1 General Principles for the Design of the Cross-section

1.1 General

The shape and size of the design cross-section derive firstly from the purpose of the tunnel (rail tunnel, road tunnel, sewer, water tunnel or pressure tunnel for a hydropower station) and thus the required clearance gauge. Secondly, the dimensions will also be influenced, as is the alignment, by the geotechnical or structural conditions in the ground to be passed through; whether earth or water pressure could occur or whether no external loading is to be expected. Thirdly, the construction process also has an effect on the design of the cross-section; for a given clearance gauge, the most economic cross-section is that which can be constructed with the least excavation and support technology and with the optimal machinery, taking into account the given basic shape.

1.2 Dependence on intended use

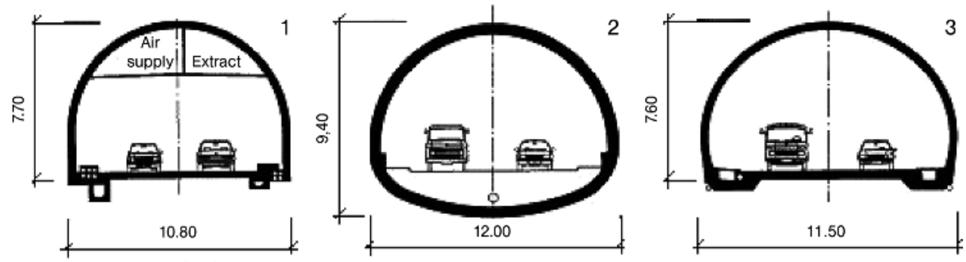
1.2.1 Road tunnels

General. The traffic conditions in a road tunnel should in principle correspond to those in the open air. Road tunnels are, however, special sections of a road and demand stringent requirements for their construction, maintenance and operation. Road tunnels have to meet particular requirements regarding road safety and operational safety. When the needs of traffic management are balanced against economy, it is therefore necessary and justifiable in many cases to limit the speed compared to parts of the road in the open air. The permitted maximum speed is thus normally limited to 80 km/h in road tunnels, which inevitably differentiates the traffic flow in tunnels from roads in the open air.

Tunnel cross-section. Road tunnels with two-way traffic and those with one-way traffic are fundamentally different. Two-way tunnels normally consist of a single tube with one lane in each direction. In one-way tunnels, the traffic in each direction is constructionally separated, for example through the provision of two bores. While in the past each bore was often laid out with two lanes without a hard shoulder, the changing composition of the traffic and ever increasing traffic loading will also demand three lanes without hard shoulder, and in exceptional cases even three lanes with a hard shoulder.

The design of the cross-section of road tunnels has to consider road traffic aspects, operational equipment and the tunnel structure. The design of the cross-section of a cut-and-cover road tunnel is often subject to different constraints from a mined underground tunnel. Some examples of cross-sections of mined road tunnels are shown in Fig. 1-1.

Handbook of Tunnel Engineering II – Basics and Additional Services for Design and Construction. First English Edition.
Bernhard Maidl, Markus Thewes, Ulrich Maidl.



1 Gotthard Tunnel, Switzerland 1969 to 1980
2 Westtangente, Bochum 1980 to 1981
3 Rennsteig Tunnel, Thuringia 1998 to 2003

Figure 1-1 Cross-sections of some mined road tunnels.

The starting point of all considerations does, of course, remain the space required for the road intended to run through the tunnel. The required total cross-section can often be twice that of the actual cross-section for traffic, and the cross-sectional area at breakdown bays of autobahn tunnels can be up to 200 m^2 and more. The space required is also influenced by the horizontal and vertical alignments selected for the project.

The design of tunnel cross-sections in Germany is based on the guidelines for the equipment and operation of road tunnels (RABT) [77], also taking into account the guidelines for road design; cross-sections (RAS-Q) [76] and alignment (RAS-L) [75]. These guidelines include requirements for the standard cross-section, the structure or vehicle gauge to be maintained, the transverse and longitudinal gradients in tunnels and the provision of breakdown bays and emergency exits.

Standard cross-section. The standard cross-section of a road tunnel has to provide dimensions to enable the installation of equipment like lighting, ventilation, traffic management and safety technology, normally outside the clearance gauge. Particularly ventilation and signage equipment may demand an enlargement of the tunnel cross-section. In order to limit the multitude of possible cross-sections – also for economic reasons – the standard cross-sections of roads in the open air are assigned to road cross-section types in tunnels. The selection of road tunnel cross-sections is carried out according to [33] (Fig. 1-2).

In tunnels intended for two-way traffic, the standard cross-section type 10,5 T with 7.50 m paved width between the kerbs is normally provided. This cross-section is also used in open-air sections where wider verges are provided due to high heavy goods traffic volumes. In the course of a road with 2 + 1 RQ 15,5 sections (two lanes with an overtaking lane), sections running through tunnels are also constructed to section 10,5 T. The overtaking lane in this case thus has to be terminated in good time before the tunnel. Special solutions like an additional crawler or climbing lanes in the tunnel are an exception. When in exceptional cases tunnel sections on main roads only provide RQ 9,5 section, cross-section 10,0 T should be used [33].

The normal layout in tunnels with multi-lane carriageways in one direction should be a reduced standard road section without hard shoulders (26 t or 33 t), although it is justifiable under certain economic or traffic conditions to provide hard shoulders. Economic aspects in this case could be the construction and operating costs resulting from the length of the tunnel or the costs resulting from congestion and accidents. The hard shoulders are available for vehicles to swerve to the side or stop in an emergency. They often allow continued multi-lane traffic flow after minor accidents or breakdowns and also simplify maintenance work without serious disruption of traffic flow. The width of hard shoulders varies depending on cross-section type (Fig. 1-2). It is

– for cross-section type	29,5 T	2.50 m.
– for cross-section types	26 T and 33 T	2.00 m.
– for cross-section type	26 Tr	1.50 m.

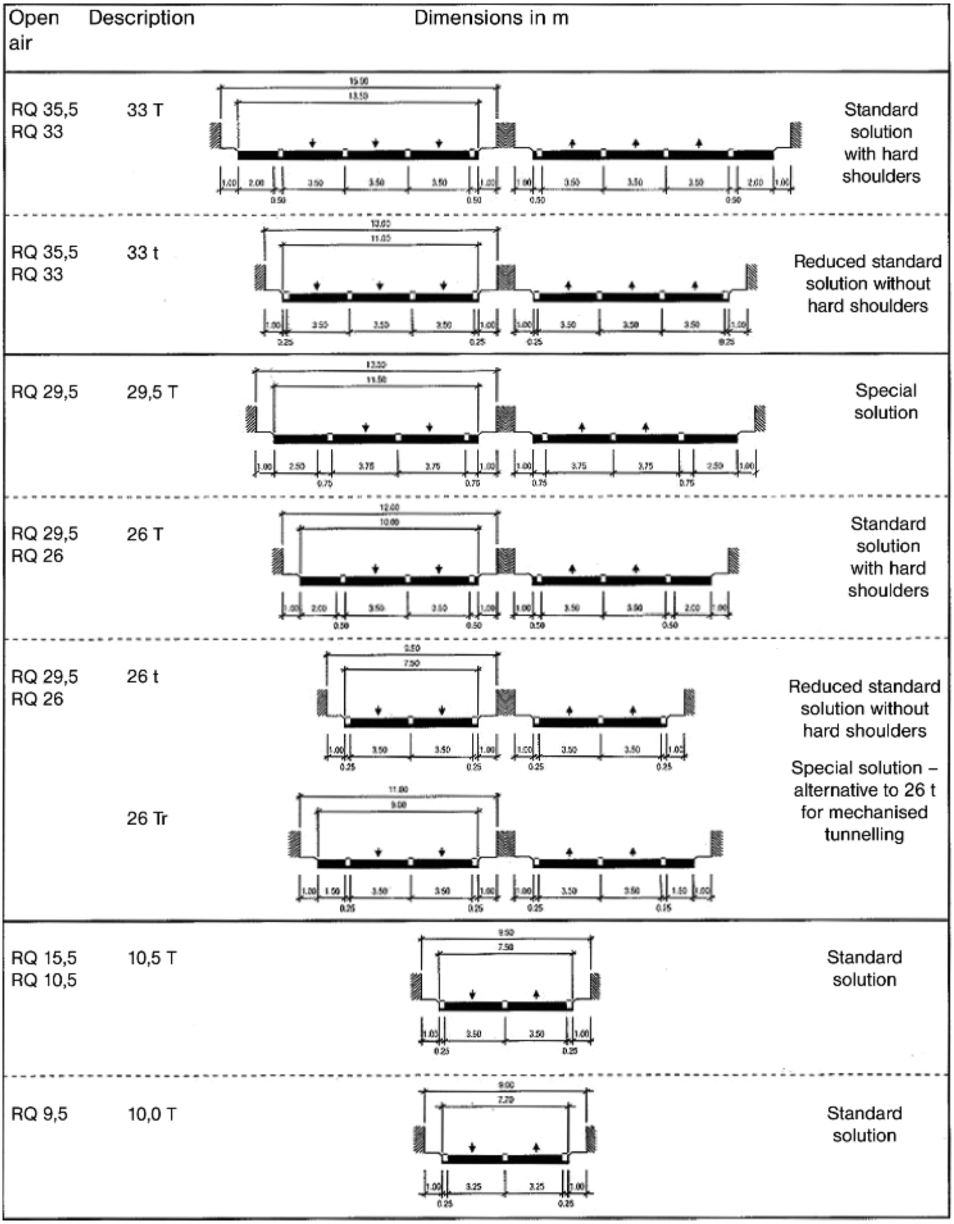


Figure 1-2 Standard cross-sections for road tunnels [33, 77].

For the layout of hard shoulders in tunnels, reference should be made to [33]. Using this decision-making process, it should be checked whether the additional utility resulting from a hard shoulder exceeds its extra cost. Using the diagrams for use with this process, it can be seen that the decision to provide the cross-sections with hard shoulders (26 T or 33 T) can only be justified under very favourable construction conditions or with a high volume of heavy good vehicle traffic combined with steep gradients. This process applies for multi-lane carriageways in one direction in road tunnel up to 2,000 m long.

The reduced form of special cross-section 26 Tr should only be considered for tunnels to be driven with shield machines. In this case, the reduced hard shoulder replaces the otherwise necessary breakdown bays along the entire length [33].

Cross-section type 29,5 T is only worth considering for very unusual cases and in any case only for very short tunnels with an exceptionally low-cost construction method.

Clearance gauge, traffic gauge. The clearance gauge denotes the space for the road cross-section, which has to be kept clear of obstructions. It consists of the traffic gauge and the safety margins at the top and the sides. The necessary cross-sectional area of the clearance gauge ensues from the traffic purpose of the tunnel. It is derived from the applicable standard cross-section in the open air; the permissible restriction of the cross-section inside structures also has to be considered (RAS-Q [76]).

The total width of the clearance gauge is the sum of the widths of the side safety margins, the carriageway, the verges and any additional lanes (for example hard shoulders) (Fig. 1-3).

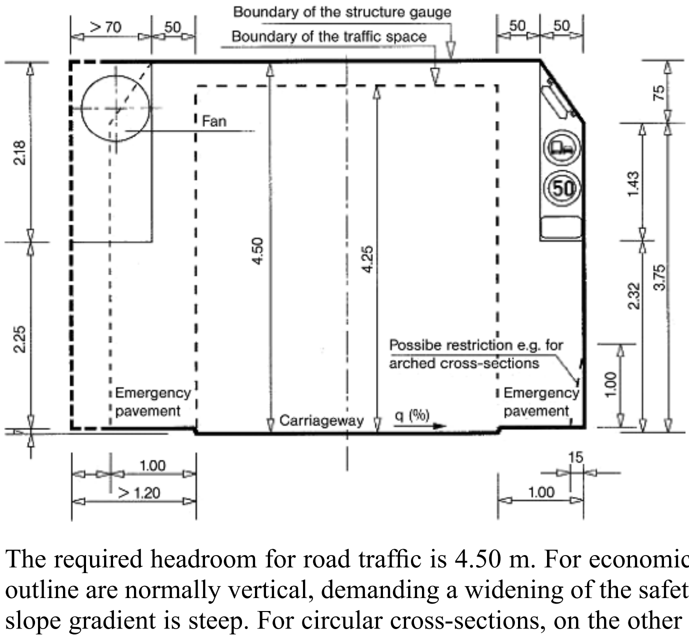


Figure 1-3 Outline of the clearance gauge in road tunnels (standard solution) [77].

The required headroom for road traffic is 4.50 m. For economic reasons, the sides of the outline are normally vertical, demanding a widening of the safety margin when the cross-slope gradient is steep. For circular cross-sections, on the other hand, it can be economic to tilt the clearance gauge with the carriageway. The outline at the sides can then be assumed to be vertical to the carriageway. It is not necessary in such cases to widen the safety margin.

The outline of the clearance gauge includes areas solely reserved for traffic. Emergency pavements are provided on each side of the carriageway, which are 1.00 m wide and have to have clear headroom of 2.25 m. These are separated from the carriageway with kerbs, normally 7 cm high. Part areas are assigned at a height > 2.25 m above the emergency side pavements, in which easily deformable furniture elements particularly traffic signs and notices can be located although these are only permitted to approach within 50 cm of the traffic gauge; jet fans required for ventilation have to be installed in niches or ceiling coves. Easily deformable light fittings are only permitted to approach within 50 cm of the traffic gauge at a height of > 3.75 m. If jet fans are located inside the normal structural dimensions, this results in widenings of the emergency pavements dependent on the diameter of the fans to be installed [77].

It is often practical to locate traffic signs on the end walls of breakdown bays. In exceptional cases, traffic signs can by located down to a minimum of 30 cm from the traffic gauge at a height > 2.25 m above the emergency pavements; but this does not apply where a widening of the emergency pavement has been provided for fans. If traffic signs have to be made with smaller dimensions than stated in the regulations [32], then this has to be agreed with the authority responsible for traffic management.

Light fittings are permitted to approach within 50 cm of the traffic gauge in exceptional cases when it can be ensured that a clear headroom of 4.10 m from the top of the emergency pavement to the underside of the light fitting is maintained at all points. Jet fans with external diameters ≤ 70 cm are permitted in exceptional cases to be located in the safety margin with a minimum distance at the side of ≥ 30 cm to the traffic gauge in the upper corners.

Gradient and cross-slope. According to the RAS-L [75], the gradient in uninhabited areas running through tunnels should be limited to 4 % if possible and a maximum of 2.5 % should be the intention, particularly for longer distances. The chimney effect, which also increases with increasing gradient, normally leads to higher longitudinal flow, which in case of fire can severely impair the rapid and effective removal of smoke by a ventilation system. In order to ensure road safety and due to the chimney effect, gradients steeper than 5 % should be avoided in road tunnels in uninhabited areas.

A minimum cross-slope of 2.5 % is specified for straight stretches in order to drain surface water [76]. Depending on the design speed, the cross-slope may have to be adapted to suit the curve radius [75]. In addition to these conventional requirements, the cross-slope of roads in tunnels has special significance in case of an accident. If a fire breaks out, any leaking flammable liquids have to be drained away as fast as possible, which is ensured by a steep cross-slope and high-capacity drainage. Slot channels with a capacity of 100 l/s should therefore be provided, with firestops spaced at max. 50 m [77].

1.2.2 Constructional measures for road safety in tunnels

Breakdown bays. Breakdown bays should be provided where the provision of hard shoulders is not economically justifiable. They are required in tunnels more than 900 m long, and under special conditions from 600 m (for example ≥ 4,000 HGV · km / bore and day) [77]. The end wall should have an angle of ≤ 1:3 in the travel direction (Fig. 1-4). It can be secured by suitable passive protection according to RPS [78]. Concrete protection walls should have an angle ≤ 1:3. In tunnels with two-way traffic, these requirements apply to both end walls.

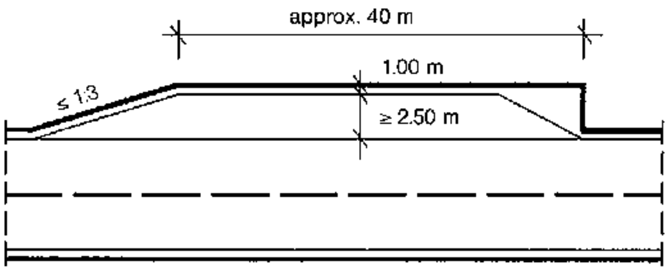


Figure 1-4 Dimensions of a breakdown bay next to a carriageway [77].

The spacing of breakdown bays should be ≤ 600 m in each direction. In tunnels with two-way traffic, the breakdown bays should be arranged opposite each other in order to enable vehicles to run in case of emergencies (turning bays).

Emergency exits, escape and rescue routes. Escape and rescue routes, which are to be signed and have lighting, should be provided in tunnels and the escape route in the traffic gauge should lead to the emergency exit and the rescue route from the emergency exit should lead to the open air directly or through safe areas.

From a tunnel length of ≥ 400 m, emergency exits should be provided at a regular spacing of ≤ 300 m [77]. Emergency exits can lead

- into the open air.
- directly into the other tunnel bore.
- through cross-passages into the other tunnel bore.
- to escape and rescue shafts.
- to escape and rescue tunnels.

Cross-passages in this case denote connecting structures between two parallel tunnel bores. They should be closed from each tunnel bore with doors. In two-bore tunnels, every third emergency access to the other bore can be designed to allow passage for fire service and emergency service vehicles in case this is required by the safety and rescue plan.

In escape and rescue shafts, escaping people are led up stairs to the open air. The stairs have to be 1.50 m wide for two-way access. The design of escape and rescue shafts should give reasonable consideration to the limited physical capabilities of disabled and older people.

Escape tunnels normally run parallel to the tunnel and connect various emergency exits from the tunnel to a common exit into the open air. The gradient should not be more than 10 % and they should have a clear passage of 2.25 m × 2.25 m.

In exceptional cases for tunnels with a high traffic volume, it can be practical to make escape tunnels more than 300 m long accessible for emergency service vehicles. This measure should however be verified as part of an overall safety plan.

The equipment of road tunnels with lighting and ventilation for normal operation and in case of fire, with drainage and also communications equipment, fire detector and extinguishing systems all pose additional requirements for the design of the cross-section. These requirements can lead to various solutions depending on the local conditions and should thus be decided for each project.

1.2.3 Rail tunnels

General. The first rail tunnel in Germany was built near Oberau in the years 1837 to 1839 and had a length of 512 m. The oldest tunnel that is still in operation is the 691 m long Busch Tunnel near Aachen, built from 1841 to 1843. Most of the tunnels that are still in operation were built in the years 1860 to 1880. These had to be maintained at greet cost through the 20^{th} century [118]. The cross-sections of early tunnels were mainly based on the clearance gauge for rolling stock. The clearance gauge encloses the cross-sectional area, into which no part of the train may extend.

For rail tunnels, the horseshoe profile was generally used, in a higher form for single-track tunnels and a flatter form for two-track tunnels. It can also be designed with vertical inner side surfaces. Today an arched profile with or without invert vault is more commonly used for conventionally driven tunnels, and a circular profile for tunnels bored by shield machines. In addition to the cross-sectional areas required for the rolling stock and tracks including signal lamps, contact shoes and any other necessary accessories, rail tunnels require a loading gauge that allows for deviations of the wagons through snaking, for example as a result of broken springs. In addition to the loading gauge determined in this way, space also has to be provided for signals, overhead, cables, lighting, pipes and other equipment required for rail operations and escape routes.

At stations, the tunnel has to be enlarged to house the platforms. It is important for rail operations that the platform is wide and long enough not to obstruct rail traffic, including consideration of traffic peaks. For this reason it is much better to provide sufficient space for platforms in advance than to be forced to undertake rebuilding measures later due to insufficient capacity [93].

Rail tunnel on new high-speed lines (NBS) of German Railways DB AG are designed according to the planned use and the resulting design speed v_E. This is categorised by new regulations (Ril 853) into four categories:

- High-speed traffic with 230 km/h $< v_E <$ 300 km/h.
- Express traffic with 160 km/h $< v_E <$ 230 km/h.
- Passenger and goods traffic with $v_E <$ 160 km/h.
- S-Bahn, urban transit with $v_E <$ 120 km/h.

The gradient on main lines should be limited to 12.5‰ and on urban and side lines 40‰. The permissible gradient should be laid down for each individual case and can, like for example in the Irlahüll Tunnel on the NBS Nuremberg – Ingolstadt at 14.5‰, also lie outside the ideal value stated above. A lower limit should also be maintained – depending on the planned use – of 2‰ (tunnel length $l <$ 1,000 m), or 4‰ ($l >$ 1,000 m). Ideally, the vertical alignments of tunnels should be ramps with the gradient in one direction for fire protection reasons.

The permissible curve radii should be limited to

$$2{,}000 \text{ m} < r_A < 30{,}000 \text{ m}$$

and determined more precisely from the design speed within this range.

The size and shape of the excavated cross-section depend on the loading gauge of the train, the lining thickness and the construction process. Depending on the various planned uses, the guideline Ril 853 specifies different track spacings in tunnels and thus various sizes of cross-sections. An enlargement of the cross-section compared to previous regulations is necessary because high pressures are created when two trains pass each other in a tunnel at high speed. The sudden change of pressure can reduce the travel comfort of the passengers in a small tunnel and more seriously can cause stresses in the windows that endanger operations.

In the following section, the most important parameters demanded in Ril 853 for the cross-sections of rail tunnels are described, depending on the planned use:

1. Tunnels for high-speed traffic at 230 km/h < $v_E \leq$ 300 km/h

In new construction and major refurbishments, the standard track spacing in straights and curves should be exactly 4.50 m, with a specified formation width of 12.1 m and a distance of the track centre to edge of formation of 3.8 m. The radius of the cross-sectional area is specified as 6.85 m for two-track tunnels, resulting in a total area above top of rails (TOR) of A = 92 m^2. The same total area results for the case of a three-centred arch for two-track traffic, for which radii of R_1 = 6.85 and R_2 = 4.00 m should be selected (Fig. 1-5). The permanent way can consist of a ballastless track or tracks laid on ballast. This choice then influences further parameters of cross-section design but not the total area of the cross-section. Details of these minor differences can be found in Ril 853.

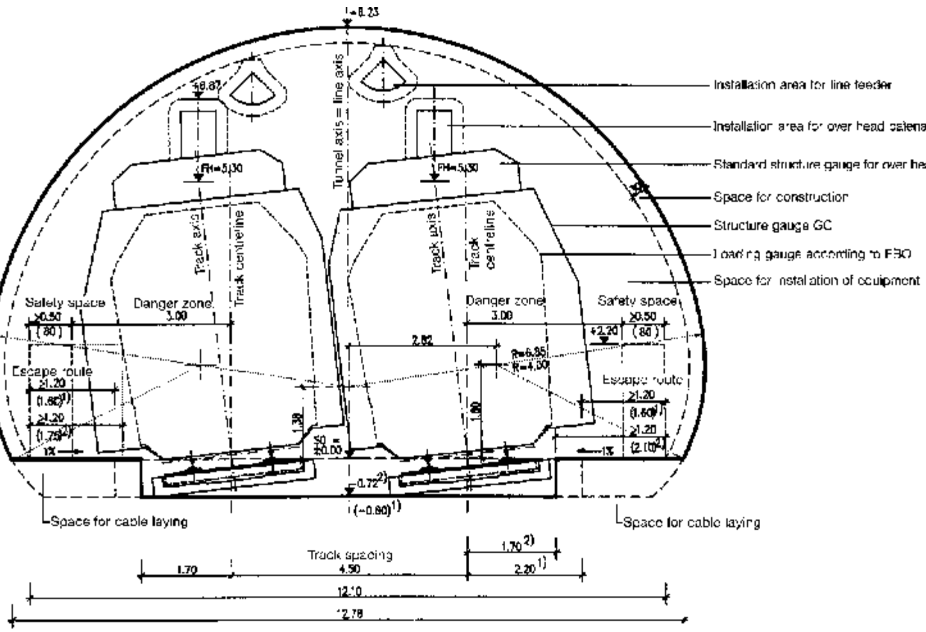


Figure 1-5 Guideline detail for a two-track high-speed tunnel with three-centred arch section according to Ril 853.

In new construction and major refurbishment of single-track tunnels, a safety space has to be maintained on the side of the cable trough, and in multi-track tunnels outside the danger area on each side. This serves for access to the tunnel and for the evacuation of passengers to an exit in case of emergency. The safety space must be at least 2.20 m high and 0.50 m wide. In all new tunnels, there must be one continuous escape and rescue path leading to the open air for each track. The escape and rescue path should lie on the side of the safety space outside the outline of the clearance gauge. The passage width of the escape and rescue path should be at least 1.20 m, and the clear headroom at least 2.20 m.

The illustration (Fig. 1-5) shows an example of these requirements and the other details of the clearance gauge for a two-track tunnel with three-centred arch section on a high-speed line. The corresponding guideline details for a single-track tunnel with circular or three-centred shape of the cross-section can be found in Ril 853.

2. Tunnels for express traffic at 160 km/h < $v_E \leq$ 230 km/h

The cross-section of a rail tunnel for express traffic only differs from that for high-speed travel in the specified dimensions according to the guideline detail. The requirements for safety spaces and escape routes are formulated independently of design speed, so the requirements are identical for all design speeds. Ril 853 specifies a track spacing of only 4.00 m for express traffic in two-track tunnels, so the required formation width at $u = 0$ reduces to 11.60 m. The required spacing of track centreline to edge of formation remains at 3.80 m. The radius of a circular cross-section also reduces to $r = 6.10$ m, from which an altogether smaller cross-sectional area of $A = 79.2$ m^2 above TOR can be calculated. As with tunnels for high-speed traffic, individual parameters can also vary with the selection of as ballastless or conventional permanent way. This is illustrated below with a guideline detail for a two-track tunnel for express traffic with circular cross-section according to Ril 853 (Fig. 1-6).

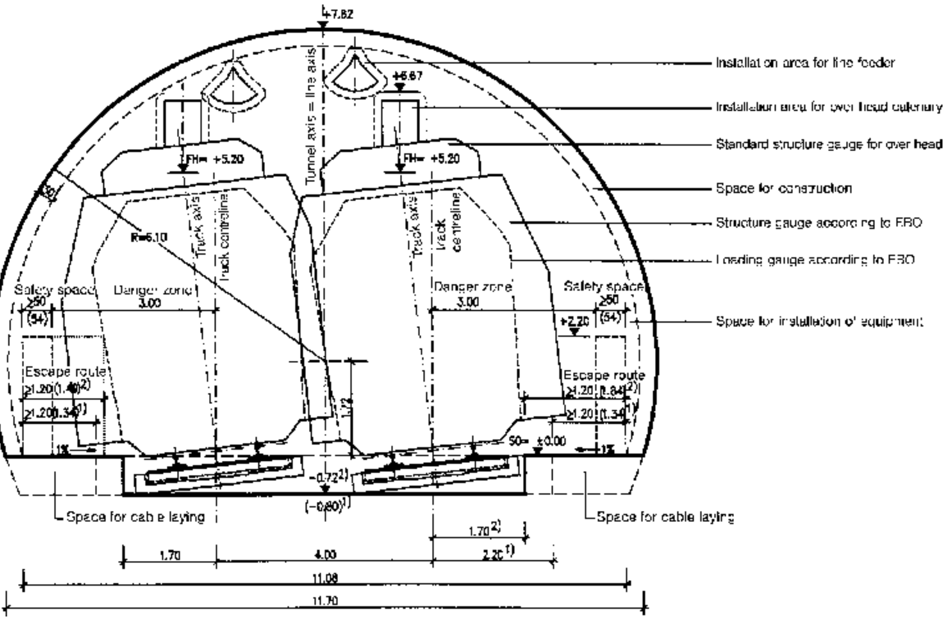


Figure 1-6 Guideline detail for a two-track express tunnel with circular section according to Ril 853.

3. Passenger and goods traffic at $v_E \leq$ 160 km/h

For passenger and goods traffic with a design speed of v_E < 160 km/h, the Ril 853 does not provide any guideline details for two-track cross-sections. Because the traffic is mixed, only single-track tunnels should be used in this case according to the guideline for civil protection from the EBA (federal rail authority), so two-way traffic has to run through separate parallel tunnels. Fundamentally, it can be stated that the distance of the track centreline from the edge of formation reduces to 3.30 m in comparison with other layouts and the formation width of open-air sections at $u = 0$ is thus 10.60 m. The dimensions for escape routes and safety spaces still apply for passenger and goods traffic since they are independent of design speed. This is illustrated below with a guideline detail for a single-track tunnel with circular cross-section (Fig. 1-7).

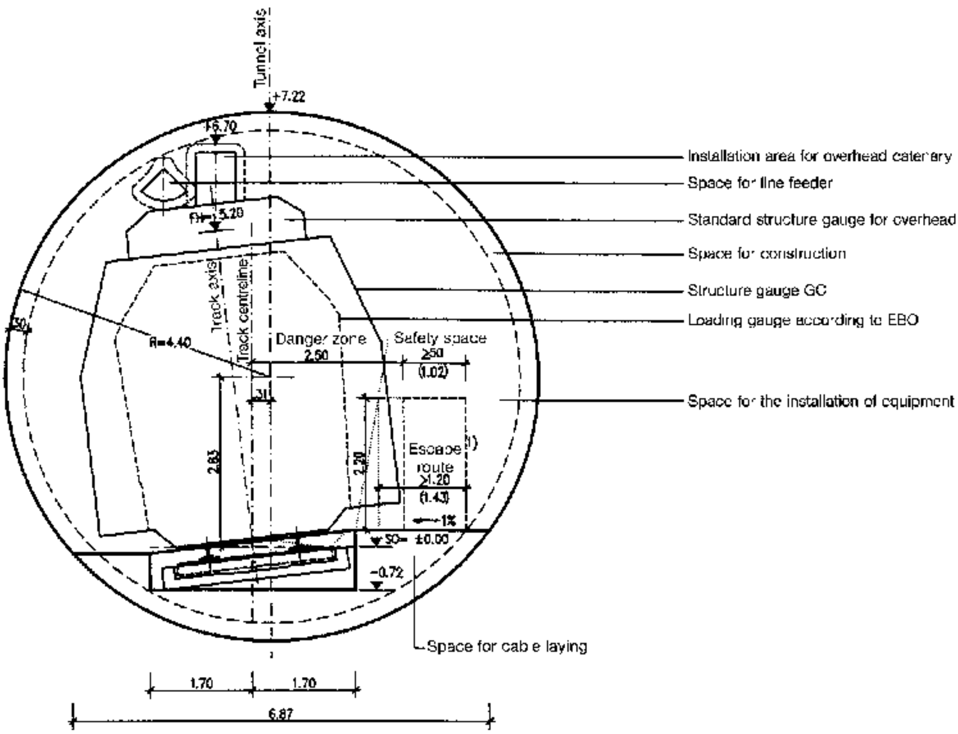


Figure 1-7 Guideline detail for a single-track tunnel with circular cross-section for passenger and goods traffic according to RiL 853.

4. S-Bahn, urban transit traffic at $v_E \leq 160$ km/h

Urban or rapid transit railways (S-Bahn in Germany) are categorised as railways according to the provisions of the general railway law and the railways construction and operation regulations [41] derived from it. In order to take into account developments in tunnelling technology and associated special processes for tunnelling inner-city rapid transit lines, the DB AG guidelines RiL 853, RiL 800.0130 and Ril 997.0101 are applicable, of which the Ril 853 has a chapter dedicated to the special features of urban rail tunnel construction.

In densely built-up urban areas, in hilly terrain or near stations at intermodal hubs, urban rail lines often run underground. S-Bahn lines in the cities of Stuttgart, Munich, Hamburg and Berlin have numerous underground stations. The locomotive-hauled S-Bahn shuttle in the Rhine-Ruhr area also partly runs underground.

S-Bahn tunnels can have either round, vaulted or rectangular cross-sections. With a permissible gradient of 40 ‰ and track radii of $R > 250$ m, smaller cross-sectional dimensions are possible than at speeds of over 120 km/h due to the lower design speed. The specified track spacing is 3.80 m, the distance from track centreline to edge of formation is 3.20 m and the specified formation width at $u = 0$ is 10.20 m.

With a clear width of 9.16 m and a clear height 5.49 m, a two-track rectangular cross-section on a straight line has an area of 50.3 m^2. In curves, this area is slightly greater due to the cant. With a clear width of 9.25 m, the Ril 853 specifies a clear height of 5.59 m and thus a total area of 51.7 m^2. It is also the case here that the selection of permanent way type can change individual parameters of cross-sectional design.

One special detail of S-Bahn tunnels is the layout of the clearance gauge for the overhead. Ril 853.1003 specifies, in contrast to Ril 800.0130, a space to be kept clear for the overhead as shown in Fig. 1-8.

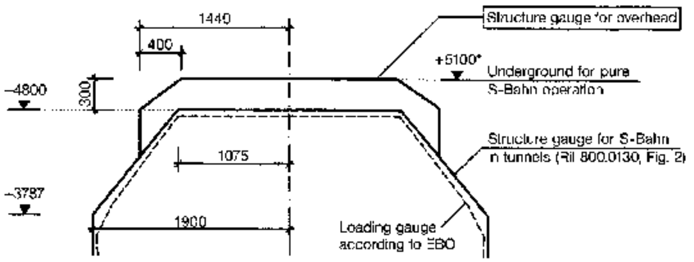


Figure 1-8 Clearance gauge for the overhead in urban rail tunnels.

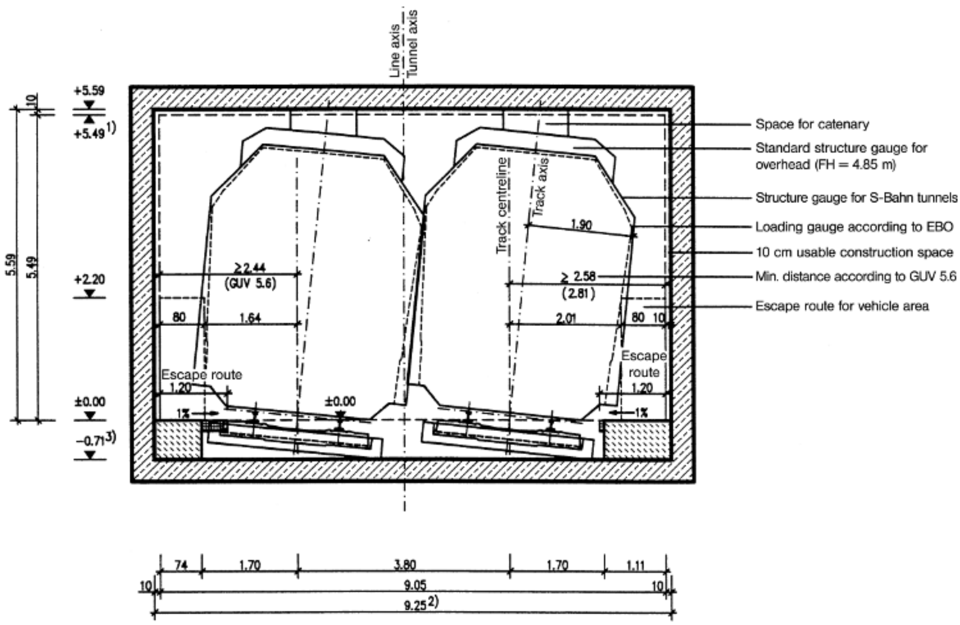


Figure 1-9 Guideline detail for a two-track S-Bahn tunnel in a curve with rectangular cross-section according to RiL 853.

An exception permit is to be obtained from the BMVBW (federal ministry for transport, building and town development) in each individual case for the application of the height of 5 100* mm above TOR according to Fig. 1-8.

In contrast to the details described until now, the safety space in S-Bahn tunnels has to be at least 80 cm wide. For the height and width of the escape route, the dimensions of 2.20 m · 1.20 still apply.

Fig. 1-9 shows as an example the guideline detail from Ril 853 for a 2-track S-Bahn tunnel with rectangular cross-section.

1.2.4 Construction of rail tunnels

The fire and civil protection requirements for the construction and operation of rail tunnels are laid down in the guideline of the federal railway authority (EBA) with the same name from 15 August 2001. The following section describes some important design principles from this guideline. More detailed information can be found in the guideline.

Fire duration and temperature curve. In order to minimise the depth of concrete spalling that could endanger passengers, a curve of temperature against time is to be assumed for design purposes (Table 1-1).

Table 1-1 Temperature curve depending on fire duration according to EBA.

Fire duration [min]	0	5	60	170
Temperature [°C]	0	1200	1200	0

These data can be used to determine the additional stresses, which have to be resisted by constructional measures (for example additional layers of reinforcement).

Safe areas, escape routes, emergency exits. Each track is provided with its own escape route next to it, as has already been mentioned in the description of the various planned uses. Localised narrowing of the escape route is to be avoided or in exceptional cases limited to a length of 2.0 m and a depth of 0.3 m. Handrails should be provided on all escape routes.

For the design and layout of escape shafts and tunnels, the limited physical capabilities of frail people and those with disabled mobility should be considered. Shafts should not exceed a level difference of 60 m and if the level difference is more than 30 m, should be equipped with a lift with dimensions 1.1 · 2.1 m. Stairs should be suitable for people passing and for the transport of stretchers according to DIN 13024.

Escape tunnels must have a cross-section of at least 2.25 m · 2.25 m, and not exceed a maximum gradient of 10 % and a maximum length of 150 m if they do not reach the open air directly but up a shaft. For lengths of more than 300 m long, rescue shafts must be accessible for ambulances.

Rescue areas and access roads. All exits and portals of the tunnel must be accessible by road. For long tunnels, a rescue area is to be provided at each portal and emergency exit. For shorter tunnels, one rescue area is sufficient.

Access roads and rescue areas must

– have secure planning status,
– have secure property status,
– be covered by an access regulation in traffic law.

In this case DIN 14090 should be complied with.

Access roads to rescue areas should be separate from exits. If this is not possible, two-way traffic with 2.50 m width must be ensured, if unavoidable by providing passing places. If rescue areas are connected to dead-end streets, it must be possible to turn.

Extinguishing water supply. Each tunnel portal must have sufficient water supply available for extinguishing fire (at least 96 m^3 at 800 l/min) within a maximum distance of 300 m.

Two-track tunnels are to be provided with a continuous dry fire extinguishing pipeline, which can be supplied from the portals and from the emergency exits.

In single-track tunnels on a two-track line, a continuous dry fire-extinguishing pipeline is to be laid in every running tunnel. In addition to the above provisions, both pipelines must be joined by dry pipes at junction structures.

It must be possible to operate dry extinguishing pipelines in sections and they are to be laid with protection.

1.2.5 Underground railway and underground tram tunnels

General. The cross-sectional dimensions of these tunnels are determined by constraints resulting from vehicle dimensions, dynamic travel properties, alignment elements, layout of safety spaces in the tunnel, location and type of power supply, environmental protection requirements (damping of vibration) and construction.

Guidelines. The following guidelines are applicable for all new design and design revisions for underground railway and underground tramlines:

1. Regulations concerning the construction and operation of tram lines (BOStrab) from 11 December 1987.
2. Guidelines for tunnels in the Regulations concerning the construction and operation of tram lines (Tunnel construction guidelines) from 30 April 1991.
3. Accident prevention regulations (UVV) of the accident insurer for trams, underground railways and railways.

For the design of urban railways, the regulations that have been introduced in the Rhine-Ruhr area [227] are widely regarded as a standard. The Stadtbahngesellschaft Rhine-Ruhr has produced detailed guidelines.

Considering the different types of vehicle at each location, the provisions regarding cross-sections only have the character of a recommendation. The shape of the tunnel cross-section is decisive for the determination of the outline of the loading gauge and the clearance gauge. Tunnels are differentiated into those with rectangular cross-sections and circular or similar cross-sections.

1.2.6 Innovative transport systems

In recent years, the development of guided transport systems for inner city public transport has been advancing in the Federal Republic of Germany.

Bus transport is being further developed, particularly for travel through tunnels, with buses being guided electronically or mechanically in the tunnel. The advantage of this principle is the considerable reduction of the cross-sectional dimensions of the tunnel compared to a manually steered bus (Fig. 1.10), which can greatly cut construction costs. This type of tunnel for buses will mainly be restricted to inner-city areas. Bus tunnels are already being designed and constructed in the cities of Essen and Regensburg. The dimensions of the tunnel cross-section derive from the size of a standard bus. These have a width of 2.50 m plus 0.25 m on each side for the rear-view mirrors and a height of 3.95 m. The mechanical guidance (Fig. 1-11) requires a road trough with a width of 2.95 m.

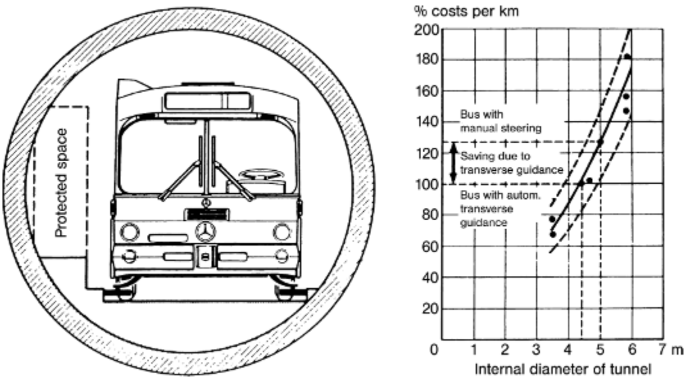


Figure 1-10 Automatically guided bus. Circular tunnel cross-section (left) and possible cost savings (right) [168].

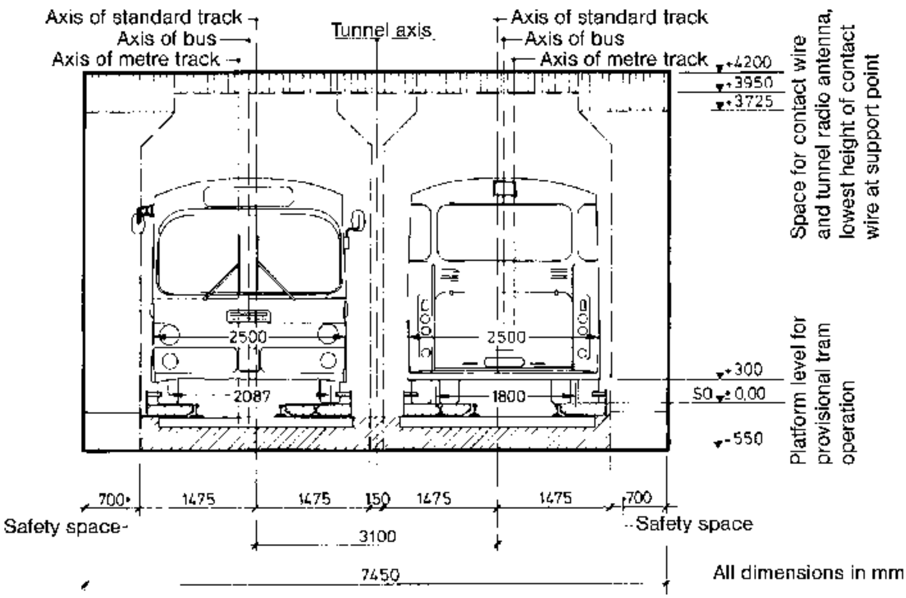


Figure 1-11 Mechanical guidance for busses. Rectangular cross-section for straight stretches of two-way tunnel [15].

1.2.7 Monorail with magnetic levitation, Transrapid, Metrorapid

A new method of transport, which has already been under development for about 30 years, is the “Transrapid” high-speed monorail with magnetic levitation, which represents an alternative between jet and train with a speed of 400 km/h (Fig. 1-12).

After the construction and testing of the Transprapid in Shanghai, an application in Germany is still in the design phase. The planning of the Metrorapid in the Ruhr area from Dortmund to Düsseldorf and in Munich between the airport and the main station has however been abandoned for financial reasons. This would have required a 4 km long tunnel bored by a shield machine.

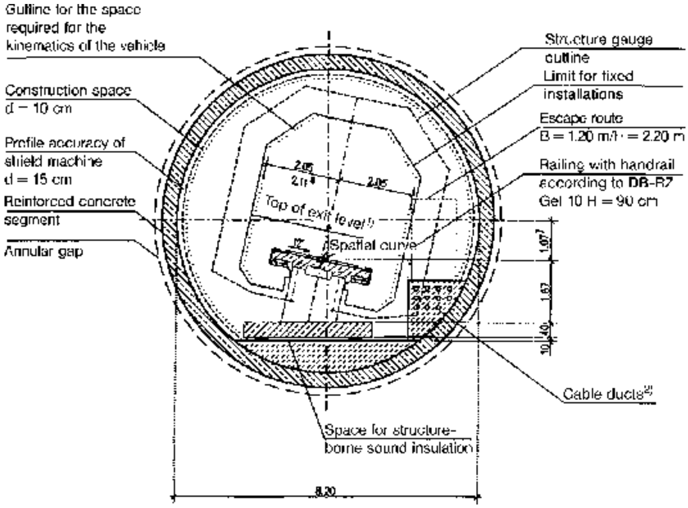


Figure 1-12 Standard cross-section for a shield-driven tunnel for a magnetic monorail.

1.2.8 Other underground works

General. In addition to the road and rail tunnels described above, tunnels are also devoted to the needs of pedestrians, skiers, shipping, drinking water supply and drainage and electricity and gas supply.

Pedestrian tunnels. These are of a similar nature to road tunnels, but the small clearance gauge, small curve diameters and the steeper permissible gradients, which can be up to 10%, and the possibility of joining them into a lift shaft lead to such a decisive simplification of their design and construction that they can be regarded as a different group. Pedestrian tunnels are found almost exclusively in inner cities and only seldom under rural roads.

The best-known pedestrian tunnels are those in Hamburg under the Elbe and in Antwerp under the Schelde. Neither of these has a staircase, but the pedestrians enter and leave the tunnels in lifts, escalators or shafts at the riverbank. The tunnel in Antwerp is a fully independent tunnel only intended for pedestrians, but the tunnel in Hamburg is for mixed traffic since there is a central single-track road with a 1.25 m wide pavement each side, similar to a road bridge [238].

Pedestrian tunnels either have rectangular or circular cross-sections according to whether they are below paving or deeper (including below water).

In order to make the pedestrians feel comfortable, pedestrian tunnels should have generous height and width. The clear headroom should not be less than 2.44 m, better still 2.75 m or more. The width is determined by the number of pedestrians.

Ski tunnels. These are becoming ever more common in many countries [128], [223]. A good example of this new sort of tunnel was opened in Saas Fee, Switzerland in December 1984 for an underground funicular railway to transport skiers. The tunnel, almost 1,600 m long, was driven at rock temperatures of 0 °C, so no water ingress had to be feared. Altogether over 80 % of the tunnel could be driven in excavation class I according to the Swiss SIA standard 198 (see Chapter 2). Fig. 1-13 shows the excavation conditions and the chosen cross-section. The tunnel was bored by a full-face machine with a diameter of 4.20 m.

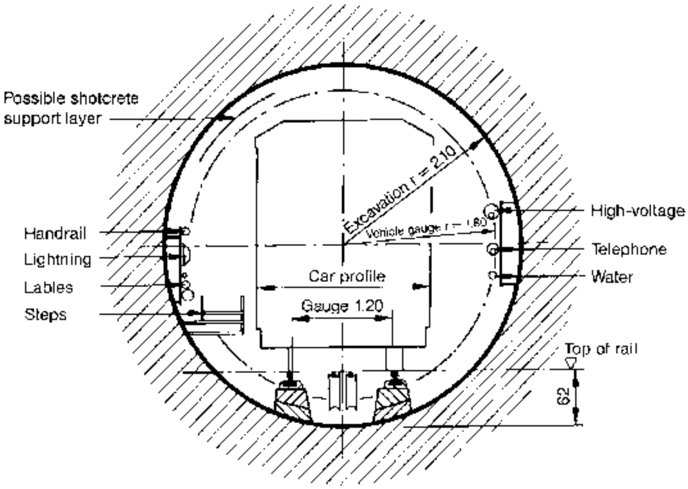


Figure 1-13 Cross-section of the Metro-Alpin Tunnel in Saas Fee [128].

Shipping tunnels. Historically, shipping tunnels were the forerunner of today's transport tunnels, as water transport was formerly more significant. These tunnels are not described in further detail here.

Tunnels to transport water under gravity mostly have a horseshoe section. The cross-sections of pressure tunnels tend to a circular form with increasing water pressure.

Utility tunnels. These are mostly in urban areas and serve to house utility supply pipes. The cross-section is normally circular or rectangular according to the chosen construction process. This sector is currently the subject of much research and development, particularly regarding the repair or replacement of old pipes and small cross-sections. The various construction processes and characteristic cross-sections are described in more detail in Chapter 7 of volume 1.

No further details are given here of the cross-sections of shafts, caverns, chambers or other applications.

1.3 The influence of the ground

General. The shape of the cross-section of tunnels also has to be suitable for the prevailing geological conditions and overburden. The size and direction of external loading mostly depends on the ground pressure. The better the load-bearing capacity of the rock mass being passed through, the less ground pressure has to be assumed in the design of the support, particularly pressure from the side. The higher the lateral pressure is in relationship to the vertical pressure, the more a near-circular cross-section will be suitable. The shape of the cross-section thus depends on the external and internal forces acting on the perimeter of the cavity (Fig. 1-14). In competent rock, which does not tend to be weathered, the excavated profile will stand up without any structural contribution from the support, and a thin layer of shotcrete can resist any effects of weathering. Ways of optimising the tunnel cross-section to an ideal shape are offered by the laws of structural geotechnical engineering.

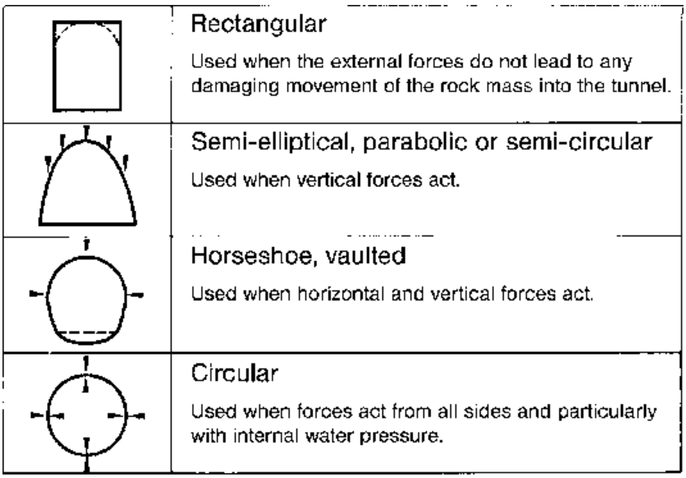


Figure 1-14 Basic cross-section shapes [135].

L. Müller [160] stated the following considerations:

"In competent rock, design is relatively unrestricted: cross-sections with vertical sides or flat vaults, even horizontal crowns are possible in stable rock as long as there are not too many joints, such as in conglomerates, some compact limestones and above all in undisturbed granite. Such tunnels are then mostly not lined or only provided with a weak lining. Fully inappropriate are linings, in this case actually only a facing, which are only installed to present a smooth face; underground cavities have their own aesthetics and should be designed according to the character of the rock; there is no reason to coyly hide it.

In fairly competent but jointed rock, profiles with weak support are used or those where systematic rock bolting provides the actual support. Also in this case we no are longer ashamed to specify an uneven lining that follows the structure of the rock, like for example is created by spraying shotcrete, and we leave the heads of the rock bolts visible even in important structures. This saves support work and concrete, which would only serve to create a geometrically precise outline by filling the hollows formed by overbreak without any actual structural purpose. Why should we not, where the surface structure imposes such an excavation shape, sometimes specify the required clearance gauge as a pointed arch or similar irregular profile, when otherwise rock bolting and concrete would have to be provided to avoid such profiles but without any actual structural purpose?

Rock that is competent but tends to subsequent loosening is often only permanently supported in the top heading, sometimes only with mesh and rock bolts. Formerly, when masonry *lining was used, the lining was often restricted to certain less stable areas and these were supported with masonry bands and corners. This practice died out with the introduction of formed concrete but should be reintroduced today with the availability of shotcrete, which can be applied as required. This would however only become established practice if saving money was regarded as a virtue and the supervisory engineers felt responsible not only for the avoidance of damage but for the economical use of construction materials.*

In competent rock, which is fractured into large to very large blocks by jointing, and if the diameter is less than twice the average joint spacing, support can be designed on the same basis as in competent rock without large joints if the anchoring is installed according to the structure of the rock mass. If the diameter is larger, a type of punching pressure on the support has to be expected, so the lining has to be designed to resist this shear or the joints have to be dowelled.

Brittle rock with medium strength, which requires transverse support to assist the formation of a protective zone, demands well rounded profiles that are approximately circular including the invert and support to all sides, possibly making use of permanent rock bolts behind a thin layer of concrete.

In squeezing and strongly squeezing rock, irrespective whether the ground pressure derives from high primary stress or low rock strength, the cross-section should always be nearly circular, although the invert is normally given a flatter profile (arched profile). The support in squeezing rock is normally made stronger without, however, having to completely abandon the advantages of a relatively slender support layer, as recent knowledge shows that the formation of a supporting ring in the rock mass, normally achieved or reinforced with systematic rock bolting, should always be the intention. The circular structure of the tunnel support must always be closed in squeezing rock, including the invert, and the curvature of the invert arch must be more pronounced the higher the ground pressure is. The closure of the invert is also very important in rock susceptible to softening.

Ground pressure acting on only one side (a), as for example is characteristic of tunnels beneath a slope, particularly slopes susceptible to creep pressure, require an asymmetric lining (Fig. 1.15), in which the abutment on the valley side, that is away from the pressure, is strengthened and this always requires a widening of the foundation.

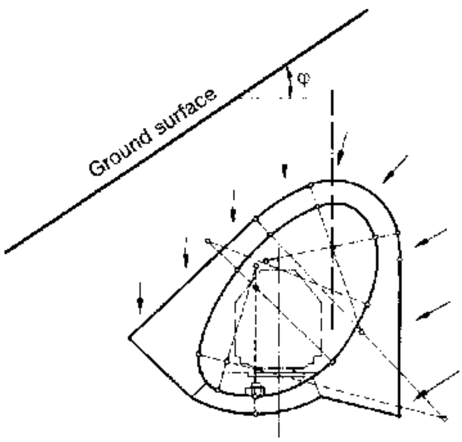


Figure 1-15 Tunnel profile for a tunnel below a slope with strong downhill thrust, designed using a classic line of thrust calculation [160].

Both measures, thickening of the abutment and widening of the foundation, are only sensible where the foundation is founded on firm ground, which is not the case when there is a downhill thrust. If suitable firm ground does not occur naturally, then the foot of the abutment has to be supported artificially with corbels, anchoring or such like.

Sideways yielding of the ground (b) can be due to steeply dipping and open joints or other loosening of the rock structure, also a comparatively high plasticity of the ground associated with a low modulus of subgrade reaction. Under such conditions, negative convergence is often observed during the supporting of the top heading, and even more often during the excavation of the bench, denoting an in-and-out movement of the top heading and bench support.

Both cases (a) and (b) require a strong invert arch; in the case of one-sided pressure, this has the purpose of supporting the pressure from above through the abutment foot on the downhill side; and in the case of ground susceptible to sideways yielding an invert arch is necessary because in this case the load-bearing ring in the surrounding ground lacks sufficient restraint and because such ground tends to plastic and pseudo-plastic invert heaving.

Ground with strong side pressure demands a strong invert arch.

Plastic (and also stiffly plastic) ground also demands an invert arch. Even in stiffly plastic types of ground, the cross-section has to be nearly circular but in plastic ground this is definitely to be preferred.

In ground susceptible to swelling, increased pressure on the invert is resisted by a particularly strong invert arch, or by a very curved invert arch. L. v. Rabcewicz [182], who always followed the principle of waiting for ground pressure to subside before resisting it with high support pressure, suggested two construction methods in ground susceptible to swelling. One has the essential feature that the walls of the cavity are initially supported with a weak support that yields under ground pressure and only when the ground pressure has subsided is a final lining installed against the first support layer to resist the pressure; this is the two-pass lining often used later as part of the New Austrian Tunnelling Method. L. v. Rabcewicz also proposed a second method of leaving a cavity between masonry lining and the rock mass, in which case it is important to make sure that the masonry is sufficiently stable. The stability is provided by masonry ribs, which are in contact with the rock mass and remain between the faces of the intended cavity.

The geological conditions relevant to construction include the primary stress in the rock mass, which denotes the stresses in the rock mass before the excavation of the cavity."

1.4 Dependency on construction process

General. The construction process that is chosen and the machines to be used in the cross-section and along the tunnel (construction and operation method) have an influence on the selection of the overall and partial cross-sections. It has an influence on the size of the final cross-section, also the profile of the excavation and to a certain extent the usable cross-section. The process- and operation-related criteria for the full-face and partial-face excavations are dealt with in Volume 1, Chapter 3.

Cross-section size. This has to be larger than the minimum profile for economic excavation, which is about 5 m^2, except when pipe jacking (see Volume I, Chapter 7) is used. Small cross-sections obstruct personnel and machinery, so the costs rise despite the smaller excavation and support quantities. Another cost factor is the ventilation. The size is no longer limited by the construction process because large cross-sections are normally divided into partial areas. Only when a tunnel boring machine (TBM) is used is the practical size limited by mechanical factors. The largest tunnel boring machines at the moment have reached diameters of 15 m, but still larger machines are planned.

Cross-section shape. This is influenced by the selected construction process and the associated machinery; for example a tunnel boring machine can only bore a circular section. All equipment associated with a TBM has to be adapted to suit the circular shape of the invert. Except for a few exceptions, this also applies to shield machines, although there have been some developments. Conventional tunnelling with its further developments including the shotcrete process also have an influence on the design of the cross-section in that a flat invert is available for mucking and transport and the excavated profile has to be enlarged more or less for the thickness required for the support.