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Chapter 23
Tunnels

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Chapter 23 Amendments – June 2006

Revision Register

Issue/ Rev No.	Reference Section	Description of Revision	Authorised by	Date
1	-	First Issue	Steering Committee	May 2006

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Chapter 23
Tunnels

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23.1 General Introduction

A tunnel is a closed or roofed structure carrying a road through, or under an obstacle. This obstacle may be anything in the path of a preferred road alignment such as a mountain, a body of water, a building or a complete development.

A short tunnel is also termed an underpass, but in general any covered length of road over 90 metres long should be treated as a tunnel (NFPA, 2001).

Tunnels are some of the most expensive parts of road infrastructure but in some cases, they are necessary to overcome circumstances where other solutions cannot be applied. The initial construction cost of a tunnel may be more than ten times that for a bridge at the same location (in terms of road carriageway provided) with high operating and maintenance costs. Yet a tunnel may still be the best option for the site for a range of reasons.

Choosing between a bridge and tunnel requires consideration of a range of factors of which cost is only one. It is often the case that the choice will be made on the basis of factors other than cost (see Section 23.2).

This Chapter describes the basis for deciding to adopt a tunnel solution, the types of tunnels that can be used and the factors to be considered in designing a tunnel.

Tunnel design is a multi-disciplinary activity requiring geometric design, structural design, electrical and mechanical engineering, fire safety engineering and communications engineering. Interaction of the specialist designers in each of these areas is necessary to obtain the best solution. Decisions on the location and form of tunnels must only be undertaken with the advice of these specialist designers.

23.2 Justification for Tunnels

Selecting a tunnel solution may be justified:

- on new routes under densely developed urban areas where land acquisition costs are high;
- through mountains to avoid steep grades and longer routes;
- under rivers and large bodies of water to keep shipways clear;
- to avoid impact on cultural heritage or environmentally sensitive areas; and
- where clearance requirements or land use prevent construction of bridges.

The high capital cost of tunnels is well known. To justify expenditure on a publicly funded tunnel, many issues other than the costs of initial construction and on-going operation and maintenance, have to be considered as they need to be with any option.

PIARC (1983) suggests three types or levels of evaluation for a tunnel or alternative structure (including alternative route options) as a solution.

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They are shown below with modifications for Queensland conditions. The factors to be considered are those:

- to which a monetary value can be attributed (quantitative);
- which are measurable but to which a monetary value cannot be given; and
- which can only be given a subjective value (qualitative).

Criteria having a Monetary Value

These criteria include both direct and indirect costs attributable to the project. These are set out in detail in the following paragraphs.

Planning and design costs include:

- surveys and field investigations including geotechnical hydrology, hydraulic etc;
- public consultation including any models and displays;
- planning and environmental reports; and
- design costs including plans, specifications and estimates.

Land Acquisition Costs include:

- land costs for private, commercial and industrial properties;
- relocation costs; and
- accommodation works.

Construction costs include:

- cost of actual structure;
- cost of operational equipment (including all traffic control equipment and fire, life and safety equipment associated with the tunnel);
- the cost of links to existing infrastructure and any necessary changes as a result of the effect of the tunnel on the total traffic network; and
- noise reduction treatment such as ventilation attenuators and sound barriers.

Operating costs include:

- ventilation and lighting;
- fire life and safety services;
- mechanical and electrical services;
- inspections;
- training of emergency services personnel; and
- traffic control.

Maintenance costs include:

- road surface;
- cleaning; and
- replacement of equipment over the life of the tunnel (over 100 years).

User benefits:

- reduced travelling times and length of travel (both passenger and commercial vehicles) offset by any toll charges (if any);
- reduced number of accidents; and
- reduced traffic flow on other roads.

Changes to land and property values and rentals:

- changes to land and property values and rentals near and above the tunnel or surface alternatives; and
- possible leasing back of resumed land after construction has been completed.
- Indirect effects:
- future developments on the surface (e.g. streets closed for a pedestrian mall); and

- changes to overall traffic patterns and transport routes with consequent changes in user operating costs.

Social costs:

Building a tunnel involving a new highly trafficked route may benefit one part of the community to the detriment of another. The net benefits (costs) should be included in the analysis of the total costs of a proposal.

Other social costs difficult to quantify are discussed in the section on "Qualitative Factors" below.

Measurable Criteria

Other criteria, which are able to be measured but are difficult to cost, may be important in deciding to adopt a tunnel solution. They may also form the basis of objections to a proposal.

Some of the measurable but difficult to cost criteria are discussed in the following sections.

Noise

Tunnels provide a means of eliminating noise from the area through which they pass. However, care will be needed at the portals and any intermediate air vents to ensure that noise levels are satisfactory. Overall reduced noise levels may be a significant reason for adopting a tunnel solution.

Main Roads (2000) sets out the criteria for levels of noise from a road before noise attenuation measures should be considered.

Air Pollution

The air pollution emanating from a section of road may be measured and added to that from the surrounding environment to establish the impact of the road and assess the suitability of the proposal.

Air pollution is concentrated at the entrance, exit and intermediate ventilation outlets in tunnels. Careful siting of these features is required to minimise the impact on the adjacent property.

Visual Intrusion

The degree of visual intrusion of road infrastructure may be a source of annoyance to some people. The extent of this effect on the overall amenity is difficult to quantify. Tunnels have the advantage of being hidden from view but the portals will need consideration from this point of view.

Ventilation outlets may have to be remote from the site, or disguised inside other structures, to achieve acceptable results.

Vibration Effects

Vibration effects on buildings and other structures should be considered for both the construction and operation stages.

Level of Service

PIARC (1983) describes "level of service" in the following words:

"This has to do with the users' feeling of well-being about driving conditions and lack of disturbance. Throughout the world, the notion of level of service attracts careful consideration since it can affect the geometric standards of the proposed road."

A quantitative assessment of the traffic Level of Service can be undertaken using the procedures of the Highway Capacity Manual (see also Chapter 5).

Qualitative Factors

There are some factors that cannot be given monetary value or completely quantified. They are largely related to environmental protection or social consequences and include:

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- displacement of people whose homes have been resumed;
- effect on Cultural Heritage sites, buildings etc;
- changes to the landscape which may increase or decrease the value of a site, including the effects on the community and tourism;
- changes in community relationships due to severance or a new route;
- aesthetic value of the project for users and the community;
- flexibility for increasing the traffic capacity of the road infrastructure in the long term future (say beyond 20 years);
- temporary disadvantages or nuisance value during the construction phase to the commercial and general community; and
- the impact on animal life and bio-diversity in general.

For a tunnel, these qualitative factors are generally positive except at the portals and at ventilation exits.

23.3 Types of Tunnels

Tunnels are constructed in a wide range of physical and operational circumstances that will determine the type of tunnel used. Types of tunnel include for example:

- cut-and-cover at shallow depth;
- cast-in-situ in a waterway;
- immersed tube for underwater crossings;
- bored tunnels; and
- tunnels excavated through rock.

Figure 23.3(a) Illustrates some typical tunnels.

Cut-and-Cover Tunnel

This type of tunnel is constructed in a trench excavated from the surface and is appropriate for shallow depths in suitable soils. Special cases of this type of construction include:

- contiguous pile wall tunnels (or variants);
- “Top Down” construction; and
- “Canopy Tube” method at surface impediments such as railways and other obstructions.
- Factors to be considered for cut and cover tunnels include:
- ease with which the soil can be excavated;
- depth of water table below the natural surface;
- availability of the surface material being removed for backfilling during the construction period and the consequences for the subsequent land use;
- the need to dewater/pump the excavation;
- stability and earth pressure on the sidewalls and loads and surcharges on the tunnel roof;
- temporary construction loads;
- uplift forces; and
- access restrictions.

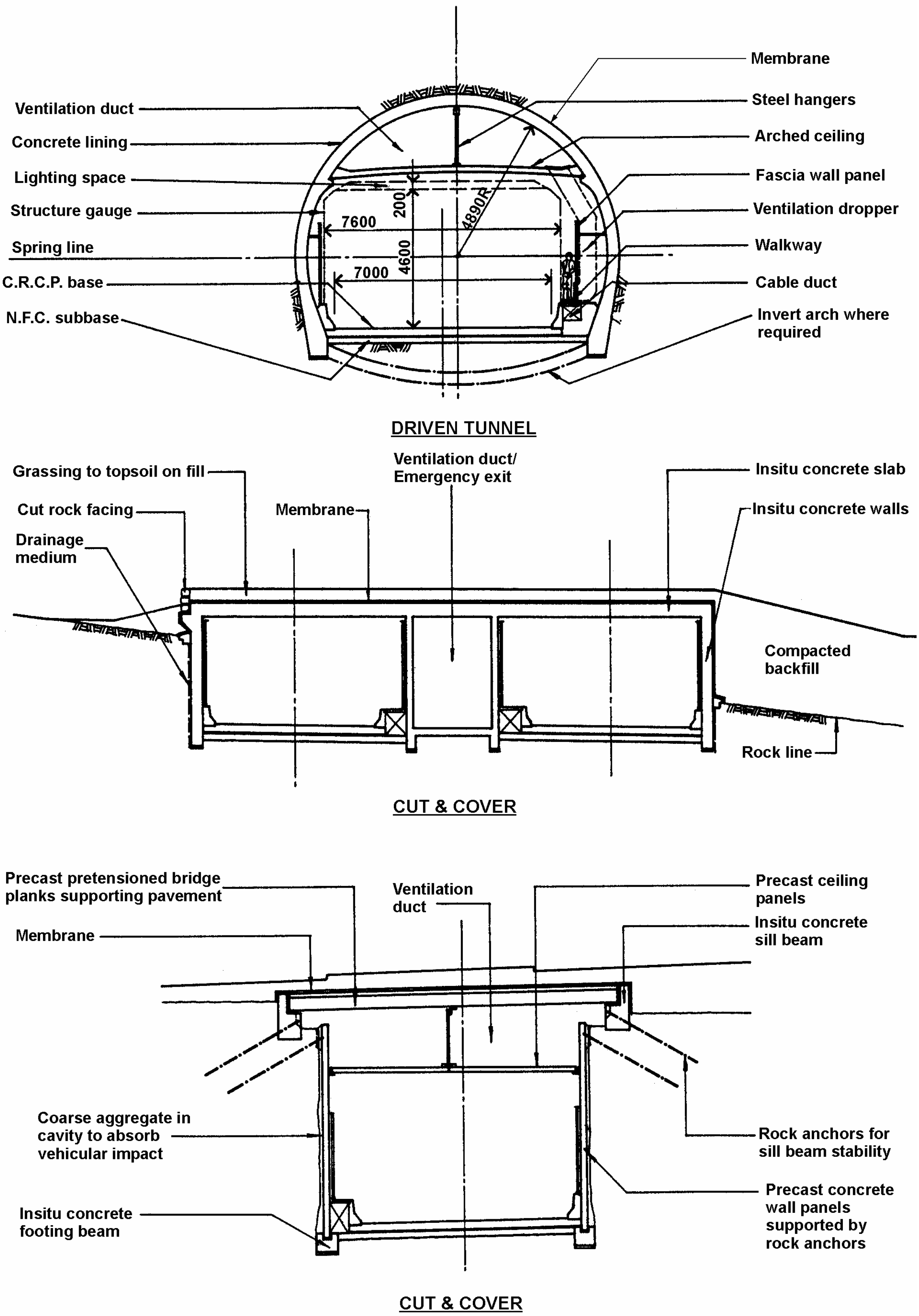

Figure 23.3(a) Typical Tunnel Types

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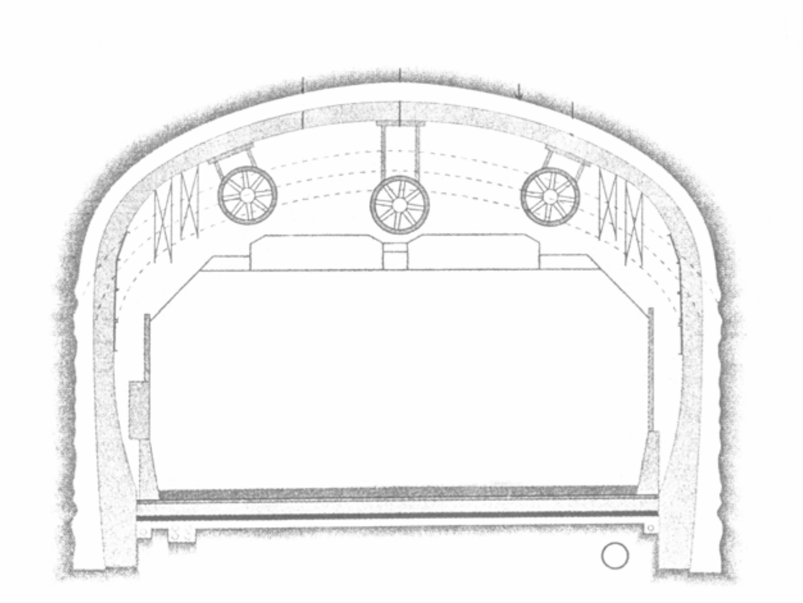

Driven Tunnel – Enlarge Section for Ventilation Fans

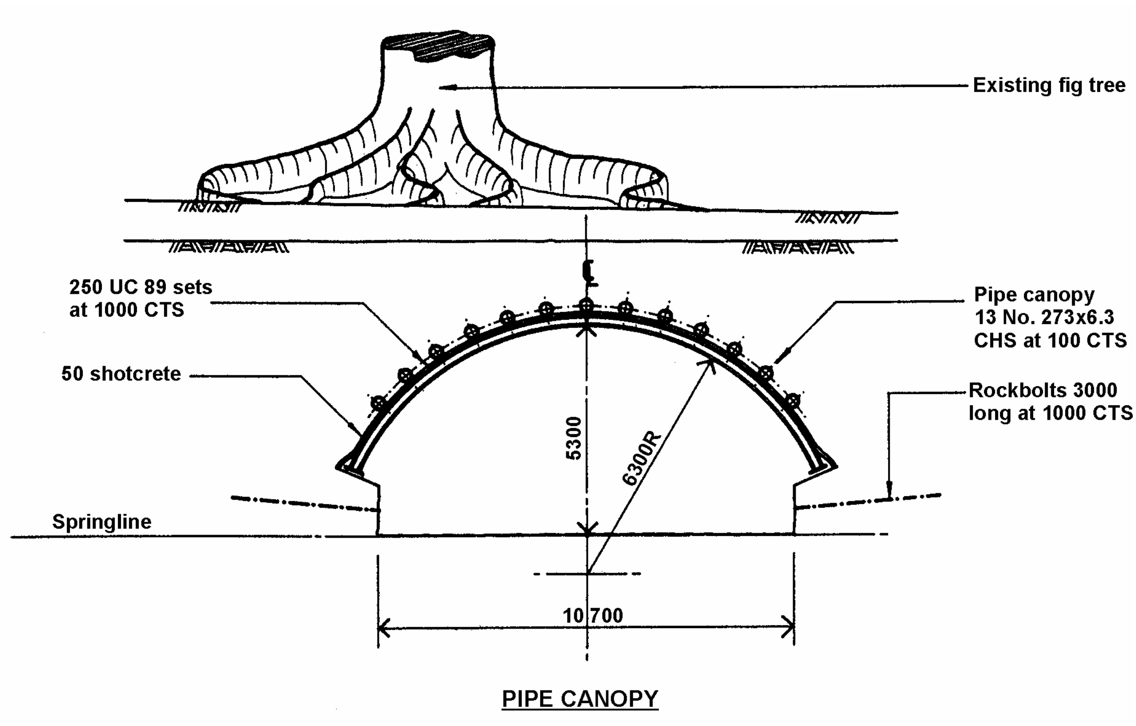

Figure 23.3(a) (continued) - Typical Tunnel Types

In the contiguous-pile wall tunnel, each side of the tunnel is formed from contiguous bored or cast-in-place piles, with or without liners depending on the soil conditions, driven to below the tunnel floor. (A typical pile wall is shown in Figure 23.3(b). The space between the walls is excavated after driving the piles, thus exposing the surface of the contiguous piles. (Temporary or permanent propping may be required.) Cladding is placed on the face of the piles to present a pleasing internal appearance to the tunnel and to achieve the required reflectivity of the tunnel walls.

Drainage using filter drains is essential, as the piles are essentially earth retaining walls.

After excavation between pile walls, capping beams are cast over the pile walls, roof slabs placed and the floor constructed.

"Top down" construction is used where traffic interruptions have to be kept to a minimum or where soil types permit this method. In this form of construction, the roof of the tunnel is constructed on the ground before the material below is excavated. This allows the surface to be reinstated while the excavation is in progress, thereby reducing the time of closure of the road on top.

The "Canopy Tube" method is used in isolated areas where traffic interruptions cannot be tolerated for any period of time and less costly alternatives can not be used. Figure 22.3(c) illustrate this form of construction. It is also referred to as "Fore Poling Method" from mining terminology. The process is:

- establish a portal by excavating a vertical face beside the road or other facility under which the tunnel is to be constructed;
- prebore holes horizontally under the surface in the direction of the tunnel (this may have to be done in stages depending on the length of the tunnel);
- insert a steel tube into the prebored hole and fill with grout;
- install a steel set at the portal to support the ends of the tubes (a steel set is a supporting frame constructed with steel I-beams);
- excavate the material under the tubes on a front in stages and install a steel set at the end of each stage (approximately 750mm centres);
- continue this process until the exit portal is reached;
- shotcrete between the sets;
- place reinforced concrete for floor, sides and roof (the extent of this will depend on the overall design, the construction process and the intended role of the steel sets in the final structure).

The design of the supports and their extent will depend on the type and extent of the material present at the site. E.g. the location and extent of competent rock will affect the extent of the steel sets and their founding level.

Figure 23.3(c) illustrates the Canopy Tube concept. The Pipe Canopy type shown in Figure 23.3(a) is another version of this concept.

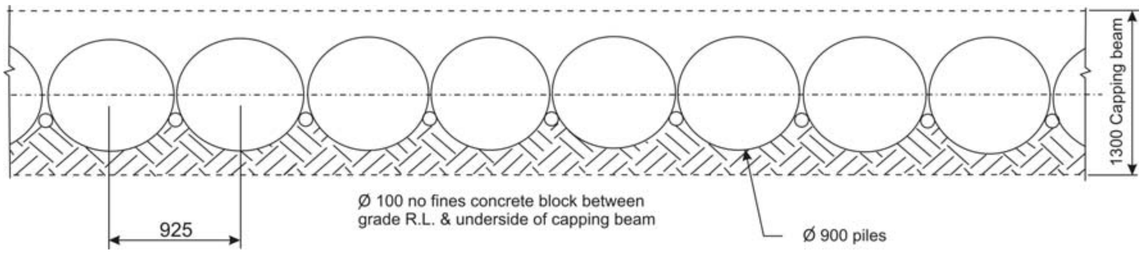

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Figure 22.3(b) Pile Wall

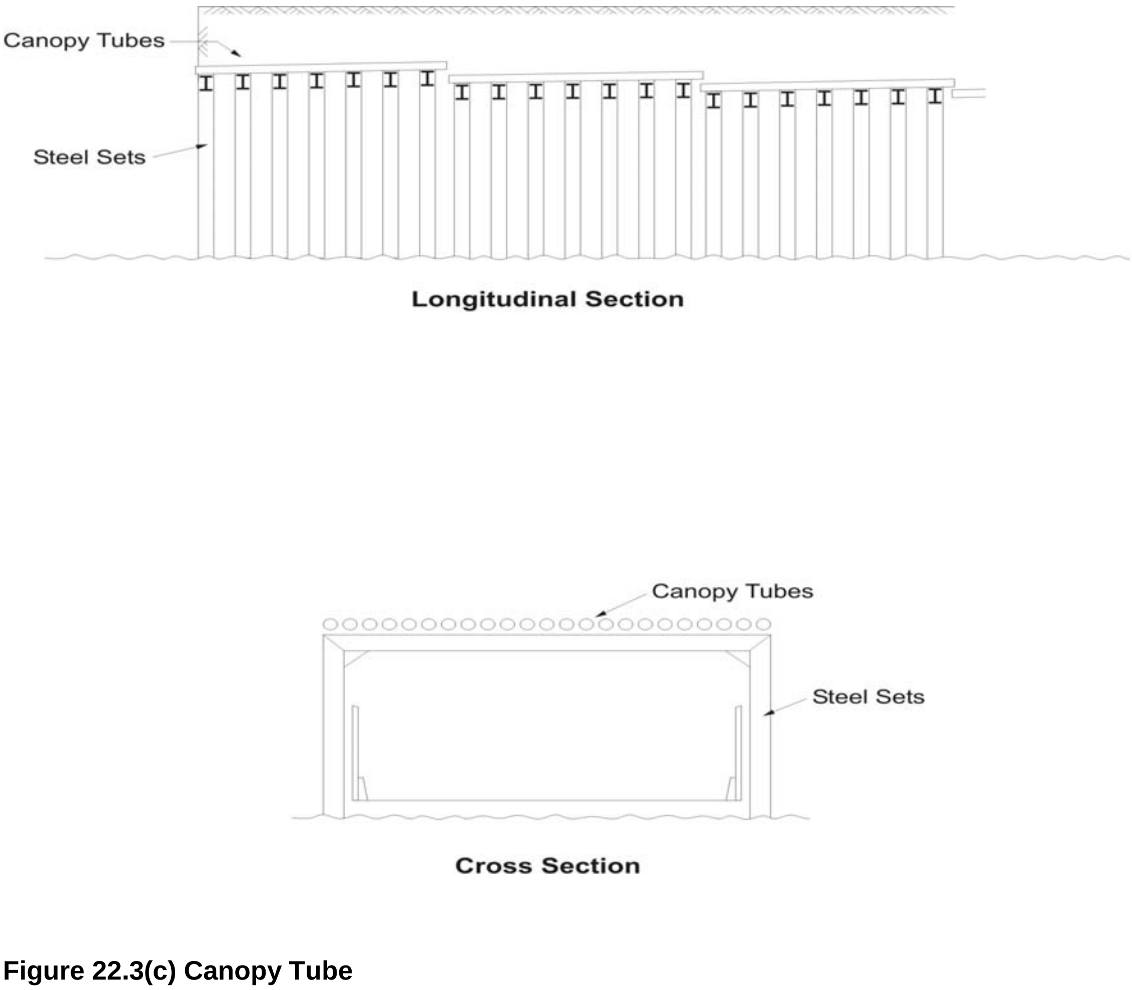

Figure 22.3(c) Canopy Tube

In an urban environment, additional considerations are:

- severance effect of the removal of surface material, cutting off access for both vehicles and pedestrians;
- cutting off and/or relocating public utilities;
- noise from the construction site;
- vibration effects on properties;
- air pollution ; and
- settlement of buildings adjacent to the excavation due to changes in the water table or excavation techniques.

Cast-in-Situ Tunnel in a Waterway

Where permitted to temporarily block a waterway, and if practical, the tunnel may be constructed in two halves or by using a number of travelling caissons.

The first half of the tunnel is constructed within a temporary caisson. On completion of the first half, the waterway above the constructed section is then opened and the second half of the tunnel constructed in a procedure similar to the first.

Immersed Tube Tunnels

For underwater crossings the immersed tube tunnel may be appropriate where conditions are right. Precast reinforced concrete sections of the tunnel are manufactured in a dry dock, floated and towed to their location above a dredged channel, sunk into position and joined to previous sections.

Bored Tunnels

Bored or driven tunnels are constructed where there is sufficient overburden.

Temporary support is required before the final lining is placed - precast segments, shotcrete and/or rock bolts depending on the material excavated. The cost of liners can vary widely depending on the soil types, presence of swelling clays, soft rock and/or water.

In tunnels excavated using the Tunnel Boring Machine (TBM), the liner is placed continuously behind the TBM as it advances. The TBM may grip the sides of the tunnel (by expanding) or thrust off the liner as it advances. There are many different types of TBM for various situations.

Under large waterways where soft ground conditions are common Earth Pressure Balance Machines (EPBM), Slurry Shield Tunnel Boring Machines (SSTBM) and shield driven tunnels have been used.

In these shields, the cutting head is enclosed within a watertight bulkhead containing earth or bentonite slurry, which stabilizes the face. Behind the sealed bulkhead the rest of the tunnel remains under normal atmospheric pressure.

Tunnelling materials (earth, rock, clay, water, bentonite and other chemicals) are directed through the TBM cutting head and out the rear end. In addition to the TBM itself, there is a considerable amount of material transportation equipment that removes these products, recycles the bentonite, and delivers power and hydraulics, water, chemicals and pre-cast segments.

Both air and water (and lubricating chemicals) can be lost through the tunnel face. Tunnels of circular cross-section are formed.

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Tunnels through Rock

Rock tunnels are excavated in a firm, cohesive medium, which may vary from relatively soft rock and sandstone to very hard igneous rocks such as granite. Excavation may be by drilling and blasting and temporary supports may consist only of rock bolts. TBMs can also be used in some circumstances.

23.4 General Design Considerations

Tunnels have distinguishing characteristics such as:

- the absence of junctions, parked vehicles, bicycles (except for rare exceptions) and pedestrians;
- an enclosed road with lateral and vertical restrictions;
- artificial illumination; and
- artificial ventilation.

Because of these characteristics, some drivers may be apprehensive about entering and leaving the tunnel and become conscious of driving too close to tunnel walls (thus possibly reducing the effective lane width), and misjudging the steepness of grades (hence misjudging braking distances). However, tunnels exhibit a better accident record than the open road, due to a combination of factors such as:

- drivers becoming more alert in the changed environment of the tunnel;
- absence of roadside obstacles;
- standard of construction; and
- safety features incorporated in the tunnel.

Where there are no Australian Standards for elements of tunnel design, and no applicable mandatory International Standards, PIARC and NFPA publications provide considerable reference and guidance material (see References at the end of this Chapter).

Some general design considerations are:

- Design Speed;
- Cross-section Elements;
- Alignment;
- Grading;
- Drainage;
- Operations (including emergency ingress and egress, and maintenance requirements);
- Ventilation;
- Fire;
- Lighting;
- Communications;
- Structural requirements; and
- Electrical requirements.

Risk analysis procedures can have benefits for safety. Designers should:

- undertake a comprehensive risks/safety analysis to determine the best operation procedures; and
- provide control systems that allow any incident to be detected in order to reduce to a minimum the response times for such incidents.

It is necessary to:

- identify the risks;
- assess the causes of possible failures;
- determine the effects of those failures; and
- provide solutions to minimise the consequences of failures.

These principles should be applied when considering the details of following sections (see also the section on "Dangerous Goods").

Design Speed

For safety reasons, the maximum allowable speed in two-way tunnels throughout the world is between 60 and 80 km/h.

In one-way tunnels, the speed limits are between 80 and 110 km/h, the higher speeds found in very long tunnels. Clearances at the "desirable" end of the range should be provided in high-speed tunnels.

Factors to consider in determining the design speed for the tunnel include:

- Speed environment on the approaches;
- Geometric limitations in the tunnel; and
- Tolerable speed reduction between successive geometric elements

Cross-section Elements

The following elements of the cross-section of a typical tunnel shown in Figure 23.4 may be taken as a guide for multi-vehicle use.

Traffic lanes	3.5 m wide (plus any required curve widening)
Shoulders	2.5 m wide to act as a breakdown lane.
Horizontal Clearance	Refer to Chapter 7, Section 7.10.3
Vertical clearance	Refer to Chapter 7, Section 7.10.4

The 2.5m shoulder provides space for broken down vehicles or emergency stopping and should be continuous through the tunnel if possible. If this shoulder is not continuous, parking bays or pull-off bays should be provided at intervals not exceeding 250m, and the width should provide the shy line distance (Chapter 7, Section 7.2.2).

In limited lane tunnels an accident or vehicle break down will cause traffic to stop and backup if the vehicle cannot be moved quickly to a break down lane or a road shoulder. The stationary traffic causes increased demand on the ventilation system as well as stress to drivers. It is therefore important that adequate shoulders or emergency pull-off areas be provided.

For roadways with separate tunnels for each direction, the shoulders next to the centre wall should be sufficiently wide to provide the shy line distance (see Chapter 7, Section 7.2.1).

Busway tunnels should be designed in accordance with the Busway Planning and Design Manual (QT and Brisbane City Council, 1998).

The available space in tunnels is also required to provide for ventilation, lighting, public utilities, drainage, access and emergency and fire equipment. Appropriate traffic control devices (extent may depend on the length and location of the tunnel) must also be provided. The overall cross section must provide for these services while maintaining the required roadway clearances.

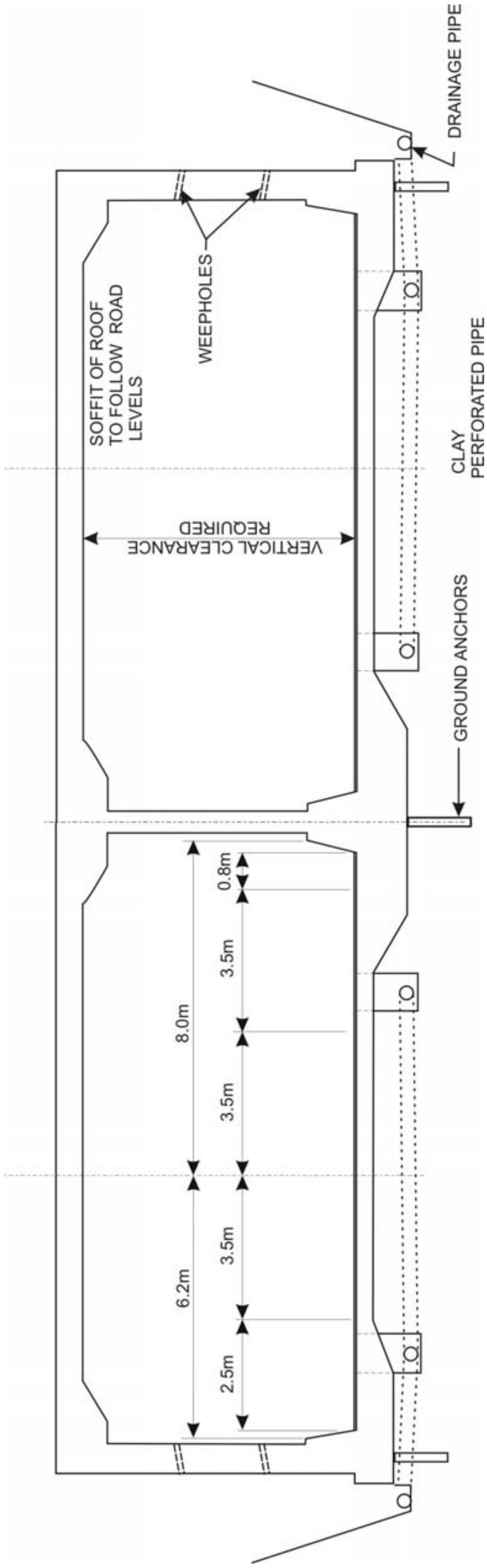

Figure 23.4 Typical Tunnel Section (6 Lanes)

Alignment

Alignment for highway tunnels should be straight, where possible. Horizontal curves based on sight distance should be of desirable radii, rather than minimum standards to alleviate the feeling of discomfort experienced by some drivers in tunnels.

The geometric requirements for busway only tunnels are set out in the Busway Planning and Design Manual produced for the South East Queensland Regional Busway Network (QT and Brisbane City Council, 1998).

Grading

Driver perceptions can be affected by the combination of the wall joints and tunnel grade. Where the wall joints are perpendicular to the grade, not vertical, this can distort the perception of distance. The TRRL Report (TRRL, 1987) gives examples of drivers' misjudgments on gradients between 3 and 5 percent, caused by this phenomenon leading to accidents. It also notes that build-up of spilt oil on gradients of 4 percent or more has caused heavily laden articulated vehicles to lose traction.

There is a direct relationship between grade and the breakdown rate of vehicles in tunnels.

Grades in road tunnels should therefore be limited to 3.5% in general. For long two lane tunnels with two-way traffic, a maximum grade of 3% is desirable to maintain reasonable truck speed.

Where a future light rail may be placed in a busway tunnel, 3% is the maximum permissible grade.

In underwater tunnels or tunnels with low points, grades should preferably not be less than 0.5%. Sumps must be provided with explosion proof pumps and electrical equipment.

Drainage

Water and other liquids may enter a tunnel from various sources such as:

- rainfall runoff from portal areas;
- rainwater carried in by vehicles;
- groundwater infiltration;
- wastewater effluent from wash-down activities;
- accidental spillage of fuel from damaged vehicles and the wash-down of such products;
- operation of fire suppression systems; and
- accidental rupture of a fire main or hydrant.

It may be more economical to allow some groundwater infiltration, removing the water by longitudinal grading or by pumping, rather than incurring the expense of trying to achieve a fully watertight enclosure.

To help drain water, it may be desirable to place the floor at a small longitudinal grade not less than 0.5% (see section on "Grading" above). A free draining tunnel will deliver economies in drainage costs.

The section on "Fire, Life and Safety" considers whether a separate drainage system should be provided for washing down spills of dangerous goods from accidents.

A single drainage system should meet the following requirements:

- specified flood immunity (100 year ARI);

- collection at portals and in the tunnel via gullies at appropriate intervals, with longitudinal pipe network to sumps - gullies and equipment must be flame proof ;
- sumps sealed and vented to the atmosphere - duty and stand-by pumps must be provided;
- sump and pump capacity designed to be compatible with the inflow rate;
- pumps and associated control gear designed to operate automatically via level switches;
- closed sumps with forced ventilation - duty and stand-by extraction fans are required. (Monitoring of pump operation at a Central Control Centre is desirable);
- wastewater complying with effluent standards specified by the relevant Authorities and drainage from the tunnel passed through appropriate gross pollutant traps for capture of hydrocarbons and other undesirable pollutants prior to discharging into waterways; and
- the drainage system designed to be easily cleaned and maintained. In particular, adequate space is required in all sumps to allow cleaning and maintenance of pipes, pumps and all associated equipment.

Operations

Some operational issues to be considered are:

- Bicycles and pedestrians;
- Dangerous goods;
- Control of entry in emergency (see also Section on Fire below);
- Manuals; and
- Training.

These are considered in more detail below.

Bicycles and Pedestrians

Bicycle lanes are rarely provided in road tunnels. Where provided, they should desirably be separate from the vehicle lanes and protected from vehicular traffic by a barrier.

In some tunnels without separate lanes, bicycles are only permitted at night or times of low vehicular traffic density.

Pedestrian walkways in vehicular tunnels are generally provided for exit in an emergency. These walkways should be not less than 1.0m wide and level with the top of the kerb. In addition to serving as a walkway for emergency exit, they can also be used by maintenance and traffic operations personnel.

The emergency walkway may sometimes be at a lower level with a mountable kerb between the walkway and the adjacent traffic lane so that the walkway may act as an emergency stopping place for vehicles. It may also be provided in a separate, enclosed combined services / escape void.

It is essential that the design provides a pedestrian walkway accessible to road users with a disability (drivers or passengers) without assistance.

Pedestrian emergency escape tunnels parallel to the vehicular tunnel and pedestrian refuge areas with independent air from the surface have been provided in some major tunnels (Rechnitzer et al, 1999). In some circumstances, remaining in the vehicle may be the preferred option. This allows radio re-broadcast (where provided) of emergency instructions.

However, fire combustion products can travel very quickly, thus engulfing passengers stranded in vehicles, eliminating visibility and means of egress, where otherwise an escape may have been possible earlier.

The ventilation system should be designed to draw smoke and fumes away from the danger (accident) area.

Dangerous Goods

The carriage of dangerous goods through a proposed tunnel must be considered at the earliest stages of the planning for the tunnel. Specialist expertise should be sought from the Dangerous Goods Unit, Land Transport and Safety, Queensland Transport. Factors to be considered are discussed in the following paragraphs.

Spillage of dangerous goods being transported through a tunnel may result in fire or explosion or other undesirable effects. In addition, accidents involving vehicles carrying hazardous goods may have disastrous consequences (explosion, toxic gas release, etc).

Hazardous goods may be classified according to their nature and the degree of hazard. Australia has adopted a system based on the United Nations classification, which provides for nine classes identified by a unique diamond for each class.

The classes of dangerous goods are:

- **Explosives** (substances or articles used to produce explosion or a pyrotechnic effect)
- **Gases** (gases stored in tanks or cylinders under pressure, compressed liquefied gases)
    - Flammable Gas (e.g. acetylene, LPG - liquefied petroleum gas)
    - **Non-Flammable Non-Toxic Gases** (some of these gases have oxidizing or corrosive effects e.g. refrigerated liquid air, compressed oxygen)
    - **Toxic Gases** (cause death or serious injury to human health if inhaled e.g. chlorine, methyl bromide, nitric oxide)
- **Flammable Liquids** (liquids whose vapours ignite on contact with a source of ignition and having a flash point not higher than 610°C e.g. petrol, kerosene, paint thinners)
- **Flammable, Spontaneously Reactive or Dangerous When Wet Solids**
    - **Flammable Solids** (solids easily ignited by external sources such as sparks and flames e.g. sulphur, red phosphorus, matches)
    - **Spontaneously** Combustible Substances (substances liable to heat spontaneously and ignite, particularly when wetted by water, or in contact with moist air e.g. carbon, white phosphorous, calcium dithionite)
    - **Dangerous When Wet Substances** (those evolving flammable gases when in contact with water e.g. calcium carbide, sodium metal)
- **Oxidizing Agents** (Substances which may not be combustible in themselves, but by yielding oxygen or other processes increase the risk and intensity of fire in other materials with which they come in contact)
    - **Oxidizing Agent** (When in contact with finely divided combustible materials, oxidizers may cause fire and burn with almost explosive violence (e.g. Calcium

Hypochlorite- Swimming Pool Chlorine, Sodium Peroxide)

- **Organic Peroxides** (Liquids or solids that support the burning of combustible materials. Under prolonged exposure to fire or heat, containers of these materials may explode. Decomposition of these substances may give rise to evolution of impurities such as acids, toxic and flammable gases e.g. benzoyl peroxides, methyl ethyl ketone peroxide, MEKP)

- **Poisonous, Toxic, Harmful and Infectious Substances** (Solids or liquids which are liable to cause death or serious injury to human health if swallowed, inhaled or by skin contact. Nearly all toxic substances evolve toxic gases when involved in a fire or when heated to decomposition e.g. Calcium Cyanide, Lead Arsenate.)
  - Toxic Substances (e.g. Industrial products)
  - Infectious Substances (e.g. medical waste)
  - Radioactive Goods (materials or combination of materials which spontaneously emit radiation e.g. uranium)
- **Corrosive Goods** (solids or liquids possessing in their original state, the common property of being able to damage living tissue to a greater or lesser extent. Many give vapours that irritate the nose and eyes, some are toxic and a few produce toxic products when decomposed e.g. Hydrochloric Acid, Sodium Hydroxide)
- **Miscellaneous Dangerous Goods Substances** and articles which present a danger not covered by other classes e.g. Aerosols, Dry Ice, Asbestos)

Before banning the carriage of these goods through a tunnel, a detailed risk assessment should be carried out to assess the suitability or otherwise of the route compared with the alternatives. Alternative routes may have adverse economic, social and environmental consequences or even create a higher risk of accidents.

Some studies have shown that:

- The total human risk can be higher on the longer route;
- The chance of multiple fatalities is greater in tunnels than on the alternative route;
- Economic risks on the tunnel route are higher than the alternative route if the tunnel can be destroyed.

In any risk assessment, the Dangerous Goods Unit of Queensland Transport should be contacted for advice. Further guidance may be obtained from Rechnitzer et al (1999), which describes the cause and consequences of nine accidents involving dangerous goods in tunnels internationally, and five accidents in tunnels that did not involve dangerous goods.

Although total banning of the transport of hazardous goods through tunnels may seem intrinsically desirable, such action may not be necessary as other measures may give a satisfactory solution with an appropriate level of safety.

The following strategies have been used to minimise the risk of accidents and the consequences of spillage in tunnels:

- restricting transit times;

- placing vehicles carrying dangerous goods in an escorted convoy (with or without restricting times of operation);
- product and quantity limitations;
- speed and distance limits;
- diversion to a route with lower risk;
- applying load limits;
- inspection of vehicles before entry; and
- guidance systems (caterpillar, Ariane thread, running rabbit etc).

Risk can also be reduced by limiting the consequences of a crash by passive measures such as:

- fire resistance of the structure and facilities;
- explosion resistance;
- road surfaces not likely to burn; and
- drainage systems directed into collector tanks.

Active measures to reduce the consequences of a crash include:

- continuous monitoring by closed circuit television;
- roadway inspection;
- fire detection;
- explosion proof radio communications equipment; and
- ventilation.

The monitoring of the passage of vehicles carrying dangerous goods, and the detection of spills and fire are described in the sections on “Fire, Life and Safety” and “Communications”.

In the event of a spillage or accident, immediate action is required and emergency systems should be well established and understood (appropriate manuals).

Control of Entry in an Emergency

Traffic signals should be provided at the entrance to tunnels to control entering traffic in an emergency. They should be so positioned that they can stop traffic from using one, two or all lanes in the tunnel as required. These signals can also be used in other circumstances such as:

- periods of maintenance in the tunnel; and
- times when congestion may threaten to overload the ventilation system and relief is required.

Appropriate signals and signs remote from the tunnel may also be required to divert traffic to alternative routes in times of closure of the tunnel.

For busway tunnels, direct communication with buses should be available to control their movements (e.g. diverting them to alternative routes when excessive delays in the tunnel occur for whatever reason).

Manuals

It is essential that detailed operating and maintenance manuals be kept for all elements of plant and equipment. All maintenance and repair work must be carried out safely with the utmost efficiency to give minimum disturbance to traffic.

Operating and maintenance manuals should cover:

- drawings;
- systems descriptions;
- systems performance;
- equipment description;
- manufacturers’ technical literature;

- any supplementary data available;
- operations procedures;
- maintenance procedures including expected replacement intervals of parts, test certificates and test reports.

These manuals can be more easily prepared at the design stage in conjunction with the operating personnel than at later stages of the process.

Detailed operational procedures at times of emergency must always be readily available to staff.

Training

Although accidents and other emergencies in tunnels may be infrequent, regular training sessions on emergency procedures should be carried out as any accident or spillage or breakdown of equipment may affect many vehicles and people in a tunnel.

Ventilation

Vehicle exhaust emissions contain toxic (notably carbon monoxide, CO), and noxious gases, smoke, and particulates.

In short tunnels, they may be removed by longitudinal ventilation, often assisted by roof mounted jet fans to give discharge at the portals, provided this concentration and subsequent dispersion of pollutants to the air at the exit to the tunnel is acceptable. Air quality is of particular concern in cases where economic justification for a tunnel has been partly based on the recovery of developable land over the roof slab.

For tunnels longer than 200 metres, longitudinal bi-directional smoke ventilation systems and control panels should be provided as required by the Queensland Fire and Rescue Service. Tunnel air velocities to ensure smoke and hot combustion gases do not spread upstream against the air flow (back layering) are shown in the section on “Fire, Life and Safety”.

In longer tunnels, special air ducts carry the polluted air away to selected exit points and others bring fresh air into the tunnel (transverse ventilation).

Fans regulating the ventilation are automatically controlled according to traffic volumes, pollution levels and fire detection. They must have manual override.

Traffic sensors are required to determine the number of vehicles in the tunnel and at what speed they are travelling. Ventilation needs are automatically adjusted as required to dilute the emissions from vehicles to an acceptable level in the tunnel. Carbon monoxide and smoke monitors are also required to automatically control fan speeds.

The ventilation system in a tunnel should be designed in accordance with recognized methods described in the Technical Committee Reports on Road Tunnels, to the Permanent International Association of Road Congresses (PIARC) 1987, 1991 and 1995.

Due to recent accidents in Europe, revised European standards are expected to be released.

The external noise levels of the ventilation plant should not exceed acceptable standards for nearby noise sensitive development. (Refer to the Road Traffic Noise Management: Code of Practice.)

Internal noise levels (i.e. those occurring inside the tunnel) should also be limited to acceptable levels. Typically, the maximum tunnel noise level resulting from the ventilation system, measured 1.5 metres above road level at the centreline of each traffic lane, should be not greater than 85dBA without traffic and with all fans operating at normal operating speed.

Ventilation is also necessary to disperse any smoke, which reduces visibility. The capacity of the system must be adequate to provide an increased effort over the normal operational requirement of steady through vehicle movement.

Other aspects of ventilation are:

- Portal discharge;
- Traffic monitoring;
- Carbon monoxide (CO), Nitrous Oxides (NOx);
- Visibility levels; and
- Occupational Health and Safety (OHS) requirements.

Portal Discharge

Calculations for the dispersal of tunnel exhaust gases at portals should be based on the PIARC requirements set out in PIARC Committee on Road Tunnels (1995a). Pucher et al (1999) provides discussion of this subject under Australian conditions.

The direction and effect of prevailing winds at the portal, together with plume buoyancy, must be considered. Recycling of diluted exhaust gases into fresh air intakes or adjacent portals with undesirable, but not toxic, effects can occur and must be considered in the design and location of the system.

Discharging tunnel air through a chimney vertically into the atmosphere is a more efficient way of diluting the exhaust gases than discharging at a portal. This method is commonly used on long tunnels (e.g. Sydney Harbour Tunnel, M5 Motorway tunnel, Sydney).

Traffic Monitoring

Traffic sensors are required to regulate the degree of ventilation required.

Sensors also assist in controlling traffic outside the tunnel, to allow traffic including buses to be diverted away from the tunnel when unacceptable traffic delays, for whatever reason, occur in the tunnel.

Carbon Monoxide (CO), Nitrogen Dioxide (NO2) and Visibility Levels

Carbon monoxide (CO) is the most dominant of the toxic vehicle gas emissions.

About 10% to 20% of the emitted nitrogen oxides (NOx) are converted to nitrogen dioxide in very long tunnels.

Visibility is reduced by the attenuation of light by small suspended particles in smoke. The particles absorb and scatter light reducing the amount reaching a driver's eye.

A light beam continually loses its intensity as it travels through smoky air. The process is defined in the formula:

$E = E_0 \times e\text{-}^{KL}$

Where

E = light intensity after travelling the distance L in smoky air

E_0 = light intensity at the beginning

e = base of natural logarithms

K = coefficient of extinction ($m\text{-}^{1}$)

L = length of light ray between emission and reception (m)

In tunnel ventilation, visibility is usually expressed by the extinction factor, K.

K = 0.005/metre - indicates clear tunnel air with visibility several hundred metres.

K = 0.007/metre - indicates a slight haziness of the tunnel air.

K = 0.009/metre - indicates an air quality providing a foggy impression.

Variations in peak visibility may occur during the day when, for example, several diesel trucks are in line, or when the ventilation is adjusting to cater for peak requirements.

Turbidity is sometimes used for the term "visibility" as defined above and in PIARC publications.

For tunnels under 300m in length, the following criteria must be met:

- Carbon Monoxide (CO): 100 ppm maximum for a 15 minute exposure period.
- Nitrogen Dioxide (NO2): 1.5 ppm maximum allowing for conversion of 10% of NOx to NO2 within the tunnel (allow for background levels of pollution in intake air).
- Visibility: K = 0.005/m maximum for free flowing traffic.

It is desirable that CO and smoke monitoring systems be installed and employed to increase the fan speeds automatically when required to deal with changes in concentrations of these gases.

Occupational Health and Safety (OHS) Requirements

For maintenance purposes, the design of walkways and access to equipment should meet OHS requirements for confined space, working conditions and safety. Air quality during maintenance should meet the requirements defined by PIARC Committee on Road Tunnels (1995a).

Bus tunnels require consideration of longer-term driver exposure.

Fire, Life and Safety

Fires in tunnels are usually caused by mechanical or electrical faults in vehicles; less frequently by accidents; and rarely by mal-functions of the installations in the tunnel.

Automatic temperature activated detectors are preferred to smoke detectors and there should be sufficient to cover the whole length of the tunnel.

Ventilation and other tunnel equipment must remain in operation for a sufficient period before failure to aid evacuation.

The desired goal is to provide an evacuation path from the tunnel and to facilitate fire fighting operations.

The highest priority in the event of a fire is the saving of life followed by the saving of property. Design and documentation of proper procedures for these situations are essential (see "Manuals" above).

Major design considerations for fire protection include:

- Fire type (cellulose or hydrocarbon);
- Detection;
- Smoke control;
- Load for ventilation purposes;
- Built in redundancy of equipment;
- Deluge / drencher systems;
- Flame proof pits;
- Foam;
- Fire hydrants;
- Evacuation egress;
- Dual drainage system; and
- Fire engineering design brief.

Evacuation Egress

In short tunnels, the tendency will be for the public to exit through the portals in times of emergency. An adequately lit route (walkway or roadway) to the portals should be provided.

NFPA 502 (NFPA, 2001) and the Emergency Services suggest that there should be an emergency exit door at each fire hydrant location with suitable supporting emergency communications.

Where there are two tubes (parallel tunnels separated by a wall), emergency doors allowing exit from one tube into the other are suitable. It would be an extremely remote possibility that an accident/emergency would occur on both sides of the wall at the same time. Footways of sufficient width to avoid doors opening into, and discharging people into the traffic lane are required. Appropriate warning lights in the tunnel being entered would also alert drivers in that tunnel to the emergency evacuation.

The doors of emergency exits should be smoke and toxic gas resistant, signed and lighted for easy recognition as an emergency exit. When opened, these doors should not obstruct the sight distance of traffic.

Detection

Fire detectors should preferably be of the linear fine wire type, which respond to increase in radiant heat. The detectors should cover the full length of the tunnel and automatically call the Fire Brigade in a Direct Brigade Landline when required.

Manual call points complying with AS 1603.5 for use by motorists, as well as fire warning bells, should be provided .

Smoke Control

For longitudinal ventilation, as soon as fire/smoke is detected there should be an automatic increase in fan speeds to help disperse the smoke and prevent back layering (moving upstream of the fire) from taking place.

Tunnel air velocities to stop smoke from spreading upstream should be greater than 3m/s. Maximum adverse wind speed should be 6m/s to cope with buoyant combustion product spread.

It should be noted that the thermal effects of fires significantly reduce tunnel airflows compared to non-fire situations. Airflow reductions of the order of 1 to 11 percent for a 10 MW fire and 51 to 62 percent for a 100 MW fire have been observed (Brisbane City Council, 1999).

As ceiling temperatures may be very high in a fire (8000°C in a test school bus fire, Rechnitzer et al, 1999), it should be assumed that at least one fan set would be made non-operational in a fire.

The required rating for smoke fans and wiring is 2 hours at 2500°C for a design fire of 30MW (truck) with allowance for de-rating to allow for operation in a hot smoke stream. In the longer tunnels, exhaust fans may remove the smoke through special conduits rather than blow the smoke longitudinally through the tunnel.

Fire Load for Ventilation purposes

For short tunnels (less than 300m) where dangerous goods are not permitted, the smoke ventilation design criteria shall be based on a 30 MW fire, equivalent to that from one bus or truck.

For longer tunnels, the design fire shall be 50 MW (equivalent to a petrol tanker).

Built in Redundancy

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It should be assumed in ventilation design, that one fan set becomes non-operational in a fire because of the high temperatures reached in the vicinity of a fire.

Deluge / Drencher System

Deluge or drencher systems, when activated, discharge at least twice the volumetric rate of water per minute than sprinkler systems for ordinary hazards (AS2118.1, 1999).

Water sprinklers or deluge systems using water are not always provided in tunnels because (PIARC, 1983):

- sprinklers (and the relevant codes) are primarily for fires in buildings. Sprinklers do not lend themselves to extinguishing vehicle fires as the vehicles are designed to shed water and keep the interior dry;
- contact with water can produce dangerous reactions with some materials;
- the steam produced can reduce visibility; and
- metal does not cool quickly even when the flames are extinguished. This means that spilt petrol continues to vapourise and may produce an explosive mixture even after the fire has been extinguished. The danger is even greater if the fuel is LPG.

Sprinklers, if fitted, should include an aqueous film forming foam (AFFF) to further prevent potential for ignition. Combined foam and water in accordance with NFPA 16 (NFPA, 1999) may also be appropriate. A range of systems is available and details should be sought from the references.

Flame Proof Pits

With the use of deluge systems, flames may be carried down from gullies into the drainage sumps. The drainage system should therefore be flame proof.

Closed sumps should have forced ventilation with duty and standby extraction fans. A gas detection system should be provided to automatically trigger an inert gas foam extinguisher if hydrocarbons are detected. Monitoring of pumping operations should be provided at a Control Centre.

Foam

The benefits of adding foam to deluge systems are obvious, particularly when dangerous goods are allowed in a tunnel, but it should be recognized that fire fighting foam is not effective against all dangerous goods (including alcohol), and other contingencies should be planned.

Fire Hydrants

Tunnels should have a Fire Hydrant System in accordance with AS 2419.

The hydrants should be placed at each portal and at evenly spaced locations not more than 90 metres apart within the length of the tunnel. This distance is consistent with standard hose lengths available.

Fire hydrants should be single head complying with AS 2419.1 - 1994, Fire Hydrant Systems - Design Installation and Commissioning or double headed complying with NFPA 502 (NFPA, 1999a).

Portable fire extinguishers, preferably of the dry chemical type, should be placed in the Central (Fire) Control Room and other selected locations. The spacing to be adopted depends on the length of the tunnel and at least one extinguisher per direction of travel should be placed in short tunnels (100m maximum spacing). The location of extinguishers should be coincident with pull-off bays where these are provided.

Dual Drainage System

The use of deluge sprinklers indicates the need for a dual drainage system to carry the water excess to normal operations away from the tunnel carriageway.

A flame-proof drainage system is required.

Fire Fighting Access

The route for fire brigade vehicles and access for fire fighting equipment must be identified and written into operating manuals for use in emergencies.

Fire Engineering Design Brief

Before detailed design of a tunnel is undertaken, a Fire Engineering Design Brief should be prepared and approved.

This brief should specify the design considerations relevant to a fire or emergency situation (see other parts of this section). This would include aspects of ventilation, drainage, emergency lighting, communications, structures and all considerations in this section.

In addition, the Brief should require the designer to provide:

- a detailed Manual for operational procedures in an emergency;
- a hazard analysis for the tunnel; and
- a quantitative risk assessment.

Lighting

Lighting at the portals of tunnels must allow drivers to readily adapt their eyesight to see the road carriageway and its limits, signs and road markings when entering or leaving a tunnel.

Tunnel lighting must make allowance for the differing light conditions external to the tunnel under all weather conditions at both the entrance and exit. The tunnel lighting is therefore zoned to allow sufficient time for the eye to adjust.

For a driver entering from sunlight, the illumination at the portals should be of a relatively high level reducing progressively to the tunnel lighting level. At night, illumination at the portal equal to that in the tunnel would be appropriate.

Luminance of 3 - 10 candelas/m2 for daytime lighting and 2 - 2.5 candelas/m2 for nightime levels is adequate (PIARC Committee on Road Tunnels, 1995c).

At the exit, the same level of illumination as at the entrance is appropriate. However, at the exit, it is preferable that a driver is not looking directly into the sun. Section 10.2.5 (Chapter 10) gives a method for determining the sun’s position and altitude (in degrees above the horizontal plane) for South and North Queensland (those for other locations may be interpolated).

Adjustment to the lighting levels may be required in short tunnels where the driver can see the exit from the entrance and this appears as a bright light at the end of a dark tube. The tunnel lighting would have to be brighter to mask this effect.

Appropriate reflectivity (60%) of the walls of a tunnel enhances the lighting within the tunnel. It is important to keep the walls clean to retain this enhancement.

Emergency lighting will be required to provide adequate illumination for evacuation in the event that the primary source is made inoperable in an accident.

Zone Lighting

Design of lighting in tunnels should be in accordance with:

- CIE 88-1990;

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- CIE 61-1984 for tunnel entrance lighting; and
- CIE 31-1976 (TC-46) for glare and uniformity in road lighting installations.

In a one way tunnel, five zones are considered for illumination design. Moving progressively into and along the tunnel, they are:

- the access (just outside the tunnel entrance);
- the threshold;
- the transition;
- the interior; and
- the exit.

In practice at least four daytime switching levels and one night time switching level on the light control panel are required to accommodate the potential variations in lighting conditions.

Counter Beam

A lighting system which produces high road surface luminance and low vertical illuminance gives relatively high contrast values for most objects on the road. Such a system will only be obtained when the lighting distribution is longitudinally asymmetrical and preferentially directed towards the driver (CIE88 - 1990).

Wall Panels

Wall panels with height 3.5m above the road carriageway and with 60% reflectivity are suitable internal fittings for tunnels. They are required to enhance the lighting in the tunnel, thereby reducing the light emission required from the luminaires, and producing a satisfactory result at optimum cost.

They should be non-corrodible, resistant to impact and abrasion, non-combustible, resistant to flame spread and easy to clean. In addition to their other properties, they should be coloured to provide an attractive internal environment and to highlight safety facilities.

Emergency Lighting

At least 15% of lighting should be maintained during emergencies (provided by Uninterruptible Power System - UPS).

Strip lighting no higher than door height along the tunnel walls may serve as emergency lights.

Communications

It is essential that communications be functional at all times in a tunnel, not only in a fire or emergency situation, but also for monitoring and maintenance operations.

The following functions are desirable:

- Control centre linked to existing communications providers;
- Closed circuit TV (CCTV);
- Radio rebroadcast;
- P.A. system with radio interruption;
- Emergency telephones;
- Mobile telephones rebroadcast;
- Staffing and traffic control centre;
- Speed cameras; and
- Bus radio rebroadcast.

The system should be designed to provide automatic incident detection as an integral part of the control systems. The elements of the system are included in the individual components described in this section and the sections on Fire, Electrical, Ventilation and Lighting. These must be designed as an integrated system to provide the level of incident detection required.

Control Centre Location

It is essential that a 24 hour manned control centre be established or maintained to receive all monitoring and emergency electronic messages from a tunnel where these facilities are installed. It is not essential that this control centre be at the tunnel itself, although this would be desirable.

Any signal denoting a fire should be automatically sent to a nearby Fire Brigade Station as well as the tunnel control centre.

Closed Circuit Television (CCTV)

CCTV allows continuous monitoring of the tunnel. The system should allow the operator to zoom in to all sections of the facility. Cameras should be located to facilitate this operation

Radio Rebroadcast

A radio rebroadcast where a message from the Tunnel Control Centre can override all local radio AM and FM stations is a most effective way of conveying a clear message for vehicles both inside and outside the tunnel (once radios are turned on). Instructions to turn the radio on can be achieved by using P.A. systems or variable signs. The design should allow for these systems.

P.A. System with Radio Interruption

Public address systems are not always clear or readily understood. However, they are much more effective once traffic is stationary. A simple message to turn radios on for more detailed messages would give a good combination of P.A. system and radio.

Help Telephones

Help telephones on the side of tunnels for use in vehicle breakdowns or accidents would be justified in the longer tunnels but considered desirable rather than essential in shorter tunnels. Spacing of these phones at 60 - 100m centres should be considered.

Mobile Telephones Rebroadcast

It is possible to make mobile cellular telephones work in a tunnel and have a message from the Tunnel Control Centre override other use.

It is illegal for drivers to use mobile telephones without a “hands free” facility in moving vehicles. However, such telephones are available to drivers with hands free facilities and to passengers in buses and cars. In addition, tunnel operational and emergency services staff can make use of these telephones.

Monitoring

The design should provide for:

- smoke and fire detectors;
- carbon monoxide monitors;
- manemometers for air velocity measurement;
- transmissometers for visibility measurement; and
- traffic sensors for ventilation needs.

All of these units are required in automatic monitoring systems in tunnels to provide essential data for the management and operation of the tunnel.

To stop over height vehicles from entering a tunnel, there should be a steel height barrier and appropriate surveillance at a suitable distance before the entrance to the tunnel. The devices should be located at a place where the offending vehicle can be removed from the traffic stream without preventing other traffic entering the tunnel.

Structural Design

Structural considerations include:

- Fire rating;
- Concrete and other cladding;
- Waterproof membrane;
- Structure design life;
- Pavement design life;
- Pavement wearing surface; and
- Loading on roof.

Fire Rating

The tunnel structure, structural lining and communication services should have a fire resistance level of 4 hours.

A fire load of 30 MW (approximately equal to one bus or truck burning) should be adopted for tunnels less than 300m long where dangerous goods are prohibited. For tunnels longer than 300m, or where dangerous goods may be carried, a 50 MW fire load should be adopted.

Concrete and Other Cladding

Concrete roofs and other structural components may be made thicker than required for structural design to make them fire resistant. Alternatively, vermiculite, perlite or proprietary products may be used for the same result.

As an example, the cost of an extra 100mm thickness of concrete cladding on one roof was judged to be equivalent to 40 mm thick cladding of a proprietary product. Each case would have to be assessed on its merits.

Testing of all materials should be in accordance with AS 1530.4 "Methods of Fire Tests on Building Materials, Components and Structures - Fire Resistant Test Elements of Building Construction".

Waterproof Membranes

Waterproof membranes and geotextile drainage layers may be used on roof slabs in tunnels.

The waterproof membrane should be seamless over the full length of the roof slab extending down to cover the joint between the roof slab and the walls. In addition, for cut and cover sections of the tunnel, a protective layer over the membrane is required to prevent rupture in the event of excavation over the tunnel, and during backfilling.

In driven tunnels, the full lining is drained by a geotextile extending to the tunnel invert.

Structure Design Life

The tunnel design life is usually 100 years.

Pavement Design Life

Pavement design life required can range from 25 to 40 years. An economic analysis should be carried out to determine the most cost effective solution. Issues to consider include:

- Frequency of rehabilitation;
- Cost of disruption to traffic during rehabilitation operations;
- Capacity to overlay within the vertical clearance provided;
- Volume and type of traffic (if a heavy duty pavement is required, a life of 40 years is required).

Pavement Wearing Surface

The wearing surface required will depend on:

- Life required (see above);
- Aquaplaning potential;
- Friction resistance required;
- Noise generation;

- Susceptibility to damage by oil droppings and spills.

Surfaces used have varied from concrete to asphalt, depending on the circumstances.

Loading on Roof

Tunnel roofs should obviously be designed for existing loads such as buildings and earth pressures.

They should also be designed for any future development above the tunnel when constructed, including roads etc. Particular attention should be paid to these locations so that the tunnel roof is not weakened during a fire.

Electrical

Considerations include:

- Dual supply (separate substations);
- UPS (Uninterruptible Power System);
- Manual override; and
- Fire resistance of wiring.

Dual Power Supply

It is essential that electrical power to tunnels be uninterrupted for ventilation and other safety reasons.

Two sources of supply from a power company are required; each rated to supply the full load of the tunnel electrical system with an automatic transfer system to enable selection of the available supply. During operation, both could be running at fifty percent capacity, and on the failure of one, the other would automatically be boosted to one hundred percent power output.

UPS (Uninterruptible Power System)

In the event that both services of supply from the power company are not available, a UPS (Uninterruptable Power System) comprising batteries or backup diesel generators should provide power for essential loads for 30 minutes at least, and 15% illumination level for 120 minutes.

Essential loads are:

- communications and monitoring equipment;
- ventilation;
- computer and safety facilities;
- signage;
- emergency power outlets; and
- 15% of lighting evenly distributed along the tunnel.

UPS for pumping equipment may be necessary depending on the circumstances and upon the design adopted. UPS for smoke removal ventilation should be in accordance with the requirements of the Queensland Fire Service.

The UPS system must include automatic static transfer switching of essential loads in case of system fault, or mains supply failure.

Manual Override

A manual override of control systems may be provided at the portals for use by authorized Emergency Services Authorities.

Fire Resistance of Wiring

A fire rating of 2 hours at 2500°C is required for the design fire load.

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Relationship to Other Chapters

- Cross-references to Chapters 5 and 7 occur throughout;
- Detailed geometric elements must be derived from the relevant chapters;
- Chapter 19 will define the ITS requirements referred to in the section on tunnels.