CROSS SECTION DESIGN FOR UNI- AND BI-DIRECTIONAL ROAD TUNNELS

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ABSTRACT

The goal of Working Group No. 4 is to develop the principles for a safe and cost effective tunnel cross section taking into consideration signalling and traffic management requirements.
Due to the costs of tunnels there is a need to minimise their cross section. On the other hand minimum cross sections might cause a decrease of the Free Flow Speed and the Road Capacity, as well as an increase of the chances on Congestion, In- and Accidents, whereas the possibilities for Incident Management and Rescue get less. In 2001 Working Group No. 4 published a report on Cross Section Geometry in Unidirectionel Tunnels, whereas the final draft of a report on Cross Section Design for Bidirectional Tunnels has been submitted in April this year. The goals of both reports are to describe the arguments considered in various countries concerning the dimensions of the cross section that are essential for traffic in terms of safety, capacity and congestion level.
It appeared essential to develop a special terminology, of which the main elements will be presented in this paper. The report on one-directional tunnels mainly deals with the cross section, whereas the report on bi-directional tunnels additionally discusses aspects such as longitudinal slopes and radii of curvature.
Both reports contain a chapter on the influence of the tunnel-geometry on capacity and speed is treated. All functions of elements of Carriageways, Off-Carriageways (hard shoulders and walkways) and Maintained Headroom are treated, and philosophies behind the various guidelines are described. Both report will provide designers and decision makers with arguments for cost-effective designs.

KEY WORDS

CROSS SECTION / TUNNEL / CAPACITY / TRAFFIC LANES / HARD CLEARANCE / WALKWAYS / OFF-CARRIAGEWAY

1. INTRODUCTION

Road tunnels generally are much more expensive than the adjoining open roads. Therefore it is not amazing that the lay-out of tunnels changes from country to country. As costs of tunnels are determined not only by their cross section but also by their length and the construction method, the design codes for tunnels in each country are determined for a great deal by the geology and the density of population.
Countries with only a few short tunnels and a lot of traffic probably can afford more expensive tunnels than countries with a lot of long tunnels with low traffic density.
In 1995 PIARC published a report containing a lot of information about traffic safety In tunnels. Although some interesting general conclusions could be drawn from this report

(for instance that tunnels in general are safer than open roads) it did not contain specific information on the effects of differences in cross sectional design. As this would require a broad investigation with a small chance on success the working group decided not to investigate the effects of tunnel design on safety, but to compare the design codes of the participating countries in such a way that the design philosophy or the functional requirements of the design of tunnel cross sections becomes clear. Priority was given to a publication on one-directional tunnels.
After finishing the work on this publication the need was felt for a supplementaty report on bi-directional tunnels. In this paper the main subjects of the reports will be highlighted.

2. UNIDIRECTIONAL ROAD TUNNELS

2.1 Limitations

The report is limited to tunnels with unidirectional traffic on roads of motorway standard or equivalent (two lanes per tube on roads with important functions and of high category)

2.2 Structure of the report

The report starts with a chapter on terminology, then there follow two introducing chapters: one on functionality and category of roads and another on capacity and speed in relation to road geometry. Than follow three chapters on the real geometry of tunnel cross sections: Traffic lanes and carriageway, the off-carriageway and the maintained headroom. Each of these chapters give a paragraph containing tables with numerical data of the seizes of the elements in the different countries, a paragraph describing functional aspects of the elements of the cross section, a paragraph with conclusions and a paragraph with recommendations

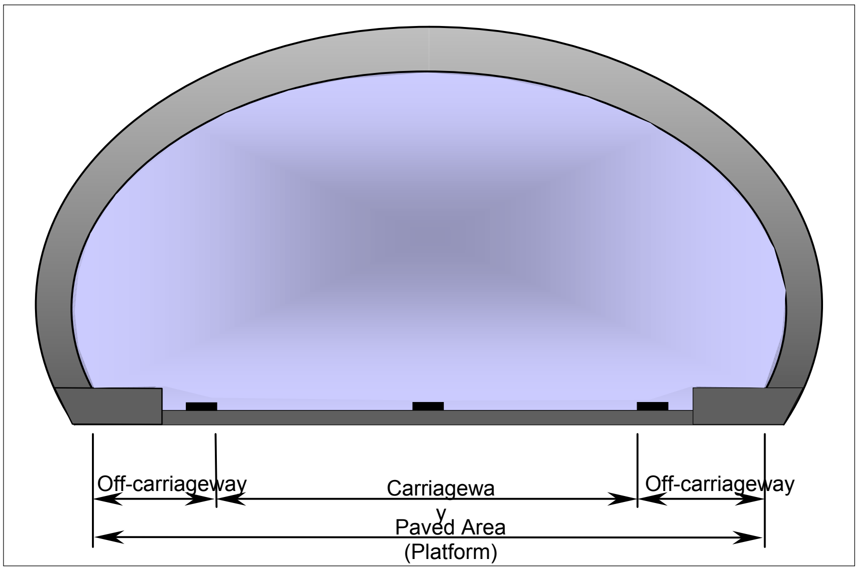

Figure 1 - Primary partition of the Paved Area (((((((P((Platform).

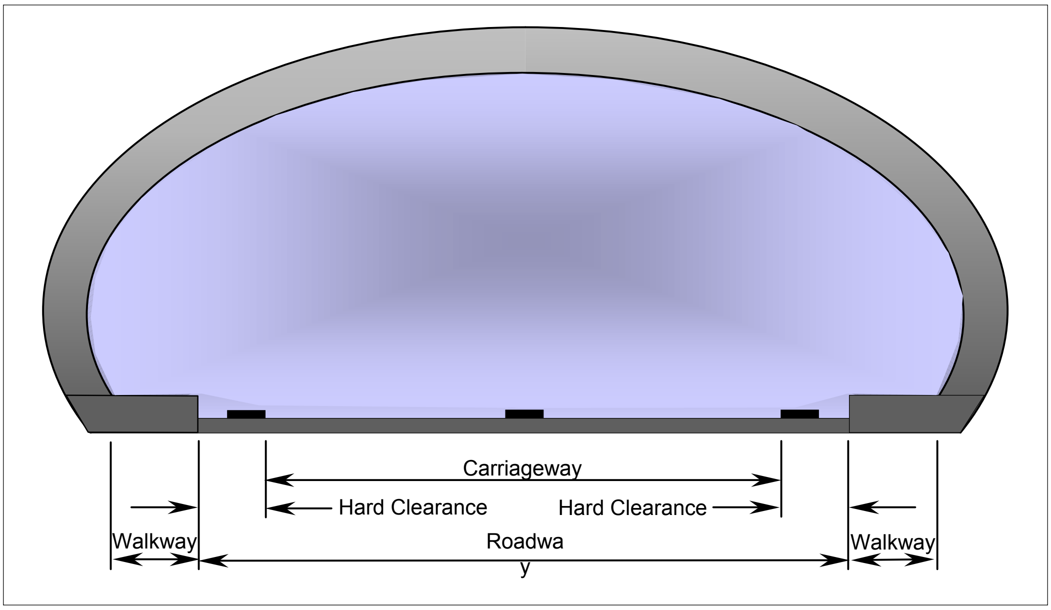

Figure 2 - Secondary partition of the platform and partition of roadway roadway.

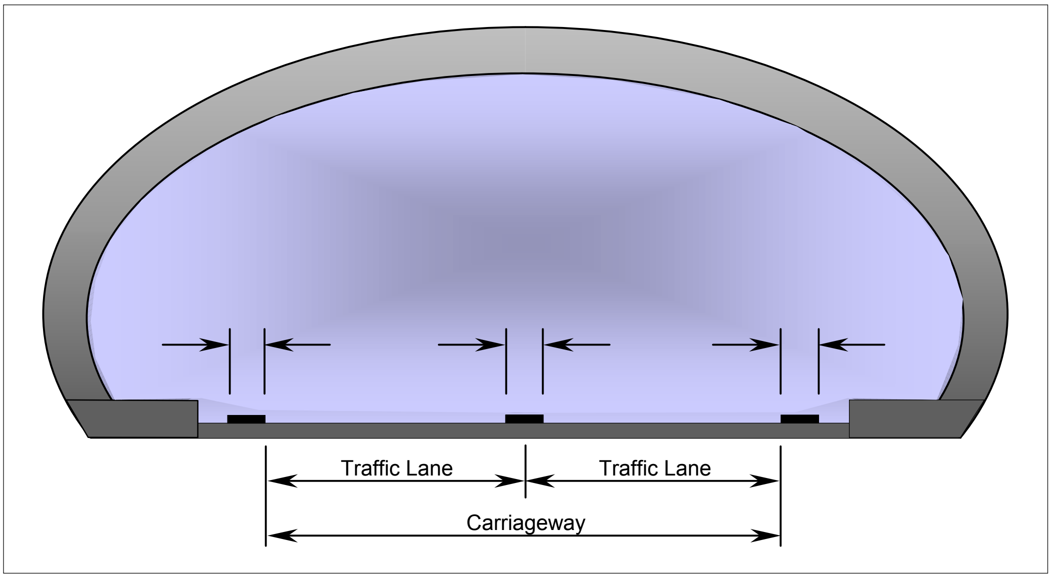

Figure 3 - Definition of Traffic Lanes and Lane Markings Markings.

2.3 Terminolgy

Understanding each other starts with using the same terminology. In the first meetings of the working group there was much discussion on what exactly was understood by some terms. What for instance is the use of terms like hard shoulder, hard clearance and verge when in tunnels the floor between the edge lane marking and the tunnel wall is nearly always consolidated. Moreover it turned out that even in the UK there are various terms that could mean the same, for instance carriageway and travelled road, and also the terminology in the UK and the USA is different.
A very new terms introduced in this report is the off-carriageway area, which means all the space between the inside of the edge lane marking and the tunnel wall. The off-carriageway contains the lateral hard clearances and the walkways of the barriers. The total width of carriageway and off-carriageway areas is called the paved area or platform.
These terms give the primary partition of the width of the tunnel. The secondary partition is given by the roadway (with its partition) and the walkways or barriers.
The roadway is partitioned in the carriageway and lateral hard clearances.
And finally we have the question of what exactly is meant by the traffic lanes and do lane markings are a part of the traffic lanes. The working group decided that the traffic lane marking, separating the traffic lanes, belongs to the traffic lanes, so that the width of the traffic lanes is measured between the inside of the edge lane markings and the centre of the traffic lane marking.

2.3 Functionality and categories of roads

This small chapter is written to give the tunnel design engineer an idea of the reasoning behind the uniformaty of roads: that they belong to networks for traffic with different functions: continental networks like the TEN or the Interstate Highways in the US to connect countries, national networks to connect urban regions and national economic centres, regional and local networks.
It is important that drivers recognize the function of the network they are travelling on from the design elements of the roads, like lengh profile, width of travel lanes and hard shoulders and so on. Apart from the function these elements will also be dependent on environmental data and from the traffic intensity.
The working group thinks it is desirable if the funcionality of the road is also recognizable from the design of the tunnel.

2.4 Capacity and speed of roads in tunnels

This chapter contains some information on what factors can influence the capacity and driving speed of traffic in tunnels. It is not meant as a guideline for traffic engineers, but can be used as first steps to the design of a tunnel. Factors that influence the capacity and speed are: the theoretical capacity of an ideal road, width of the traffic lanes and the off-carriageway area, the percentage of heavy vehicles, length and inclination and finally the driving behaviour.
The report presents tables with which it is possible to get good ideas of the practical capacity and the expected velocity.
Perhaps most interesting for tunnel engineers is the effect of the width of the off-carriageway area on the capacity, as this is one the factors that has much effect on the costs of construction. Moreover it is very difficult to increase the width of tunnels in a later stage and therefore tunnels often are bottlenecks in the networks and therefore the cause of much economic losses.

2.5 Traffic Lanes and Carriageways

This is the first chapter in which measures of the widht of traffic lanes, carriageways and lane markings, prescribed in the different codes are compared. The most discussed item in the working group was the effect of traffic lanes narrower than 3.50 m (widths of 3.25 m) in combination with a speed reduction to 100 km/h. It is generally considered as very difficult to enforce this speed on roads with low average daily traffic volumes.

2.6 The Off-Carriageway area

This chapter was by far the most difficult, which is understandable as again this determines the total width of the tunnel tube and therefore is very sensitive to costs. It also is the most extensive chapter as many functions can be attributed to the elements and functions of the off-carriageway area.

The following elements were discerned:
edge lane marking, redress lane, hard clearance, emergency lane, object distance, walkway, safety barriers and guard rails.

The following functions were identified:
traffic lane capacity, preventing collisions against the tunnel wall by cars,having crossed over the edge lane markings, decreasing the consequences of collisions of the cars against the wall, stopping sight length, possibility to park broken down vehicles, use by police and rescue teams, possibility to fasten ventilation fans and traffic signs, tunnel maintenance and gravity drainage.
The chapter also describes the design philosophy of the French and German guidelines in determining the width of hard clearances and emergency lanes.
A special paragraph is dedicated to the functions of walkways, but also the disadvantages are shown: The main functions are to provide for pedestrians in special circonstances, to enable opening of emergency doors, orientating lines for motorists, to prevent collisions against the tunnel wall, to reduce traffic speed, protection of tunnel equipment, space for cables and ducts, integration with drainage system. In some countries the walkway is only slighty elevated to enable the parking of broken down vehicles. In France walkways are not necessary when there is an emergency lane. The Netherlands and Sweden do not use walkways at all. The Netherlands due to the some serious accidents that happened in the past, Sweden to enable wheel chairs to reach the emergency doors.
Due to the many pro’s and con’s the designer of tunnels is advised to consider and and weigh all the functional possibilities and consequences and to lay down the the choices in a document, which has to be confirmed by the responsible authorities.
Special attention is given to the location of cables and ducts: preferably not in the traffic area as this would require closing of lanes when work has to be done (cables added or changed)

2.7 Maintained headroom

There appears to be great uniformity about the minimum size for the maintained headroom, viz. 4.50. Some counties prefer somewhat higher headrooms. But additional to the maintained headroom allowances are considered necessary as safety zones for signs, luminaries and fans, allowance is necessary for these signs, luminaries and fans themselves and some countries consider allowances for inaccuracies in construction, bending of the construction and later pavements.

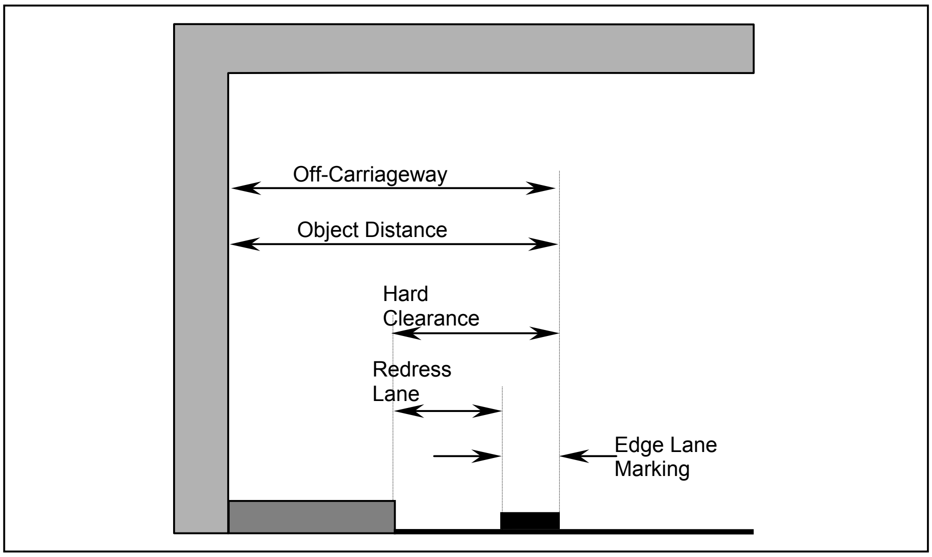

Figure 4 - Elements and functions of off carriageways in case of walkways.

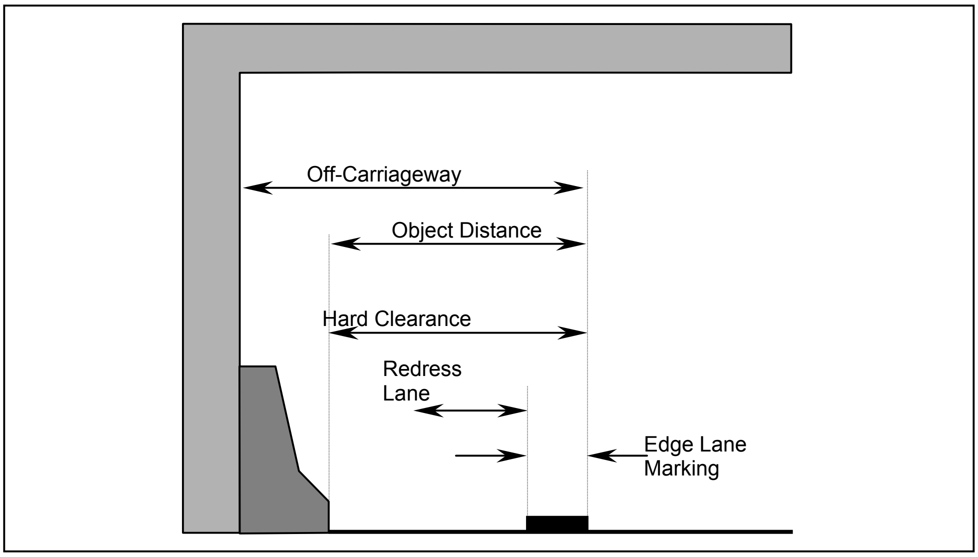

Figure 5 - Elements and functions of off carriageways in case of safety barriers.

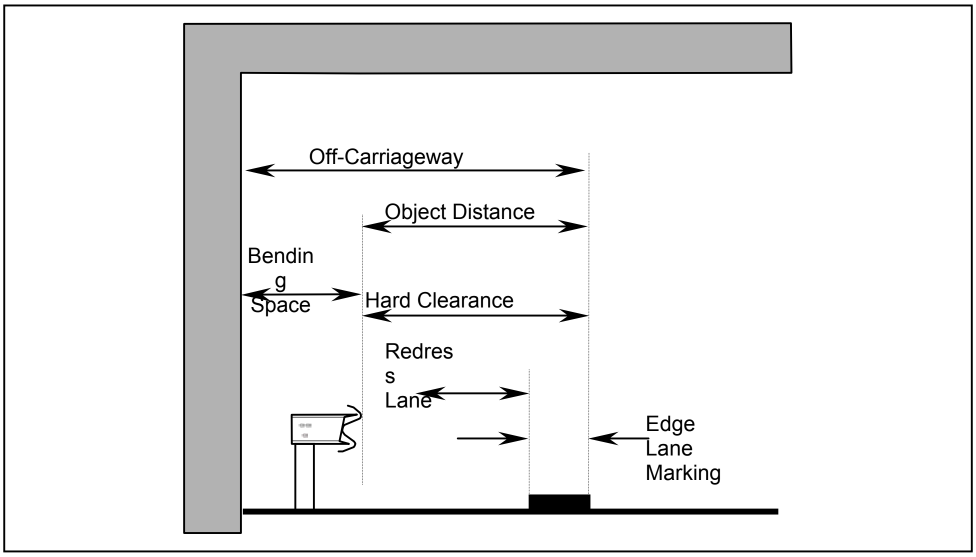

Figure 6 - Elements and functions of off carriageways in case of flexible guard rails.

3. BI-DIRECTIONAL ROAD TUNNELS

3.1 Structure of the report.

This report shares the terminology and general approach of the document about uni-directional tunnels, but adapts and extends it to cover tunnels with a single gallery and two directions of travel.

3.2 Safety considerations.

The main criteria in deciding whether to build a single or twin-tube tunnel shall be projected traffic volume and safety. Other aspects shall also be taken into account, such as percentage of heavy goods vehicles, length and gradient etc.

The safety criteria tend to increase the section (wide hard clearance, comfortably wide walkways, facilities for disabled people, long visibility distances, possibility of overtaking a stopped vehicle at any point, etc.). The economic criteria lead to cross sections that are more restrictive than those used for open roadways with similar traffic density and geometric conditions.

There are, nevertheless, certain basic principles that must be upheld in bi-directional tunnels. For instance: it should be possible for one heavy goods vehicle to overtake a stopped heavy goods vehicle without completely interrupting traffic in the opposite direction. For safety reasons, if there is only one lane of traffic for either or both directions, overtaking a moving vehicle in this direction must be forbidden.

Also, to avoid congestion inside the tunnel, the cross section point of a tunnel where there is the minimum capacity for passage of vehicle traffic should be located before the tunnel itself or in the entry section of the tunnel in each direction, it should never be located at any intermediate point or at the exit.

3.3 Traffic Capacities.

In the case of a two lane tunnel with one lane of traffic in each direction of travel, there are many more similarities to the behaviour of multiple lane highway than to that of a two-way roadway. In this case, even today, going through a two-way tunnel heightens driver attention, and drivers are also aware that there is no overtaking in the tunnel.

When making a capacity study it must be defined whether sections of the tunnel are to be considered separately, or the complete tunnel as a whole. Of course, if the cross section varies, the minimum section will define the capacity of the whole. In regard to the longitudinal section, a study should be made of combining a series of ramps with various gradients into a single ramp of average gradient, or whether each should be studied separately. In these cases various estimates should be made to determine the point which most limits the capacity. This usually coincides with the point of the slowest speed for heavy vehicles.

This chapter describes the procedure for estimating the capacity of a tunnel, as it involves individual and separate determinations of the partial capacities for each of the directions of travel. The capacity is determined in two steps; the first is to calculate the theoretical capacity on the basis of the free flow speed. The second step is to adjust this theoretical capacity depending on the presence of heavy vehicles and the type of drivers to obtain the practical capacity.

3.4 Incident and accident rates.

The approximate incident rate in bi-directional tunnels is estimated at about 750 incidents per 10^8 vehicles per kilometre, with a dispersion of ± 40%. This figure is approximately

25% higher than that of uni-directional tunnels. An incident is defined as a vehicle stopping inside the tunnel for any reason except traffic congestion.
The slope of the tunnel has a significant influence on the number and frequency of incidents, this rate being obviously higher in the upward than in the downward direction. This seems to be due to the fact that drivers tend to exit the tunnel by their own means if this is at all possible.
Additionally to the gradients inside the structure, steep or long gradients in access roads to the tunnel increase incidents rate inside the tunnel.
In general, tunnels have an accident index similar to or lower than equivalent open roads. In many cases these indexes are even lower. Bi-directional tunnels have accident indexes involving injuries that are between 25 and 30% higher than single direction tunnels.

3.5 Horizontal alignment.

Straight alignments should not necessarily be avoided, but they should not be more than 1500 m in length because the effect of excessive concentration on one point could distract the driver, or even induce an unconscious increase in the speed.
For the same reason, the last few metres of a tunnel should have a gentle curve in plan view, in a direction that does not limit the visibility, whereas in bi-directional tunnels it is better to provide greater visibility in the direction entering the tunnel as this is the direction where the loss of vision because of variation in the lighting level is most intense.
The recommended maximum speed in bi-directional tunnels is 90 km/hour, or even less if the geometry of the tunnel (section, curves or slope) involves other limiting factors. In this case, the speed limit should correspond to a safe speed under the prevailing tunnel and traffic conditions.

3.6 Vertical alignment.

Steep inclination of the pavement alignment (more than 3.5%) makes ventilation more difficult as the chimney effect becomes powerful, and considerable resistance must be overcome to establish an air flow against this effect. This becomes even more important in the event of fire, as hot gases have even more tendency to rise.
The lengthways slope of a tunnel should not exceed 4**%** in bi-directional tunnels. In the event that it is necessary to adopt steeper gradients, the design of the ventilation system should take this effect carefully into account.
Adhering to the principle of not having a section with minimum traffic capacity inside a tunnel, any changes in the slope of the pavement should preferably be from high to low steepness. Whenever this distribution is not possible, for example in submerged tunnels, careful consideration should be given to the possible formation of traffic hold-ups due the reduction of carrying capacity inside the tunnel.

3.7 Lane widths.

In general, international recommendations coincide to a very large extent in suggesting that traffic lanes have widths that are equal to or in excess of 3.25 m, with a recommended value of 3.50 m, which should always be used whenever the tunnel carries heavy vehicle traffic.
The traffic lane markings in the centre should be double continuous lines to effectively prohibit any overtaking.
It is also recommended that the traffic lane markings in the centre of the tunnel should be painted as rumble strips, in an attempt to reduce head-on accidents by invasion of the traffic lane in the opposite direction. Good results can also be obtained by using cat eyes as road markings or small barriers set into the pavement to improve guidance and reduce the risk of accidental invasion of the lanes with traffic flow in the opposite direction.

3.8 Hard Clearance widths.

In bi-directional tunnels, both left and right hard clearance widths should be equal. The only exception could be the tunnels with more than one lane at the same direction.
It is important to respect the safety criteria that requires a minimum travel width (traffic lanes + hard clearance) of 8 m 50 cm, as this is the distance required for a heavy goods vehicle to overtake another vehicle that is stopped without completely interrupting traffic in the opposite direction.
Furthermore, it is also recommended that the hard clearance enable a vehicle to stop without impeding or restricting traffic flow in the opposite direction. This means that the recommended width of the traffic lane plus the width of the hard clearance should be more than 5 metres 50 cm.
The best possible situation would be for the hard clearance to enable a vehicle to be stopped completely off the carriageway and this would require a minimum width of 2.50 m.

3.9 Central median strip.

One possible solution for limiting the total width of the tunnel without excessively compromising safety considerations would be to include a strip or non-usable traffic lane separating the directions of a bi-directional tunnel. If it is used, this central strip should enable a width of between 1,0 and 2,5 metres, and could enable a certain reduction in the width of the side hard clearances.

3.10 Recommendations

The table below summarises the recommended characteristics for bi-directional tunnels with two traffic lanes. The dimensions indicated as minimum should be adopted for any level of traffic or length of tunnel. The dimensions corresponding to the restricted section may be used for tunnels of a certain importance although, whenever possible, the section should be adapted to the recommended dimensions.
These recommendations are based on common practice in various countries, as well as on the opinions of the experts on the PIARC WG4 committee. However, there may be other solutions to the problems discussed, and national standards could take different approaches to some of the situations dealt with in the report.

Table summarising recommendations.

Type of section	Central median strip (m)	Traffic lanes (m)	Hard clearance (m)	Walkways (m)	Roll over walkways (m)	Total width between walls (m)
Minimum without walkways	-	**3.50**	0.75	-	-	8,50
Minimum with walkways	-	**3.50**	0.75	0.60	-	9.70
Minimum with roll over walkways	-	**3.50**	0.50	-	0.60	9.20
Restricted with walkways	-	**3.50**	2.00	0.60	-	12.20
Restricted with roll over walkways	-	**3.50**	1.75	-	0.60	11.70

Table summarising recommendations.						
Restricted with central median strip	2.00	**3.50**	0.50	0.60	-	11.20
Recommended	-	**3.50**	2.50	0.60	-	13.20

3.11 Off-Carriageway widths and visibility distances

The off-carriageway is understood to be the total space of the hard clearance and the walkway. This strip, apart from providing the design functions of its components, should also provide sufficient visibility distance on any curves inside the tunnel to be able to safely stop a vehicle when should there be any obstacle. In the majority of countries the standards include this type of consideration, associating visibility and stopping distances with the speed, radius of the curve and the slope of the roadway.

3.12 Maintenance operations

This chapter gives information about the criteria to be used for planning maintenance operations in bi-directional traffic tunnels, as it implies serious affections to vehicular flow. It is therefore convenient to make a prior study for the selection of the equipment to be installed in a tunnel with special emphasis on technical, functional and economic aspects, as well as the maintenance requirements of these installations.
It is especially important to plan maintenance operations that affect vehicle traffic, as these may be the cause of accidents involving users of the tunnel, or the workers operating the maintenance equipment.
The existence of a work area inside a tunnel must be intensively indicated, and the works signalling must always begin outside the tunnel in both directions of travel. In the work area itself, the traffic speed should be adjusted to comply with the effective width of the available traffic lanes.
In the event that the available width of the traffic lanes is less than 2.70 m, traffic should only be allowed in alternating directions, one direction at a time, using either traffic lights or barriers. The alternative traffic flow should be established through the whole tunnel, separating traffic lanes with cones or light barriers, which should be reinforced by additional devices on approaching, and in the area of the works themselves

4. NEW DEVELOPMENTS

In Germany a method has been developed to decide on the question: emergency lane yes of no? The extra costs of construction are weighed against the lesser costs due to less congestion and less damage. It turns out that only for tunnels on motorways with a high Intensity/Capacity ratio the addition of an emergency lane can be economical.
This method has stimulated the Dutch Centre for Tunnel Safety to set up a decision supporting model, also based on the economic pro’s and con’s, but this time taking into account the costs of wounded and dead due to accidents.