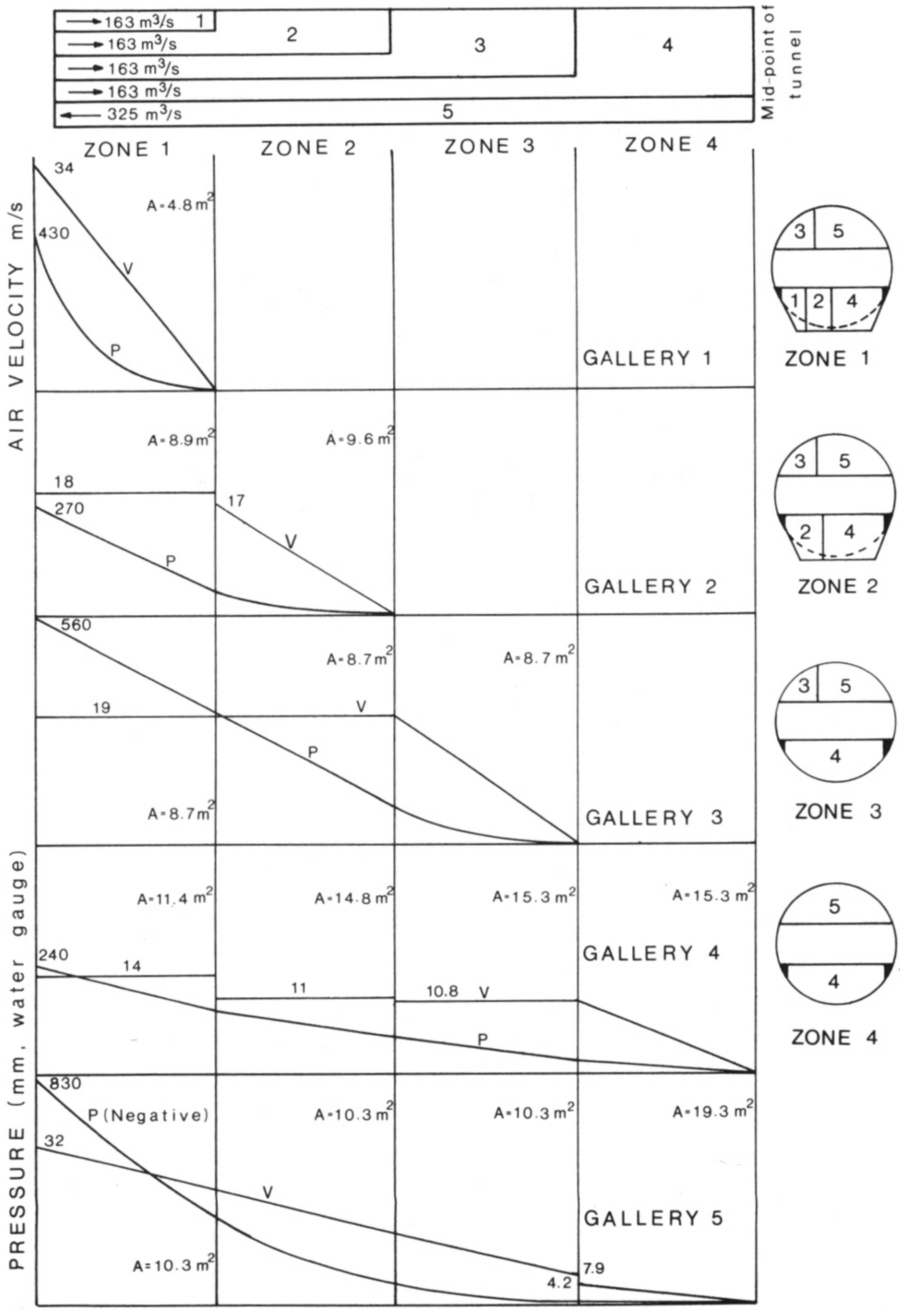


Fig 14 The Mont Blanc ventilation scheme applied to a Northumberland Strait tunnel. The invert of the tunnel is slashed to increase the cross-sectional area of the galleries in zones 1 and 2.

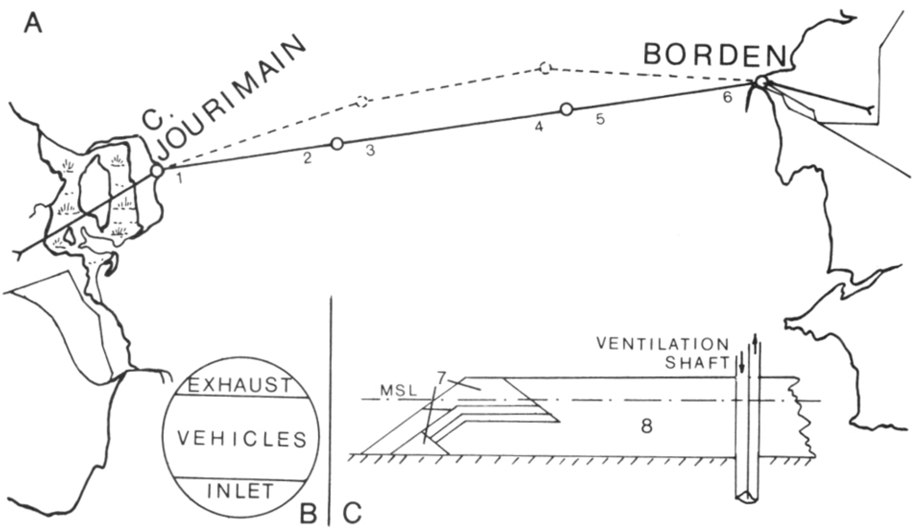


Fig 15 Option IV. A: Possible position of ventilation shafts in the Strait. 1-6, ventilation zones in the tunnel. The dashed line is an alternative position which would put the shafts through exposed rock bottom. B: Diagram of tunnel cross-section. C: Cross-section of protective island. 7, armour stone, 5 kg to 7 tonnes; 8, rock spalls and consolidated sand.

mechanical integration, using the above basic formulae and considering the airway in 100- or 300-metre increments. If the results are valid as a first approximation, they show a substantial range in the pressure and power requirements.

The pressure is probably the most critical factor. Axial flow fans can move enormous volumes of air, at pressures usually less than 50 mm, water gauge. As pressure increases the construction tolerances become important, and costs increase accordingly, but even 20 years ago axial flow fans capable of 500 mm pressure were in colliery service in France. The Danish firm that supplied the fans for the Gotthard tunnel informs me that they have supplied fans with capacities over 400 $m^3 s^{-1}$ at pressures greater than 800 mm, or even much more, and that some of them have now been in service for more than ten years (Novenco, 1988). Axial flow fans with variable pitch rotors are desirable because of ease of adjustment and the possibility of reversal of the air flow.

By placing fans in series, either immediately adjacent to one another or at intervals in the airway, the total pressure capability is increased two, three, or more times. It must be remembered, however, that a series fan placed well along the tunnel must have a special fan room, with hoisting equipment, and that replacement of major parts may be very difficult.

The airways must also respond to the air pressures and velocities. Losses due to friction-induced turbulence must be kept to a minimum, of course. In addition, in Option I for example, the maximum pressure difference between the airways is 2 x 520 mm, which translates to 1040 kg m^{-2} on the surface of the dividing wall. This is several times the force normally allowed as wind load in building design. Obviously separation of the airways requires more than hanging a curtain between them! A similar situation occurs in Option IIa, where the pressure difference between the exhaust airway and the vehicle space is 800 mm, or 800 kg m^{-2}.

Table II Data for a Northumberland Strait Tunnel under Various Ventilation Options

Option	I*	Iα*	II*	IIa*		IIb*		III+				IV+			
INLET AIRWAYS				1st	Main	1st	Vent.								
Gallery or Zone No.				Quarter	Tunnel	Quarter	Tunnel	1	2	3	4	5	1+2	3+4	5+6
Length, m.	6500	6500	6500	3250	3250	3250	6500	1625	3250	4875	6500		1900	2500	2100
Area, m²	18	18	20	20	10	10	12	4.8	8.9	8.7	11.4		15	15	15
Perimeter, m	17.1	18.5	15.5	15.7	14	16.5	12.6	9.5	12.1	12.6	13.3		17.5	17.5	17.5
Max. Air Velocity, m/s	29	29	26	26	26	26	22	34	18	19	14		13	17	14
Max. Pressure, mm, w.g.	520	550	340	620	325	380	580	430	270	560	240		41	89	54
Theor. Power[1], 60% eff., kW	4500	4700	2900	5400		1650	3000	1150	720	1480	640		130	360	180
EXHAUST AIRWAYS															
Area, m²	18	18	20	20	10	20						10.3	19	19	19
Perimeter	17.1	21.5	23.5	23.5	14.0	23.5						13.7	26.4	26.4	26.4
Max. Air Velocity, m/s	29	29	26	26	26	26						32	10	13	11
Max. Pressure mm, w.g.	-520	-620	-500	-800	-325	-500						-830	31	66	41
Theor. Power[1], 60% eff., kW	4500	5300	4300	6800		4300						4400	96	270	140
Total Power[2], kW	18000	20000	14400	24400		18000		16800				2400			
Excavation x-section, m²	154	137	133+20	133+20	133	133	12	111				111			
Total Excavation[2], m³x10⁶	2.0	1.8	2.0	1.9		1.9		1.5				1.5[3]			

* Air supply: 80 m³/s/km.
+ Air supply: 100 m³/s/km.
1 For one-half of tunnel only.
2 Shore to shore, excluding approach ramps.
3 Excluding shafts.

In Option III, walls subdividing the tunnel invert provide support for the roadway, which reduces the stresses within it, and so its thickness and cost. In zone 4, posts are required to fill this duty.

Option II has some features not immediately apparent. If the parallel ventilation tunnel is driven first, it provides a positive check upon all rock and hydraulic conditions for the main tunnel, and may act as a drain to relieve pressure in any aquifers encountered. It can also be used to provide access, should grouting or other procedures be needed to control water or bad ground in advance of the main tunnel. Detailed knowledge of conditions should reduce the contingencies for unknowns which contractors include when bidding on a job. In the Gotthard tunnel, and presumably in this one, refuge rooms (Schutzräume) for about 60 persons are spaced at intervals of about 250 m along one side of the tunnel. If they are suitably placed, an assured air supply for these rooms can come directly from the ventilation tunnel, which is also available as an emergency tunnel.

In Option IV, the two additional ventilation shafts are not minor engineering problems, are expensive, and are probably politically impossible at present. First, although producing negligible effects upon tidal currents, and so upon the fishery, there is the question of obstructions in a navigable waterway. Second, they must be stable. Preliminary examination 30 years ago indicated that protective islands 200 m in diameter at the top would not be disturbed by the moving ice. Since then, much design experience has become available from drilling operations in the Beaufort Sea. Third, such an island, in 20 m of water, with sides sloped 1 : 1.5 covers an area of about 53,000 m^2. Its sloping sides have an area of about 26,000 m^2, for a net loss (?) of lobster habitat of about 50 per cent.

The shaft itself might well be a concrete caisson sunk through the island, and sealed into the bedrock beneath; the portion in the bedrock is a standard mining operation. The portion above the bedrock would be expensive, but the islands do provide a space for the disposal of spoil from the tunnel. Two islands would require about 2×10^6 m^3, of which about half would be rock spalls; the balance is armour stone, which is available at Port Hastings.

Without fairly reliable figures for excavation costs, it is not possible to infer the most suitable tunneling scheme. The low power and excavation requirements of Option IV are probably completely offset by the matter of shafts in the Strait. Option III also has relatively low power and excavation requirements, and roadway costs would be somewhat less than where the entire road is not supported from beneath. If a circular tunnel is adequate to sustain the rock and hydraulic pressures, excavation by boring is likely to be less expensive than by standard drill and blast procedures. Although excavation is at a maximum in Option II, power requirements are comparable to those of Option III and the engineering and safety advantages of the parallel ventilation tunnel may well be considered to offset the costs of excavation. It is probable then, that Option II would be the one likely to be chosen.

Acknowledgements

I am indebted to R.A. Gees for information about the Gotthard and Arlberg tunnels, to K. Moran for data from exploratory drill holes, and to F. Ramel for information about the Mont Blanc tunnel.

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(Received 16 December 1988).