Comparison and Review of Safety Design Guidelines for Road Tunnels

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Fire Technology

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Abstract

Many road tunnels are built worldwide each year for various reasons. Some drivers may enjoy the reduction of travel time or the convenience of driving. On the other hand, for those who are engaged in fire safety, an increase in the number of road tunnels presents another problem at the same time because road tunnels have more danger potential than normal structures with the viewpoint of fire prevention and suppression. However satisfactory safety measures against fires have not yet established or are in process of development.

This study pays attention to the ways of ensuring advanced fire safety level of road tunnels on the tunnel design stage. A few kinds of road tunnel guidelines of several countries and organizations are compared to each other. The main focus of the comparison is the application criteria of guidelines and installation spacing. The comparison provides several interesting discussion topics; similarities or differences between detailed requirements and popularity of each fire safety equipment or facility. In particular, it contributes to lead specific recommendations to be proposed for Korean fire and road authorities which main author works for. The recommendations and the discussion may also help tunnel countries to examine their existing guidelines and develop better ideas for new guidelines.

Key words: fire safety guideline, tunnel category, annual average daily traffic, fire safety equipment, fixed fire suppression system, sprinkler system in tunnels.

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Preface

This study has been sponsored by the Korean Government Long-Term Fellowship Program and SP Technical Research Institute of Sweden. This Fellowship is aimed at providing advance training for middle officials of the Korean Government by sending them abroad for two years of post-graduate study. Hak Kuen Kim, the main author of this report, has worked as a fire officer for 10 years in Korea. During his service, he has experience from various fields of public fire safety, including: fire fighting, enforcement and the revision of regulations, planning and budget in the national and the municipal emergency services. In 2006, he was selected to receive this fellowship. Now he is working for the Fire Technology Division of SP as a guest researcher. After his 2-year study, he will return to Korea. The experience and knowledge gained in Sweden will contribute to the development of fire safety in Korea.

1 Introduction

The Korean economy has advanced briskly since the 1970's coupled to development in civil engineering. Many road and tunnels have been built nationwide to speed up the transportation of resources and people. In 1996, the number of road tunnels was 170. In 2005, this number had increased to 817, with a steady increase as shown in Table 1.1 and in Figure 1.1 [1]. Building a road tunnel can contribute to the decrease of environmental pollution and enhance the convenience for passengers. On the other hand, it poses safety problems to be solved and safety in road tunnels is emerging as a major issue.

In 2003, a significant fire occurred in the Hongjimun tunnel which is located in Seoul. All traffic around the tunnel was stopped for more than 2 hours and many tunnel users[1)] were frightened by this incident. Moreover, this accident was televised throughout the nation and people realized the seriousness of fire safety in road tunnels. In 2005, another tunnel fire attracted the public's attention. A truck carrying a missile propellant caught fire and subsequently exploded. This fire accident caused the government to investigate whether existing fire safety guidelines of road tunnels are acceptable to ensure tunnel users' safety. A large number of engineers, scientists and government officers started examining the actual condition of road tunnels and tried to find reasonable solutions. As the result of their efforts, some guidelines for road tunnels have been revised in 2004 and 2005 to strengthen their requirements for fire safety equipment. However, it is not easy to evaluate to what extent revised requirements represent improvements or whether they can be accepted as reasonable guidelines when they are compared to those in other countries.

In this study, tables of comparisons have been compiled from various guidelines and recommendations for countries and organizations, in order to compare the fire safety level in each country. The countries included in this study include: some European tunnel countries, USA, Australia, Japan and Korea. Further, recommendations from EU, UNECE (United Nations Economic Commission for Europe) and PIARC (World Road Association) were reviewed for more information. This work can contribute to the evaluation of standard levels of fire safety and improve the requirement of future tunnel guidelines.

Table 1.1 Increase in total number and length of road tunnels in Korea [1].

Road Tunnel	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
The Total NO.	170	184	312	351	397	528	583	603	667	817
The Total Length (km)	136	150	174	212	240	339	378	390	432	551

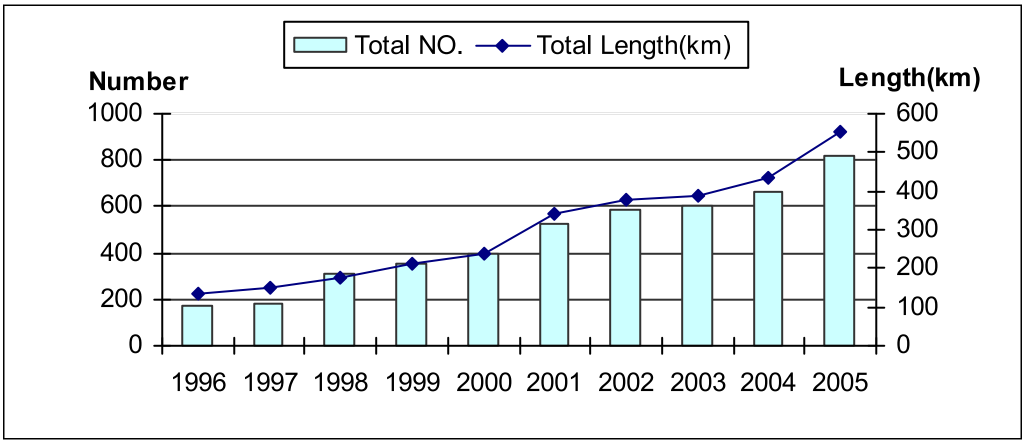

Figure 1.1 Increase in total number and length of road tunnels in Korea [1].

[1)] In this study, "tunnel users" mean drivers and passengers of vehicles in road tunnels.

1.1 Fire safety guidelines for road tunnels studied

Many fire safety documents for road tunnels have been compared in this study. Table 1.2 lists their titles, ID, type of document, publishers and publishing year. The structures and administrative status of documents differ depending on their nature or purpose. However, the word "guidelines" as used in this study also includes regulations, standards, and directives as well as guidelines themselves. Documents related to design of road tunnels can be classified and defined like below [2];

- **Regulation documents** contain specific mandatory requirements and are produced by a legal government entity.
- **Standard documents** contain mandatory language, and they are usually produced by a technical entity such as an association or society. These documents by themselves have no legal standing except where they have been adopted by or on behalf of a government agency by legislative action.
- **Guideline documents** provide, to the reader, recommended practices which can be applied in the design, construction, installation, operation and safety of the fire life safety and fire protection systems in a road tunnel. These documents are usually prepared by technical associations: however some have been prepared by governmental agencies.

A legislative document as a directive has another status than a guideline and this is important to remember when comparing the different documents.

Table 1.2 Guidelines of different countries included in the comparison [3, 4, 5].

Country	Title	ID	Type	Publisher/Year	Ref.
Australia	Fire Safety guideline for road tunnels	-	Guideline	Australasian Fire Authorities Council (2001)	6
Austria	Guidelines and Regulations for Road Design	RVS	Guideline	Transportation and Road Research Association (2001)	7
France	Inter-ministry circular n°2000-63 of 25 August 2000 relating to the Safety of tunnels in the national highways network	Circ 2000/63A2	Regulation	Ministry for intra structure, transport, spatial planning tourism and the sea (2000)	8
Germany	Guidelines for equipment and operation of road tunnels	RABT 02	Guidelines	Road and Transportation Research Association (2002)	9
Japan	Design Principles, Volume 3 (Tunnel) Part (4) (Tunnel Safety facilities)	-	Guideline	Japan Highway Public Corporation (1998)	10
Korea	National Fire Safety Codes	NFSC	Regulation	Korea National Emergency Management Agency (2005)[a)]	11
	Guideline for Installation of Safety facility in road Tunnels	GIST	Guideline	Ministry of Construction & Transportation (2004)	12
Norway	Roads Tunnels	Håndbok 021	Guideline	Norwegian Public Roads Administration, Directorate of Public Roads (2004)	13
Sweden	Tunnel 2004	Tunnel 2004	Guideline	Swedish National Road Administration (2004)	14

Country	Title	ID	Type	Publisher/Year	Ref.
UK	Design manual for roads and bridges, Volume 2 Highway structure design Section 2, Part 9, BD 78/99: Design of road tunnels	BD78/99	Guideline and Requirement	The Highway Agency (1999)	15
USA	Standard for road tunnels, bridges and other limited access Highways	NFPA 502	Standard	National Fire Protection Association (2004)	16
EU	Directive2004/54/EC of the European parliament and of the council	Directive 2004/54/EC	Directive (Regulation)	European Parliament and the Council (2004)	17
PIARC	Fire and Smoke Control in Road Tunnels	PIARC	Guideline	PIARC (1999)	18
UNECE	Recommendations of the Group of Experts on Safety in Road Tunnels. (Final Report)	TRANS/AC. 7/9	Guideline	UNECE Ad hoc Multidisciplinary Group of Experts on Safety in Tunnels (2001)	19

a) New regulations dealing with the fire safety in road tunnels has been established on 27 July 2007.

2 Korean guidelines

This report compares guidelines of different countries, but has a special focus on Korea. Therefore the guidelines of interest in Korea are presented in more detail in this section. There are two guidelines concerning the fire safety of road tunnels in Korea. One is NFSC and the other is GIST. NFSC is an acronym for National Fire Safety Codes. It is under the jurisdiction of NEMA (National Emergency Management Agency). This code consists of 32 specific notifications and each notification regulates the specifications of fire safety equipment. There is no single notification which deals with all fire safety equipment in road tunnels. Further, NFSC does not contain general safety equipment for road tunnels such as emergency lanes, emergency bays and CCTV (Closed-Circuit Television). Its main interest is fire safety equipment used in case of a fire.

GIST is an acronym for Guideline for Installation of Safety facility in road Tunnels. It has been established by the Ministry of Construction & Transportation of Korea and was revised in 2004. It deals with safety equipment for road tunnels, for example, parallel escape tubes, emergency cross-passages and emergency telephones as well as hand held extinguishers and pressurized hydrants.

The relationship between the two guidelines appears to be complementary. GIST adopts many of the NFSC requirements as their provisions although some specific application limit and installation spacing may differ between the two. However, GIST is a stricter guideline associated with fire safety for tunnel than NFSC at present. NFSC gives tunnel designers or owners more freedom, which lets them decide the safety level of the tunnel depending on risk analyses and performance criteria.

In conclusion, it can be said that when a new road tunnel is planned, the tunnel designers follow GIST and also refer to NFSC for more detailed information on fire safety equipment. The detailed requirements for road tunnels of NFSC and GIST are shown in Table 2.1 and 2.2.

Table 2.1 Summary of NFSC related to road tunnels

Fire Equipment		NFSC (National Fire Safety Codes)	
		Before the revision	Existing requirements (2004 version)
Fire Suppression	Hand held extinguisher	All Tunnels. Small sized extinguishers[a)]: at every 20 m. Large sized extinguishers[b)]: at every 30 m. Two 3.3 kg extinguishers.	All Tunnels. At every <**50 m** on **the both sidewalls of lanes.** Two 3.3 kg extinguishers (≥ 3 unit capacity).
	Pressurised fire hydrants system	≥1000 m tunnels. At every ≤25 m. 130 L/min, 0.17 MPa	≥1000 m tunnels. At every **<50 m.** 130 L/min, 0.17 MPa
	Fixed fire suppression system	No reference	No reference
Detection & Warning	Alarm push button	≥500 m long tunnels. At every ≤25 m spacing	≥500 m tunnels. At every **<50 m**
	Loudspeakers	No reference	No reference
	Automatic fire detection system	No reference	**≥1000 m tunnels**
Evacuation	Emergency exit signs	No reference	No reference
	Emergency lighting	≥500 m tunnels. Not more detailed information	≥500 m tunnels. Not more detailed information
Assistant Firefighting	Smoke control ventilation	No reference	**≥1000 m tunnels**
	Fire department connections	≥2000 m long tunnels	≥2000 m tunnels
	Fire brigade power tool sockets	≥500 m tunnels. At every ≤25 m	≥500 m tunnels. At every **<50 m**
	Radio rebroadcasting for fire brigade	≥500 m tunnels	≥500 m tunnels

Note: The data written in bold indicate that they have been revised in 2004.
a) Small sized extinguishers have from 1 to 9 unit capacity.
b) Large sized extinguishers have ≥10 unit capacity for Class A fire or ≥20 unit capacity for Class B fire. Unit capacity indicates the extinguisher's ability to suppress fires. When an extinguisher can extinguish 2 types of wood cribs it can be designated as 3 unit capacity extinguishers. The wood cribs consist of 144 and 90 wooden sticks, respectively.

Table 2.2 Summary of GIST related to road tunnels

Fire equipment	Class 1	Class 2	Class 3	Class 4	Comment
Hand held extinguisher	●	●	●	●	At every <50 m
Pressurised fire hydrants	●	●	-	-	At every <50 m
Water mist system	△	-	-	-	Installation is recommended if the tunnel length is ≥3000 m and ≥60×10^3 veh×km/day/tube for bi-directional tunnel or uni-directional urban tunnel. For uni-directional tunnel in non-urban area, 90×10^3 veh×km/day/tube.
Alarm push button and siren	●	●	●	-	-
Automatic fire detection system	●	●	● a)	-	a) tunnels are bi-directional traffic or uni-directional traffic in urban areas.
Loudspeakers	●	●	●	-	At every <50 m
Emergency telephone	●	●	●	-	At every <250 m
CCTV	●	●	● b)	-	b)) tunnels are bi-directional traffic or uni-directional traffic in urban areas.
Radio rebroadcast	●	●	●	△ c)	At every 200-400 m. c) only if ≥200 m tunnels
Information sign (Lane-use Control Sign)	●	●	-	-	At every 400-500m.
Emergency lighting	●	●	●	● d)	d) only if ≥200 m tunnels
Emergency exits sign	●	●	●	-	-
Emergency cross passage	●	●	●	-	250–300 m spacing
Parallel escape tube	● e)	△ f)	-	-	e) Bi-directional tunnel or uni-directional tunnels with more than 2.0 of risk index. f) Bi-directional tunnels or uni-directional urban tunnels expected to be congested.
Shelters	● e)	△ f)	-	-	
Emergency stopping lane	●	●	-	-	-
Smoke control ventilation	●	●	●		In tunnels with bi-directional traffic or congested uni-directional tunnels.
Wireless communication system for fire brigade	●	●	●	△ g)	g) If radio communication systems are installed
Fire department connections	●	●	-	-	At every <50 m
Fire brigade power tool sockets	●	●	●	-	At every <50 m
UPS system	●	●	●	● h)	h) Only if any fire equipment is installed
Emergency generator	●	●	● i)	-	i) tunnels are bi-directional traffic or uni-directional traffic in urban areas.

Note that the symbols “● ”and “△ ” indicate required and recommended facilities respectively.
Class 1: ≥3000 m, Class 2: ≥1000 m but <3000 m, Class 3: ≥500 m but <1000, Class 4: <500 m tunnels.

3 Establishment of requirements

When specific requirements of fire safety equipment are established, two ways of approaches can be found in most countries studied: tunnel length system and combination system of tunnel length and other parameters.

Tunnel length systems determine the requirements or recommendations by the length of the tunnels. They consist of a few length intervals which have a certain range of values. Although it is occasionally found in some tunnel length systems that some parameters such as traffic volume and traffic types of tunnels affect the application of the guidelines. However, their influences are substantially limited and the related requirements should be regarded as an exception for principles. A typical example of tunnel length systems is presented in Figure 3.1.

Sicherheitsanlagen	Tunnellängen	≤ 400	> 400 ≤ 600	> 600 ≤ 900	> 900
Bauliche Anlagen	Seitenstreifen	○	○	○	○
	Pannenbuchten 1)			○	●
	Wendebuchten 2)			○	●
	Notausgänge		●	●	●
	Notgehwege	●	●	●	●
	Höhenkontrolle	○	○	○	○
Kommunikations-einrichtungen	Notrufstationen	3)	●	●	●
	Videoüberwachung	○	●	●	●
	Tunnelfunk 6)	●	●	●	●
	Lautsprecheranlagen	7)	●	●	●
Brandmeldeanlagen	Manuelle Brandmelde-einrichtungen		●	●	●
	automatische Brandmeldeeinrichtungen	4)	●	●	●
Löscheinrichtungen	Handfeuerlöscher		●	●	●
	Löschwasserversorgung	6)	6)	●	●
Brandnotbeleuchtung			●	●	●
Fluchtwegkennzeichnung		●	●	●	●
Leiteinrichtungen / Visuelle Führung		●	●	●	●

● Standardausstattung
○ Ausstattung bei besonderer Erfordernis (z.B. Lkw-Fahrleistung ≥ 4000 Lkw × km / Röhre und Tag)

Figure 3.1 Summary of requirements of Germany [9].

The combination systems are based mainly on the matrix of the tunnel length and traffic volume. Each parameter is considered for elevation to the upper categories which require more safety measures. The categories of tunnels with heavy traffic volume or long length are elevated into the higher ones. In general, the traffic volume is given in AADT (Annual Average Daily Traffic, unit: no. of vehicles) which is the estimated average daily traffic volume in both directions of a tunnel bore after opening. In addition to traffic volume, risk analyses are adopted for the formation of matrix in some countries. A typical example of combination systems is shown in Figure 3.2.

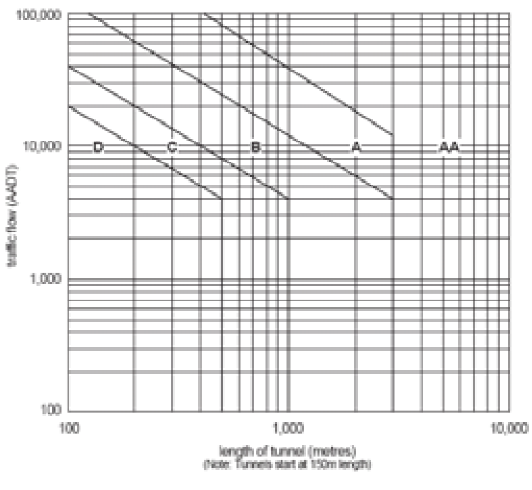

Figure 3.2 Road tunnel categories of UK [15].

3.1 Tunnel length systems

The tunnel length systems are established in five tunnel countries: France, Germany, Korea (NFSC), USA and EU. Typical examples are NFSC of Korea and NFPA 502 of USA where requirements are dependant only on the tunnel length. The other countries occasionally consider supplement factors such as traffic volume and tunnel location when they apply their guidelines to the tunnel concerned. However, these factors do not have influences throughout guidelines.

There are large differences in length intervals and the minimum length for application between countries. France has more divided length intervals and more supplement factors than NFSC of Korea and NFPA 502 of USA which has only three length intervals. Comparisons of the tunnel length systems are shown like Table 3.1.

Table 3.1 Comparisons of the tunnel length systems in different countries

Country	No. of length interval	Notch value (m)	Minimum length of application	Supplement factor
France	7	300, 500, 800, 1000, 1500, 3000, 5000 m	300 m	Location, traffic type, traffic volume
Germany	4	All tunnels, 400, 600, 900 m	All tunnels	Traffic volume
Korea (NFSC)	4	All tunnels, 500, 1000, 2000 m	All tunnels	-
USA	3	90, 240, 300 m	90 m	-
EU	3	500, 1000, 3000 m	500 m	Traffic volume

3.2 Combination systems of tunnel length and traffic volume

Combination systems are adopted in six countries among the ones studied here: Austria, Japan, Korea (GIST), Sweden, Norway and the UK.

The categories of Japan, Sweden, Norway and the UK are decided by the matrix of tunnel length and traffic volume. Categories of Norway are affected by traffic volume more than length. Korea (GIST) carries out the risk analysis for determining the elevation to upper categories which is based on the evaluation of six risk factors. Traffic volume is also included into these six factors. In particular, Austrian classification is determined by traffic volume per hour, not AADT and other factors such as mean directional split and number of dangerous goods transports. All tunnels seem to be considered for application in Austria.

In Sweden, there are three tunnel categories: TC, TB and TA (See Figure 3.3). They are decided, depending on tunnel length and traffic volume which is the average annual daily traffic (AADT) estimated 20 years since the opening of the tunnel.

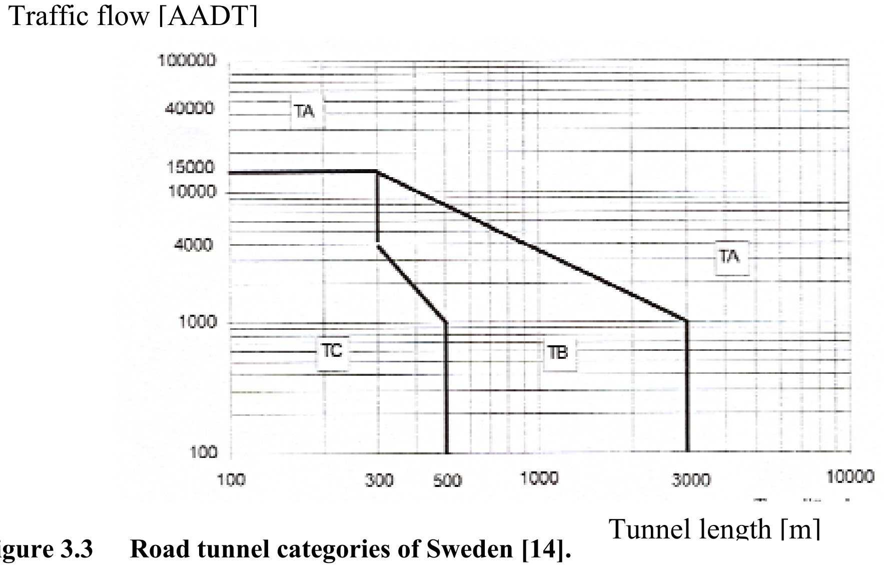

Figure 3.3 Road tunnel categories of Sweden [14].

In Japan, all tunnels are classified as five categories: AA, A, B, C and D, depending on the annual average daily traffic flow (AADT) and the tunnel length as shown in Figure 3.4. The AADT is the estimated traffic volume 10 years after opening [10].

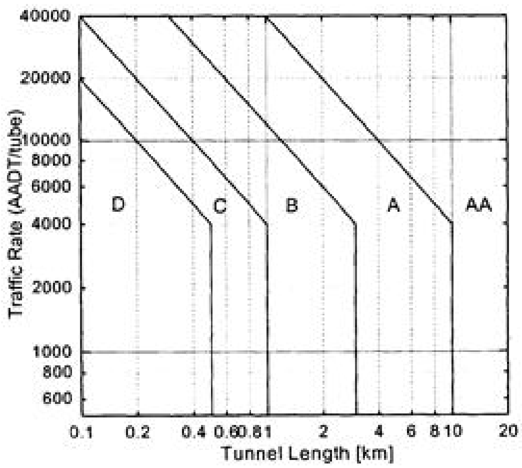

Figure 3.4 Road tunnel categories of Japan [3].

In the UK, the provision of safety facilities is related to the annual average daily traffic flow (AADT) for the tunnel design year, which is typically 15 years from the date of opening, and the length of the tunnel. Tunnels are separated into categories AA, A, C, C, D and E according to length AADT as shown in Figure 3.2. Categories for AADT in excess of 100,000 vehicles per day may be calculated by extrapolation of the graph. The UK gives the recommended basic provisions for each category. The provisions should be regarded as starting point for establishing design requirements rather than be rigidly adhered to if there are valid reasons not to do so [15].

In Norway, the tunnel categories are based upon traffic volume and tunnel length. (See Figure 3.5. The traffic volume is normally given in AADT (Annual Average Daily Traffic volume) which is the total annual traffic divided by 365 and is given as the estimated total traffic volume in both directions, twenty years after opening, AADT(20). In addition, the tunnel categories are the basis for a specific cross-section, number of traffic lanes, need for emergency lay-bys and turning points together with safety equipment. For example, Tunnels with a single lane (AADT< 300 on country roads) are defined as Tunnel

Category A. The cross-section of these tunnels is shown in Figure 3.5 where 5.5 means that the total width of the road surface is 5.5 m. If traffic volume AADT(20) prescribes tunnel Category E, a decision of when to construct the second tube shall be made [13].

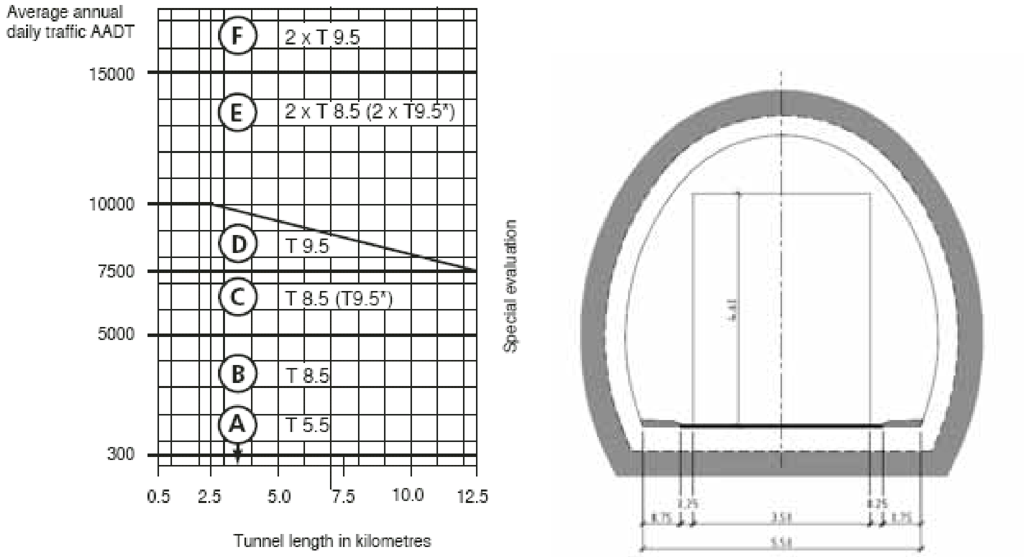

Figure 3.5 Road tunnel categories and tunnel cross-section T5.5 of Norway [13]

In Korea, GIST, which is one of the guidelines concerning the fire safety of road tunnel, adopts the system of tunnel categories as shown in Table 3.2. Basically, the categories are determined by the tunnel length but after a risk analysis they can be elevated to upper categories which have more danger potential. The risk analysis is carried out by evaluating six risk factors as shown in Table 3.3. The elevation of categories happens if the arithmetic average of index values of all risk factors is over 2. However, this consideration does not apply to Class 4 [12].
For example, when a new tunnel is designed as 1500 m long one, it is designated as Class 2. However, if risk factors from 1 to 6 are 4, 2, 3, 2, 3, 1 respectively, the average is 2.5 and the class of the tunnel is revised into Class 1.

Table 3.2 Road tunnel categories of Korea [12].

Class	Tunnel length (L)
Class 1	L ≥ 3000 m
Class 2	1000 ≤ L < 3000 m
Class 3	500 ≤ L < 1000 m
Class 4	L < 500 m

Table 3.3 Determination of risk analysis in Korea [12]

Risk factor	Risk factor	Scope	Risk degree	Index
1	AADT [a)] * tunnel length (AL) (10^3 Veh·km/tube·day)	AL < 8	Very low	1
		8 ≤ AL < 16	Low	2
		16≤ AL < 32	Medium	3
		32 ≤ AL < 64	High	4
		AL ≥ 64	Very high	5
2	Gradient (G)	G < 1 %	Low	1
		1% ≤ G < 3 %	Medium	2
		G ≥ 3 %	High	3
3	Percentage of HGV (H)	H < 10 %	Low	1
		10 % ≤ H < 25 %	Medium	2
		H ≥ 25 %	High	3
4	The passage of dangerous goods	Prohibited	None	0
		Allowed	High	2
5	Congestion (C)	C ≥ Service level [b)] C	Low	1
		C ≥ Service level D	Medium	2
		C ≥ Service level E	High	3
6	Traffic type	Uni-directional	Low	1
		Bi-directional	High	3

a) Estimated traffic volume 20 year after opening.
b) Service levels are developed to classify the degree of congestion of road tunnels and determined by the combination of the traffic speed and volume etc.

In Austria, the classification is determined by the danger class (See Table 3.4), which follows from the danger potential of the tunnel concerned. The danger potential, G, is defined as $G = MSV \times g_R \times g_K \times g_G$, where the traffic volume per hour (MSV) is given as the 30[th] hour peak traffic volume. Lorries have to be considered using the personal car equivalent of 2.5. For the other factors, g_R indicates mean directional split, g_K means additional points that may cause conflicts (merging lanes and/or crossings in the tunnel and in the portal areas) and g_G indicates permission or number of dangerous goods transports respectively [20].

Table 3.4 Road tunnel categories of Austria [7].

Danger potential, G	Danger class
Up to 1000	I
1001 to 2500	II
2501 to 10000	III
More than 10000	IV

It is difficult to make any general comparison between the different tunnel categories. However, it is clear that most of the countries which adopt the tunnel category systems, use the combination of the traffic volume and tunnel length. Categories of Norway are mainly affected by traffic volume and in one case both traffic volume and tunnel length. On the other hand, in Korea, tunnel length is the main factor which determines the category. Austria and Korea carry out the risk analysis when they decide the categories of tunnels.

The specific criteria of two parameters which determine the categories vary among the countries; the minimum lengths of tunnel for application of guideline are all tunnels (Korea), 100 m (Japan and Sweden), 150 m (the UK) and 500 (Norway). The minimum values of AADT are 100 (Sweden and the UK), approximately 250 (Norway), and 500 (Japan). The numbers of the categories are three (Sweden), four (Austria and Korea), five (Japan and the UK) and six (Norway). In addition, the methods for calculating AADT are different in the five countries: 10 (Japan), 15 (the UK) and 20 (Korea, Norway and Sweden) years after opening. The comparison of the category systems studied is presented in Table 3.4.

Table 3.1 Comparison of the combination systems in different countries.

Country	The number of category	Minimum lengths of tunnel for application of guideline (m)	Minimum values of AADT	Estimation year of AADT after opening (year)
Sweden	3	100	100	20
Japan	5	100	500	10
UK	5	150	100	15
Norway	6	500	250	20
Korea	4	All tunnels	All AADT	20
Austria	4	All tunnels	Traffic volum per hour.	-

It is known that there are advantages in adopting a tunnel category system to decide the basic safety facilities to be installed for the safety of road tunnels. However, care should be taken when such a system is selected and used, as each tunnel has its own nature and environment and some of the differences are not considered by the category systems.

3.3 Comparison of establishment of requirements

It is interesting that Korea adopts different application systems in two governmental documents dealing with fire safety issues for road tunnels: tunnel length system in NFSC and combination system in GIST. Each system has its own advantages and disadvantages and preference for systems is solemnly up to each country. However, optimal balance between tunnel length and traffic volume seems to be the best for ensuring the fire safety because tunnels are special structures where vehicles pass by unlike the general buildings.

For clear understanding and distinguishment, comparison between tunnel length system and combination system is presented in Table 3.5.

Table 3.5 Comparison between tunnel length system and combination system.

Comparative Items	Tunnel length system	Combination system
Key factor	Tunnel length	Tunnel length and traffic volume (AADT)
Supplementary factor	Traffic volume, tunnel location, types of traffic etc.	Rrisk analysis etc.
Elevation to upper classes	Limited and exceptional.	General consideration.
Advantage	Easy to understand. Simple application of guideline.	Reflection of both traffic volume and tunnel length.
Disadvantage	Underestimate of the importance of traffic volume.	Difficulty in estimating expected traffic volume.
Country	France, Germany, Korea (NFSC), USA, EU	Austria, Japan, Korea (GIST), Sweden, Norway, the UK

4 Comparison and discussion

In the following a tabulated summary of regulations world-wide is given for different types of application fields. The specific figures and information has been compiled from several literature sources. To distinguish each literature source, different text styles are used in this section. The requirements written in Italics have been taken from the paper "Fire safe Design, Road Tunnels" [20] written by Niels Peter Høj in 2003. Underlined data have been obtained from a document "A study on revision in guideline of safety facilities in road tunnels (Korean)" [3] written by Korean Tunneling Association (KTA) in 2004. Requirements written using normal font come from the original guidelines (Australia, France, Korea, Norway, Sweden, the UK, USA, EU Directive, PIARC and UNECE). The examples are shown like these; *a) this type of text means that the information used is obtained from the Høj's document,* b) this type of text means that the information used is obtained from KTA's document, c) this type of text means that the information used is obtained from the original guidelines.

4.1 Fire fighting facilities

4.1.1 Hand held extinguishers

Hand held extinguishers are regarded as an effective apparatus in the early stages of a fire. According to an investigation in Japan by the Sudo Highway Public Corporation, hand held extinguishers have been used more frequently than any other apparatus when extinguishing tunnel fires; 53 % of all fires in Japan (1962–1992) have been suppressed by hand held extinguishers only [3].

The requirements of hand held extinguishers in different countries are shown in Table 4.1.

Table 4.1 Hand held extinguishers in different guidelines.

Country		Application criteria	Capacity & Spacing	Comment
Korea	NFSC	All tunnels	Two 3.3 kg (≥3 Unit capacity). <50 m Spacing.	-
	GIST	All tunnels	Two 3.3 kg (≥3 Unit capacity) extinguishers. <50 m Spacing.	Extinguisher removal alarms recommended.
Australia		-	Dry chemical extinguishers (equipment niche, 60m spacing) and CO_2 extinguishers [a)]	a) adjacent to all electrical switchboards, control panels etc.
Austria		*>500 m*	*6 l and 9 l extinguishers,* *250 m spacing.* *(at each fire fighting equipment recess and emergency telephone station)*	*Automatic alarm on opening door to extinguisher.*
France		≥300 m	Two 6 kg (unit capacity) and at least 13A and 183B performance. 200 m spacing (emergency recesses)	Extinguisher removal alarms may be provided.
Germany		*>400 m*	*Two 6 kg (net) extinguishers,* *<150 m spacing* *(at emergency call station)*	*Automatic alarm on equipment.*

Country	Application criteria	Capacity & Spacing	Comment
Japan	Class D (≥100 m)[b)]	Two 6 kg extinguishers, 50 m spacing.	b) It means that the minimum length of Class D is 100 m.
Norway	Category ≥B	Two (Category D and F) 6 kg extinguisher (NS EN 3) Category B: 250 m spacing [c), d)] Category C, D: 125 m spacing [c), d)] Category E: 125 m spacing [c)] Category F: 62.5 m spacing [c)] c) Additionally installed outside each tunnel entrance. d) Mounted on one side at given spacing and located together with all emergency telephones on the opposite side.	Extinguisher removal alarms should be provided
Sweden	All classes	In tunnel ≥500 m there should be extinguishers at each portal and at least every 150 m.	The extinguisher should fulfil SS-EN 3-7. They should contain 6 kg ABC-powder and manage the test fires 34A and 183B.
UK	Class AA, A and B	Two extinguishers (13A fire ratings of BS EN 3 Part 1) 50 m spacing (emergency point)	Class C tunnels can be applied.
USA	≥240 m[e)]	9 kg (maximum) extinguishers (2-A: 20-B: C). ≤90 m spacing	e) ≥240 m where the maximum distance from any point within the tunnel to a point of safety exceeds 120 m, otherwise ≥300 m. This exception applies to all the comparable tables bellow.
EU	≥500 m (with exceptions)	Two extinguishers. ≤150 m spacing (≤250 m in existing tunnels)	At emergency stations together with a telephone.
PIARC	-	The minimum content of 6 kg when the traffic includes mainly passenger cars. The maximum of 9 kg when heavy goods vehicles are numerous.	Extinguisher removal alarms recommended.
UNECE	-	-	Fire extinguishers should be installed systematically in tunnels and at their entrances.

Note: In the table, *Italics*: Høj [20], underline: KTA [3], normal font: Original guideline.

Hand held extinguishers are included in all guidelines studied. This indicates that a portable extinguisher is one of the basic pieces of equipments in road tunnels. The application criteria do not show significant differences between guidelines. The minimum length of targeted tunnels varies from all tunnel lengths to 500 m: all tunnel lengths in Korean regulations, 100 m in Japan, 240 m in USA, 300 m in France, 400 m in Germany and 500 m in Sweden and EU with exceptions. Norway and the UK have minimum application classes: Category B in Norway and Class B in the UK. However, the installation spacing varies considerably; the maximum spacing is from 50 m (Korea, Japan and the UK), 60 m (Australia), 90 m (USA), 150 m (Germany, Sweden, and EU), 200 m (France) and 62.5–250 m (Norway) and 250 m (Austria). It is common that the extinguishers are provided in emergency recesses with other facilities such as emergency phone and hydrants. For that reason, the spacing of extinguishers corresponds to that of emergency recesses or emergency call stations.

Almost all countries (Austria, France, Germany, Japan, Norway, Sweden, USA and PIARC) in this section require at least two 6 kg-extinguishers. In Austria and the USA, 9 kg-extinguishers are recommended. Further, CO_2 extinguishers, installed adjacent to all electrical switchboards, control panels etc. are mentioned in the Australian guidelines. Korea requires two extinguishers which have three unit-capacity as minimum capacity. In general, a 3.3 kg-extinguisher is regarded to have three unit-capacity and used as a home fire extinguisher in Korea. Unit-capacity indicates the extinguisher's ability to suppress fires. When an extinguisher can extinguish two types of wood cribs which consist of 144 and 90 wooden sticks respectively, it is designated as a three unit-capacity extinguisher. It seems to be doubtful whether two 3.3 kg-extinguishers with three unit-capacity each have sufficient abilities to suppress tunnel fires effectively. Almost all fires which occur in tunnels are vehicle fires or vehicle related fires. Vehicles contain a certain amount of flammable fuels and in particular trucks often carry heavy loads of flammable goods. In addition, typical tunnel environments such as existing air flow and restriction of access make it difficult for tunnel users to control fires. For these reasons, extinguishers installed in road tunnels should have more capacity than those used in houses or general buildings.

The provision of automatic alarms on equipment can be found in the guidelines of Austria, France, Germany, Norway, the UK and PIARC. However, there is no provision in NFSC of Korea concerning extinguisher removal alarms which would enable tunnel operators to be informed of the use of their equipment should an extinguisher be removed. For quick response in tunnel fires, efficient equipment removal alarm systems are necessary.

4.1.2 Water supply and hydrants

Pressurized fire hydrants are connected to the water mains or the tanks of water that are used by tunnel users or by the fire brigades. They have a greater capacity than hand held extinguishers. It is desirable that only trained persons handle the equipment because a novice could damage the equipment or hurt other people in the immediate vicinity.

The requirements of water supply and hydrants in different countries are shown in Table 4.2.

Table 4.2 Water supply and hydrants in different guidelines.

Country		Application criteria	Capacity & Spacing (hydrants)	Comment
Korea	NFSC	≥1000 m	130 L/min, 0.17 MPa ($1.7\ kgf/cm^2$) <50 m spacing	Minimum water discharging time: 20 min
	GIST	≥1000 m	190 L/min, 0.3 MPa ($3\ kgf/cm^2$), <50 m spacing	Minimum water discharging time: 40 min
Australia		-	At 60 m spacing At 60 m spacing (hose reels)	Unequipped hydrants with fittings are located in each equipment niche.
Austria		*Class III,IV*	*1200 L/min (20 L/s), 0.6 MPa, 250 m spacing*	*Recommended for all classes Minimum water discharging time: 60 min.*

Country	Application criteria	Capacity & Spacing (hydrants)	Comment
France	≥300 m (urban). ≥500 m (non-urban)	1000 L/min (60 m^3/h), 0.6 MPa, 200 m spacing.	-
Germany	*≥600 m or ≥400 m if >4000 HGV[a)] ×km/tube/day*	*1200 L/min, 0.6-1.0 MPa (6-10 bar) <150 m spacing*	*For <400 m tunnels, Fire hydrant shall be placed at the portals*
Japan	≥Class A or Class B (≥ 1000 m)[a)]	130 L/min, 0.17 MPa, (1.7 kgf/cm^2), 50 m spacing	a) Class B (≥ 1000 m) indicates that tunnels are Class B and their lengths are ≥1000 m.
Norway	≥Class B	-	- Water for fire extinguishing • Separate wells (about 6 m^3) linked to the drainage system. • tank vehicle (approx. 6 m^3)
UK	Class AA, A, B, C	100 m: Hydrants 50 m: Fire hose reels	For Class D tunnels, fire hydrants can be applied. Fire hose reels normally provided in tunnel Class AA, to be considered in Class A, B, C.
USA	≥90 m	≤1920 L/min (500 gpm, flow rate). 0.69 MPa (6.9 bar) ≤ 85 m spacing	Standpipe systems shall have an approved water supply that is capable of supplying the system demand for a minimum of 1 hour.
EU	≥500 m	≤ 250 m (hydrant)	Hydrants: At near the portals and inside the tunnels.
PIARC	200–1000 m (according to the case)	1000 L/min, 0.5 MPa (standpipe) 100-200 m (hydrants)	-
UNECE	-	-	Water supply should be prepared for firemen

Note: In the table, *Italics*: Høj [20], underline: KTA [3], normal font: Original guideline.
a) HGV means heavy goods vehicles.

Most EU nations require the installation of pressurized fire hydrants in tunnels longer than 300 m (urban, France) – 600 m (Germany). Korea and Japan only require the tunnel designers to set up fire hydrants in tunnels longer than 1000 m. In addition, the water pressure and flow rate of the hydrant in the Korean guidelines are low compared to those required in most European countries. The water pressure and flow rate in European guidelines are 0.4–1.0 MPa and 1000–1200 L/min, respectively. The requirements of Korea for pressure and water flow are 0.17-0.3 MPa and 130–190 L/min, respectively.

The installation distance of fire hydrants is 50 m in Korea and in Japan. In European countries it is in the range of 50 m to 250 m, in USA it is 85 m and Australia it is 60 m.

The minimum water discharging time is also presented in some guidelines: 20 minutes (NFSC, Korea), 40 minutes (GIST, Korea), and 60 minutes (Austria and USA). Note that the minimum time is considerably shorter in Korea than in Austria and the USA.

4.1.3 Fire department connections

Fire department connections are designed to provide fire fighters close to the accident with sufficient water to extinguish fires through water outlets installed outside tunnels. These connections usually consist of plumbing, water inlets, water outlets, water discharge apparatus, and pumps. Such requirements can be found in American, Japanese, Korean, Swedish and the UK guidelines.

It is interesting to note that fire department connections are not specified in the guidelines of European countries with the exception of Sweden and the UK. Instead, the various European guidelines strengthen the capacity of hydrants, such as discharge time and discharge volume of water. Further study is needed to determine to what degree these requirements are complementary, i.e. whether the installation of fire department connections does obviate the need for long hydrant discharge times for example.

The requirements of fire department in different countries are shown in Table 4.3.

Table 4.3 Fire department connections in different guidelines

Country		Application criteria	Spacing of hose connections	Comment
Korea	NFSC	≥2000 m	<50 m	Discharge equipment such as nozzles and hoses shall be prepared beside discharge valve.
	GIST	≥Class 2 (≥1000 m)	<50 m	Water outlets are to be spaced inside hydrant cabinets.
Japan		Class A, Class B (≥1000 m)[a)]	-	a) Class B (≥1000 m) indicates that tunnels are Class B and their lengths are (≥1000 m).
Sweden		All classes	≥Class TB: at each portal and at least every 150 m	-
UK		Class AA.	100m	To be considered in Class A and B.
USA		≥ 90 m	≤85 m	-

Note: In the table, *Italics*: Høj [20], underline: KTA [3], normal font: Original guideline.

The National Fire Protection Associate (NFPA), based in the USA, requires the installation of standpipe systems, when the tunnel length is 90 m or greater. In Korea and Japan, greater tunnel lengths (1000 m or 2000 m) are specified. The recommended distances between water outlets are shorter in Korea (50 m) than in the USA (85 m) and the UK (100 m) and Sweden (150 m). Up until year 2004, the nominal length of a tunnel requiring such installations in Korea was 2000 m according to GIST and NFSC. In 2004 the distance was shortened to 1000 m in GIST although related provisions of NFSC have not yet been changed.

It is difficult to compare the minimum length of targeted tunnels because comparable information is generally not available between countries. The existing requirements of NFSC should be reviewed by the Korean fire authorities because fire department connections are by definition mainly for fire brigade use. As the relevant experts they should define suitable requirements.

4.1.4 Fixed fire suppression system

In this study, fixed fire suppression systems are defined as the fire fighting equipment, such as sprinkler and deluge systems, which are designed and installed at the ceiling or wall of constructions in the tunnel, for purpose of suppression or control of fires.

The requirements of fixed fire suppression system in different countries are shown in Table 4.4.

Table 4.4 Fixed fire suppression system in different guidelines.

Country		Application criteria	Comment
Korea	NFSC	No reference	-
	GIST	Installation is recommended if ≥3000 m long tunnel and heavy[a)] traffic flow.	a) $\geq 60\times10^3$ veh×km/day/tube for bi-directional tunnel or 90×10^3 veh×km/day/tube for uni-directional tunnel. <u>A sprinkler system has been installed in Joogryeng tunnel first in Korea</u>
Australia[b)]		-	AFAC (Australasian Fire Authorities Council) strongly advocates the installation of suitably designed, manually controlled deluge/sprinkler systems. b) Although not legislated, sprinkler systems are installed in most new tunnels in Australia.
Austria		-	Austria has two tunnels with sprinkler systems: one in a very short tunnel with manual activation only, and a second one in a 5.4-km long tunnel that is in the installation phase [24].
France		-	There are no tunnels with sprinklers in France today [18].
Japan		<u>Class AA</u> <u>Class A:≥3000 m, ≥4000 veh [c)]/day and bi-directional tunnel</u>	Until 1999, it is known that sprinkler systems have been installed in 82 tunnels in Japan [18]. c) Veh means the number of vehicles which pass the road tunnels.
Norway		-	Dry water-based sprinkler system has been installed in 2 tunnels. (800 m vålreng tunnel and the 3200 m Fløyfjell tunnel) [16].
Sweden		-	Fixed fire suppression systems should be installed if leading to significantly raised safety for people according to risk analysis. Fixed fire suppression system has been installed in Tegelbacken tunnel [16].
UK		-	Automatic fire extinguishing systems are not considered suitable.
USA		-	There are three road tunnels that have been equipped with sprinkler systems: the Central Artery North Area (CANA) Route 1 tunnel in Boston, MA, and the I-90 First hill Mercer island and Mt. Baker Ridge tunnels in Seattle, WA. [16].
PIARC		-	Taking into account this exclusively economic aim (protection of property and not safety), sprinklers are generally not considered as cost-effective and are not recommended in usual road tunnels. However, sprinklers can be used in ancillary rooms in tunnels and other tunnel facilities, where appropriate.
UNECE		-	The technology is not yet sufficiently advanced to be able to recommend the use of built-in automatic fire extinguishing systems in tunnels.

Note: In the table, *Italics*: Høj [20], <u>underline</u>: KTA [3], normal font: Original guideline.

It is reported that fixed fire suppression systems have been installed in Australia, Austria, Japan, Korea, Norway, Sweden and USA. The use of sprinkler systems is mandated in Japan and Australia. Europe does not have a regulation that requires a water system [24]. There are no detailed specifications in the compared guidelines included in this study. Indeed, a sprinkler system has already been installed in a tunnel in Korea, despite the fact that relevant provisions have not yet been made in NFSC and GIST.
Most countries appear not to have taken a firm stand on codes and requirements for fixed fire suppression systems in tunnels. However, after various catastrophic tunnel fires in Europe such as the Mont Blanc tunnel fire in 1999 and the St. Gotthard tunnel fire in 2001, more attention has been drawn to the installation of the fixed fire suppression systems in tunnels. AFAC (Australasian Fire Authorities Council) strongly advocates the installation of suitably designed, manually controlled deluge/sprinkler systems [6]. Nowadays, it has been agreed that a fixed fire suppression system might be effective for tunnel fires because they could confine the spread of fires to within a short distance from the origin of the fire and decrease the temperature around the fire scene. Therefore, such systems could potentially help fire brigades approach the seat of the fire and suppress the fire more quickly.

4.2 Fire detection and communication

4.2.1 Manual fire detection system (alarm buttons)

Manual fire alarm equipment is a useful mean to enable tunnel users to inform tunnel operators or other drivers what is happening inside the tunnel. This equipment has found broad acceptance because it is easy to handle and economical to maintain.

The requirements of manual fire detection system in different countries are shown in Table 4.5.

The minimum length of targeted tunnels for alarm push buttons is approximately 500 m in all countries which are included in this study; and there is no large difference between countries. The spacing varies, however, from 50 m (Korea, Japan and the UK) to 250 m (Austria). It is common that alarm push buttons are installed together with other fire safety equipment such as a fire extinguisher or an emergency telephone in the emergency call station. For that reason, the spacing of alarm push buttons is same as that of emergency call stations in most countries.

Austria has two kinds of buttons in its tunnels; one is for SOS, the other is for fire. Thus, two buttons are needed at each emergency telephone station, which complicates the occupant self-help system and it could be worthwhile to review whether this situation is optimal. The PIARC recommendation is to use one button only because when several are provided with different meanings, many people push the wrong button or all buttons in an emergency situation [18].

The authors suggest that alarm buttons should be installed in all tunnels, regardless of their length, if other fire detection equipment or monitoring equipment is not installed. The reason is that the cost setting up the manual fire alarm systems is relatively low. Moreover, in many circumstances it can be the most effective equipment and enables tunnel operators to obtain information more quickly and to act properly provided the equipment is set up and maintained well. Further, it is recommended that alarm buttons should be placed inside the fire hydrants box or near the fire extinguishers, for the user's convenience and guarantee of quick response of tunnel safety staff.

Table 4.5 Alarm push button in different guidelines.

Country		Application criteria	Spacing	Comment
Korea	NFSC	≥500 m	<50 m	-
	GIST	≥500 m	<50 m	Installed around the hydrant cabinets or inside fire extinguisher cabinets
Austria		*>500 m*	*250 m*	*Two push buttons (SOS, fire) at each emergency telephone station.*
France		-	-	Alarm push buttons may be provided, depending upon the hazards presented by a tunnel and its traffic, and the manner in which it is operated.
Germany		*≥400 m*	*<150 m*	*Installed in each emergency call station.*
Japan		≥Class C	≤50 m	Recommended to be installed with emergency telephone.
Sweden		All classes	≤150 m	Alarm push buttons or emergency telephones should be coordinated with the escape routes. Should be installed on both sides of the tunnel tube if three lanes or more.
UK		≥Class D ≥100 m	50 m	-
USA		≥240 m	≤90 m	Also at all cross passages and means of egress from the tunnel.
PIARC		-	-	Push button alarms are optional.

Note: In the table, *Italics*: Høj [19], underline: KTA [2], normal font: Original guideline.

4.2.2 Automatic fire detection system

Almost all fire detectors are based on heat, heat increase or smoke. The use of smoke based detectors has a high potential for false alarm problems because of smoke exhaust from diesel vehicles. On the other hand, fire detectors in tunnels shall be more sensitive than those in other building because of the air flow inside tunnels which is generated by vehicular movement or the ventilation system. Proper actions should be taken to combat these sources of error.

The minimum length of targeted tunnels varies from 100 m (the UK) to 1500 m (Austria). It appears that Japan has similar safety standards to those of France as tunnels longer than 300 m with high traffic flow have automatic fire detection systems installed. The requirements in France vary depending on the location, traffic type and traffic volume. It is common that the automatic fire detection systems are linked to a mechanical ventilation system and installed in unmanned tunnels.

There is a discrepancy between the minimum length for installation between NFSC and GIST: ≥1000 m in NFSC and ≥500 m (i.e., ≥ Class 3) in GIST. The provisions of NFSC can be considered to be out of date. GIST has been revised recently from 2000 m to 500 m, in the direction of placing more strict requirements based on lessons learned from several disastrous tunnel fires. The requirements of automatic fire detection system in different countries are shown in Table 4.6.

Table 4.6 Automatic fire detection system in different guidelines.

Country		Application criteria	Comment
Korea	NFSC	≥1000 m	-
	GIST	≥500 m or ≥Class 3[a)]	a) Only where tunnels are bi-directional and urban tunnels, Otherwise, ≥1000 m or Class 2. If the tunnels are ≥2000 m, installation of tunnel monitoring equipment such as CCTV should be considered for detection of smoke or flame from fires. If the tunnel's length is between 500 m and 1000 m, automatic detection systems can be replaced with automatic accident detection systems.
Austria		≥1500 m [18]	*Automatic fire detectors in operation rooms and at lay by. Generally in the tunnel if there is a mechanical ventilation system.*
France		≥300 m[b)]	b) For tunnels where hazardous goods are permitted - Urban uni-directional or non-urban heavy traffic uni-directional: ≥300 m - Non urban heavy traffic bi-directional: 500-1000 m (applicable) b) For tunnels where no permanent human supervision - Urban bi-directional: 300–1000 m (≥1000 m, possible) - Non-urban low traffic bi-directional: ≥1000 m. - Non-urban heavy traffic bi-directional: ≥800 m.
Germany		*>400 m*[c)]	*C) only for tunnels with mechanical ventilation system.*
Japan		<u>≥Class A</u>	<u>Not in tunnels without ventilation system.</u> <u>Automatic detection system can be applied in tunnel longer than 300 m if the traffic flow is considerably high.</u>
Sweden		≥Class TB	-
UK		≥Class D ≥100 m	All buildings and ancillary structures shall be zoned and provided with one or more fire alarm systems to a suitable standard. Where such buildings or areas are not manned, automatic fire detectors shall be provided and monitored remotely.
USA		≥240 m	For tunnels where 24-hour supervision is not provided. Automatic fire detection systems shall be capable of identifying the location of the fire within 15 m
EU		>500 m	At least one of the two systems (automatic incident detection and fire detection system) is mandatory in tunnels with a control center.
PIARC		-	Fire detection systems can be useful in tunnels that are long or complicated, especially when dangerous goods are allowed or when it is necessary to precisely determine the location of the fire. Detectors can also be helpful in unmanned tunnels with transverse or semi-transverse ventilation

Note: In the table, *Italics*: Høj [20], <u>underline</u>: KTA [3], normal font: Original guideline.

4.2.3 Loudspeakers

Loudspeakers are the method which tunnel operators have available to inform the tunnel users of the emergency situations occurring in a tunnel. This equipment is mainly installed in shelters and exits where evacuating users are supposed to wait in the event of a fire.

The requirements of loudspeakers in different countries are shown in Table 4.7.

Table 4.7 Loudspeakers in different guideline in different guidelines.

Country		Application criteria	Spacing & Comment
Korea	NFSC	No reference	-
	GIST	≥500 m [a)]	a) Only if tunnels have smoke ventilation systems or emergency escape facilities.
Austria		*Class III, IV*	*It shall be placed at portals, lay by and turning area.*
France		-	A separate sound system (loudspeaker) is necessary in shelter.
Germany		*>400 m with ≥4000 HGV× km/bore per day.*	*It shall be established within the tunnel and at the portals if the tunnels are monitored by video.*
Japan		<u>Class AA,</u> <u>Class A (≥3000 m)</u>[b)]	b) Class A (≥ 3000 m) indicates that tunnels are Class A and their lengths are ≥3000 m. <u>≥50 m spacing (designed to be used in connection with radio rebroadcast system).</u>
Sweden		Class TA	Sound alarm should be installed in tunnels of all classes. Devices for giving the occupants guidance on evacuation should be installed in Class TB and TA.
EU		≥500 m	Mandatory where evacuating users must wait before they can reach the outside.
PIARC		-	Generally not recommended in road tunnels because of some problems; the use of a single language; communication is normally only possible in tunnels with acoustic treatment; the noise from the vehicles and fans. Whenever the difficulties are overcome, it is possible to use loudspeakers.
UNECE		-	Loudspeakers should be recommended only if they are useful, e.g. at traffic lights in front of tunnel portals, when all traffic is stopped or along escape routes during evacuation.

Note: In the table, *Italics*: Høj [20], <u>underline</u>: KTA [3], normal font: Original guideline.

The minimum length of targeted tunnels which have some requirements, are from 400 m (Germany) to 500 m (Korea and EU). The location of installations is mainly around emergency escape facilities such as escape routes and shelters.

The loudspeakers have some disadvantages. One disadvantage is the noise from vehicles and fans, which can render speakers useless. According to a report by UNECE, loudspeakers should be recommended only if they are useful, e.g. at traffic lights in front of tunnel portals, when all traffic is stopped or along escape routes during evacuation; in tunnel tubes they are often useless because of the noise of traffic and ventilation [17]. Some measures should be taken to alleviate these problems when loudspeakers are considered.

4.2.4 Emergency telephones

Emergency telephones can be useful tools in that they enable tunnel users to report to the tunnel operators more detailed information such as the location of a fire and victims involved in contrast to the sparse information that can be related through the activation of simple alarm buttons. They are also regarded as the basic equipment because they can be used in other emergency situations than fires.

Emergency telephones are discussed in most guidelines. The minimum length of tunnels is 200 m (Japan), 300 m (France), 400 m (Germany), 500 m (Austria, Korea and EU). The maximum Spacing is 50 m (the UK), 150 m (Germany, Sweden, and EU), 200 m (France and Japan), 250 m (Austria and Korea), and 50–500 m (Australia). In Norway, the Spacing varies from 250 m to 500 m depending on the class of tunnel.

It is common that the emergency telephones are provided in emergency recesses with other fire facilities such as fire extinguishers and hydrants. For that reason, the spacing of emergency phones corresponds to that of emergency recesses or emergency call stations.

In Norwegian guidelines, requirements relating to mobile phones are also presented. Consideration of how to use mobile phone equipment is necessary and desirable because increasing numbers of drivers are expected to depend on wireless communication rather than public phones.

Provisions relating to emergency telephones are found only in GIST and not in NFSC. Emergency telephones should be included under the category of fire detection and warning equipment in NFSC because the emergency telephone is used more than any other equipment when an accident happens in a tunnel [3]. Furthermore, PIARC recommends that all road tunnels with a sufficient length or traffic be equipped with emergency telephones.

The requirements of emergency telephones in different countries are shown in Table 4.8.

Table 4.8 Emergency telephones in different guidelines.

Country		Application criteria	Spacing	Comment
Korea	NFSC	No reference	No reference	-
	GIST	≥500 m	<250 m	Telephones shall be put in the booth on the wall
Australia		-	50–500 m	It is recommended that these communication points be installed at fire service point (hydrant, extinguisher etc).
Austria		*>500 m*	*250 m*	*It should be installed together with 2 alarm push buttons.*
France		≥300 m	200 m (emergency recess)	It shall be also installed in the emergency access (urban two tubes) and along the emergency routes (the other tunnels).
Germany		*≥400 m*	*≤150 m and at start and end of the escape routes.*	*It shall be separated from the traffic space by doors.*
Japan		≥Class D (>200 m)[a)]	≤200 m	a) Class D (>200 m) indicates that tunnels are Class D and their lengths are >200 m.

Country	Application criteria	Spacing	Comment
Norway	Category B, C, D, E, F	Class B: 500 m Class C: 375 m Class D: 250 m (both sides) Class E: 500 m Class F: 250 m	It is additionally installed outside each tunnel entrance. Mobile telephone equipment is recommended for ≥Category B tunnels.
Sweden	All classes	≤150 m	Alarm push buttons or emergency telephones should be coordinated with the escape routes. Should be installed on both sides of the tunnel tube if three lanes or more. The emergency telephones should be automatically surveyed.
UK	Class AA, A, B, C	50 m	It shall be at the emergency points together with fire hose reels.
EU	>500 m (with exceptions)	≤150 m	At emergency stations together with two extinguishers.
PIARC	-	-	It is recommended that all road tunnels with a sufficient length or traffic be equipped with a system of emergency telephones.

Note: In the table, *Italics*: Høj [20], <u>underline</u>: KTA [3], normal font: Original guideline.

4.2.5 Radio communication systems

Radio communication systems can relay radio broadcast programs to receivers in cars using the tunnels in normal situations. Such systems can also enable emergency services to communicate with head office or operations centre when an emergency situation occurs. For that reason, it is desirable that radio communication systems be designed to be interrupted by the emergency response personnel.

The requirements of radio communication systems in different countries are shown in Table 4.9.

Table 4.9 Radio rebroadcast systems in different guidelines.

Country		Application criteria	Comment
Korea	NFSC	≥500 m (for emergency services)	Wireless communication system for fire brigade can be used also for radio rebroadcast if radio rebroadcast systems do not interrupt fire brigade's communications
	GIST	≥500 m (for emergency services and tunnel users)	For 200-500 m tunnels, radio communication systems are recommended. For tunnels built in radio rebroadcast systems, they should be able to be used for wireless communication systems for fire brigade.
Austria		*Class IV: Tunnels must have a radio rebroadcast system and wireless communication system for rescue staff.*	-

Country	Application criteria	Comment
France	For emergency services. ≥500 m: Urban tunnels ≥800 m: Non-urban tunnels For users ≥1000 m : Urban tunnels (≥800 m[a)]) ≥3000 m: Non-urban tunnels (≥1000 m[a)], ≥800 m [b)])	a) If there is human supervision. b) If there is human supervision and low traffic. If radio broadcast stations are relayed, and there is a control unit, it must be possible to interrupt these relays in order to broadcast safety messages to users.
Germany	-	*For police, fire brigade and rescue service, permanent coverage of all necessary radio bands shall be provided. Minimum one FM band radio station with traffic radio service shall be broadcasted in the tunnel.*
Japan	Class AA, Class A (≥3000 m)[c)] (for emergency services and users)	c) Class A (≥3000 m) indicates that tunnels are Class A and their lengths are ≥3000 m. Radio rebroadcast should be able to be interrupted and relay the message of tunnel operators throughout tunnels when an emergency situation happens.
Norway	>500 m	The broadcasting equipment shall provide satisfactory coverage through the entire tunnel and be installed with an “interruption facility” for transmission of traffic information.
Sweden	Class TA	-
UK	Class AA To be considered in Class A, B, C	Tunnels shall be provided with a means of maintaining radio communication with emergency vehicles, emergency personnel and maintenance staff. An additional re-broadcast system could be installed by the service provider to maintain continuity of their service.
USA	≥240 m	A separate radio network capable of two directional radio communication for fire department personnel to the fire department communication center shall be provided.
EU	≥1000 m and >2000 vehicles per lane (for emergency services)	Radio re-broadcasting equipment for emergency service use shall be installed
	≥500 m (for tunnel users)	Mandatory where radio is re-broadcasted for tunnel users and where there is a control center.
PIARC	-	A radio communication system is recommended in important tunnels (long or with much traffic). The first priority is to allow the communication of the emergency and operation services.
UNECE	Tunnels under human surveillance	Transmit emergency messages to road users by radio can be possible. Emergency services channel is necessary.

Note: In the table, *Italics*: Høj [20], underline: KTA [3], normal font: Original guideline.

Most of the countries studied have the requirements relating to radio communication systems both for tunnel users and for emergency authorities. Comparisons show that such systems are universal and that they are typically designed both for emergency services and for drivers.

France has complicated requirements. The minimum length relating to requirements concerning wireless communication varies from 500 m to 3000 m, depending on whether the tunnel is urban or non-urban and whether the communication is for emergency staff or for users. Similarly, the EU tunnel directive has two different criteria: ≥500 m tunnel for use of tunnel users and ≥1000 m tunnel and >2000 vehicles per lane for use of emergency services. Other countries apply single criterion to the tunnel no matter whether it is for tunnel users or emergency services. The minimum application length is 240 m (USA), 500 m (Korea and Norway) and 3000 m (Japan). The guideline of Japan shows a great difference.

The Korean existing requirements for radio communication can be considered to be reasonable compared to those of other countries. Even 200 m long tunnels are recommended to be equipped with wireless communication systems for fire brigade and users.

4.3 Structural measures relevant to safety

4.3.1 Parallel escape tube

Parallel escape tube means a separate escape tube for the evacuation of tunnel users parallel and adjacent to the main road tunnel. Tunnel owners might hesitate to establish parallel escape tubes in tunnels because of the large cost and the extra space needed. Nevertheless, this structure is one of the facilities which can ensure safe escape for tunnel occupants in bi-directional traffic tunnels or long ramp tunnels.

The requirements of parallel escape tube in different countries are shown in Table 4.10.

Specific data on application criteria are not given in the European and Australian guidelines. The formulation of their guidelines is rather descriptive. Generally, their guidelines recommend that installation of a parallel escape tube can be considered when the tunnels include bi-directional traffic and other escape facilities are not available.

Korea and Japan provide specific requirements for a parallel escape tube. The minimum length of targeted tunnels is 1000 m in Korea and 3000 m in Japan. However, the requirements of Korea are dependent on the risk degree, traffic type, location and risk of congestion when escape facilities are considered. Similarly, ventilation and traffic type are considered in Japan.

Due to the considerable investment required when setting up the escape tube, it is recommended to consider various factors which might influence the safety of tunnels and emerging research before such a requirement is made. UNECE proposes to consider traffic volume, tunnel length, longitudinal gradient and type and capacity of ventilation as the main criteria.

Table 4.10 Parallel escape tube in different guidelines.

Country		Application criteria & Comment
Korea	NFSC	No reference
	GIST	≥3000 m tunnels with bi-directional or uni-directional tunnels with more than two of risk index [a)]. ≥1000 m and bi-directional tunnels or ≥1000 m and urban tunnels expected to be congested can be installed.
Australia		A separate egress tunnel should be provided in tunnels, particularly within bi-directional tunnels or tunnels in which adjacent tunnel cannot be used for escape purposes. For unidirectional tunnels, escape to adjoining road tunnel can be considered, however traffic management of the adjoining tunnel is required.
Austria		*Escape tubes for foot passengers or vehicles could be used to minimize the escape routes.*
France		Arrangements for the evacuation and protection of users and emergency access shall constitute an essential safety feature. The type of arrangements are to be selected in the following decreasing order of preference: - Direct communication with the exterior wherever this can be provided under reasonable conditions, - Communication between tubes, when there are two tubes, and this communication can be provided through an intermediate airlock, - Parallel safety tunnel if this is otherwise justified, - Shelters with access-ways protected from fire if none of the above arrangements can be used.
Germany		*The longitudinal slope shall not be more than 10 %; the cross section shall be 2.25 m×2.25 m (parallel escape tube).*
Japan		<u>Class AA,</u> <u>Class A, ≥3000 m, bi-directional and longitudinal ventilation system tunnels)</u>
UK		A separate service tunnel should be considered on a whole life cost basis. Such tunnels may also be used for evacuation purposes during an emergency.
PIARC		Escape corridor or separate escape gallery can be one of evacuation possibilities.
UNECE		In single-tube tunnels, constructing special escape routes or safety galleries is associated with elevated costs. The main criteria to be considered are traffic volume, tunnel length, longitudinal gradient and type and capacity of ventilation.

Note: In the table, *Italics*: Høj [20], <u>underline</u>: KTA [3], normal font: Original guideline.
a) Risk index means the numerical mean value of 6 factors which affect the safety of tunnels.

4.3.2 Emergency cross-passage

Emergency cross-passage is a route through which passengers trapped in tunnels can evacuate from the tube in trouble to the neighboring tube or to a parallel escape tube, i.e. a connection between tubes or a tube and escape tunnel.

The requirements of emergency cross-passage in different countries are shown in Table 4.11.

Table 4.11 Emergency cross-passage in different guidelines.

Country		Application criteria	Spacing	Comment
Korea	NFSC	No reference	No reference	**-**
	GIST	≥500 m or bi-directional tunnels with a parallel escape tube	<250 m	For tunnels ≤1200 m, spacing can be <300 m.
Austria		-	*250 m[a)]*	*a) For tunnels without no fire ventilation and for tunnels with a longitudinal gradient >3 %*
France		≥300 m: Urban tunnels ≥500 m: Non-urban tunnel	200 m (urban) 400 m (non-urban)	A shorter spacing is to be used in tubes which are frequently congested and which have more than three lanes.
Germany		*≥400 m*	*≤300 m*	*Escape routes must be indicated and illuminated.*
Japan		For uni-directional tunnel, ≥750 m. For bi-directional tunnel, ≥400 m	750 m (uni-directional tunnels). 350 m (bi-directional tunnels)	The actual installation distance is 200–300 m.
Norway		Category E, F (twin-bore tunnels)	250 m	-
Sweden		All classes	≤150 m.	The time for escape to portal, escape route or other safe haven must not be longer than that the tunnel can be evacuated before the conditions become critical. The gradient of an escape route cannot be higher than 8 %. Class TA should have increased fire protection, e.g. shorter distance between escape routes.
UK		Class AA. To be considered in Class A and B	100 m.	-
USA		≥240 m	≤200 m	-
EU		≥500 m and the traffic volume is >2000 vehicles per lane	≤500 m	Mandatory with exceptions
PIARC		-	-	The most common escape route in two tube tunnels is a connection (cross passage) between the two tubes. The distance between connections should depend on traffic density and emergency rescue scenarios, for instance 100 – 200 m in cities.
UNECE		Twin-tube tunnels	200-500 m	-

Note: In the table, *Italics*: Høj [20], underline: KTA [3], normal font: Original guideline.

The minimum length of tunnels to which such requirements are applied is 240–750 m. The minimum length can be adjusted depending on tunnel type (Japan), the tunnel location (France), and traffic volume (EU). The maximum spacing is from 100 m (the UK) to 500 m (EU and UNECE). The spacing can vary according to tunnel length (Korea), tunnel type (Japan), location (France), risk of congestion (France), the number of lanes (France), ventilation (Austria) and gradient (Austria). In Japan, the practical spacing is shorter (200–300 m) than that presented in the guideline (350–750 m).

4.3.3 Turning areas

Turning areas are also called turning bays in the UK. Turning areas make it possible for vehicles to turn around and escape from the tunnel where an accident has occurred. Other safety facilities such as emergency lanes and emergency lay-bys can also function as turning areas for light vehicles. However, only designated turning areas are compared in this section.

The requirements of turning areas in different countries are shown in Table 4.12.

Table 4.12 Turning areas in different guidelines.

Country		Application criteria	Spacing	Comment
Korea	NFSC	No reference	No reference	-
	GIST	≥1000 m	≤750 m	Emergency stopping lanes can be used as turning areas.
Austria		*Class III and IV with bi-directional traffic.*	*1000 m*	*A turning area is necessary instead of each fourth lay by.*
France		≥1000 m	800 m	For tunnels ≥1000 m long with two tubes and cross-passages, turning areas are not needed.
Germany		*>900 m*	-	*To be considered for 600–900 m long tunnels.*
Norway		Category B, C, D	Category B: 2000 m Category C: 1500 m Category D: 1000 m	Turning points are built into bi-directional traffic tunnels.
UK		>5000 m	≤1000 m from the middle of a tunnel.	To be considered in Class AA

Note: In the table, *Italics*: Høj [20], underline: KTA [3], normal font: Original guideline.

The minimum length of targeted tunnels is 900 m (Germany), 1000 m (France and Korea) and 5000 m (the UK). The UK shows a large difference compared with other countries. France has some exceptions to the application of their requirements, i.e., tunnels with more than two lanes or a cross-passage, can be excluded from application. This exception appears to be reasonable because a greater width of tunnel or a cross-passage can be used as turning areas. Germany and the UK have recommended requirements so that the number of targeted tunnels can be increased. In Austria and Norway, long tunnels with bi-directional traffic are required to be equipped with turning areas.

The installation intervals are 750 m (Korea), 800 m (France), 1000 m (Austria). In Norway, the spacing varies from 1000–2000 m depending on the tunnel classes. The UK demands turning bays which are not far from the middle of tunnels. The comparison table shows that in general, the requirements are not applicable for short tunnels.

4.4 Emergency access for rescue staff

These facilities are designed to provide the fire brigade with easy access to the tunnels. In this section, separate emergency vehicle gallery access, cross-passages for rescue vehicles and emergency services parking, are discussed.

4.4.1 Separate gallery for emergency vehicles

A separate gallery for emergency vehicles is a route which helps fire engines to approach the accident closely, while not being affected by toxic fumes, heat or traffic congestion.

The requirements of separate gallery for emergency vehicles in different countries are shown in Table 4.13.

Table 4.13 Separate gallery for emergency vehicle in different guidelines.

Country	Requirement
Austria	*It could be used to minimize the ways for rescue staff.* *According to this, the tunnel category could be influenced.*
Germany	*This may be relevant for tunnels longer than 300 m with high traffic load. The need for this arrangement shall be documented as part of safety concept.*

Note: In the table, *Italics*: Høj [20], <u>underline</u>: KTA [3], normal font: Original guideline.

Separate galleries for emergency vehicles have been specified in two countries. The minimum length of targeted tunnels is 300 m (Germany). However, these requirements have not been applied to lightly trafficked tunnels. In practice, not many tunnels are expected to be equipped with a separate gallery for emergency staff.

The comparison shows that a separate gallery is not a basic facility installed in road tunnels. A decision concerning installation has to be made after a thorough evaluation of the economic benefit and necessity for this arrangement.

4.4.2 Cross-passage for rescue vehicle

This facility is a similar to a cross-passage for pedestrians. However, it needs other provisions and conditions, such as dimension and design, because it is for rescue vehicle passage.

The requirements of cross-passage for rescue vehicle in different countries are shown in Table 4.14.

Concerning targeted tunnel, the minimum length is 400 m (Germany), 500 m (Austria and Korea), 1000 m (France) and 1500 m and twin-tube tunnels (EU). Considering the fact that cross-passages are used as emergency routes between tubes, targeted tunnels should be twin-tube types.

Targeted tunnels are required to have cross passages for rescue services every 500 m (Austria), 750m (Korea), 800 m (France), 900 m (Germany), and 1500 m (EU). Some requirements concerning spacing are fixed values (Austria and France) and others give maximum figures (Germany, Korea, EU and UNECE). Like the cases of Austria, Germany and Korea, it is common that cross-passages for rescue staff are designed at a certain interval, e.g., every second (Austria) or third (Germany and Korea) cross-passage is designed to accommodate rescue services.

The minimum requirements of EU do not seem to be in conflict with any of the European guidelines studied in this section. The minimum length and spacing shows a significant variation between countries.

Table 4.14 Cross passage for rescue vehicles in different guidelines.

Country		Application criteria	Spacing	Comment
Korea	NFSC	No reference	No reference	-
	GIST	≥500 m or bi-directional tunnels with a parallel escape tube.	≤750 m	Cross passage for ambulances.
Austria		*>500 m*	*500 m*	*At every second emergency call station*
France		≥1000 m	800 m	-
Germany		*≥400 m*	*≤900 m*	*For two tube tunnels, every third cross passage can be constructed.*
EU		Twin-tube tunnels longer than 1500 m	≤1500 m	Cross-connections for emergency services are mandatory.
UNECE		Twin-tube tunnels	600–1500 m	-

Note: In the table, *Italics*: Høj [20], <u>underline</u>: KTA [3], normal font: Original guideline.

4.4.3 Emergency services parking

Emergency services parking is a kind of parking lot for fire brigade and police where emergency vehicles can stop and prepare proper action near the ends of a tunnel.

The requirements of emergency services parking in different countries are shown in Table 4.15.

Table 4.15 Emergency services parking in different guidelines.

Country	Requirement
France	A location 12 m long and 3 m wide for parking an emergency vehicle shall be provided outside, close to the ends. In addition to this, in all tunnels having two tubes, an arrangement enabling emergency vehicles to turn around/move from one roadway to another shall be provided externally, close to the portals.
UK	If necessary, an area close to the tunnel portals shall be provided for the parking of police and emergency services vehicles and equipment when attending a tunnel incident.
USA	Where a tunnel is a high-capacity facility in a congested urban area, it can be appropriate to house fire apparatus at the tunnel portal (s)

Note: In the table, *Italics*: Høj [20], <u>underline</u>: KTA [3], normal font: Original guideline.

Not all European countries have established requirements for the emergency services parking at portals. Related requirements are found only in France, the UK and USA. The requirements of the UK and USA do not give further specific specifications on the targeted tunnels. In the USA, the installation depends on the tunnel location and risk of congestion.

It appears that the need for parking facilities for emergency services has not been given as much attention as other requirements. For long tunnels with a heavy traffic flow, the installation of emergency services parking can be worth considering.

4.5 Lighting

4.5.1 Emergency lighting

The requirements of emergency lighting in different countries are shown in Table 4.16.

Table 4.16 Emergency lighting in different guidelines.

Country		Application criteria	Capacity & Spacing	Comment
Korea	NFSC	≥500 m	An average of ≥1 lux at any point.	It shall be supported by a emergency power supply at least 20 min.
	GIST	≥200 m	Ensuring a minimum 1/8 or 1/2 level of normal lighting when maintained by an UPS or by an emergency generator respectively. Emergency lighting can be installed at parallel escape tubes, emergency cross-passages and shelters etc.	When emergency lighting has batteries, they shall ensure the one hour-operation.
France		≥300 m[a)]	Every 10 m on each side (emergency lighting+marker light). A minimum level of lighting over the roadway and walkways of an average of 10 lux, and 2 lux at any point.	a) This lighting is not compulsory in light traffic tunnels.
Germany		*≥400 m*	*≤ 25 m*	-
Japan		<u>≥200 m</u>	<u>Ensuring a minimum 1/8 or 1/2 level of normal lighting when maintained by an UPS or by an emergency generator respectively.</u>	-
Norway		≥ Category D	62.5 m (Emergency exit lighting)	Priority lighting is determined by every fourth or fifth light continuing to operate for about 1 hour following a power breakdown.
Sweden		All classes	Reserve lighting should be available before the guidance lighting is started if the general lighting is not working. Reserve lighting should have an average luminance of 0.3 cd/m^2 in the lane closest to tunnel wall. The guidance lighting should be automatically started if failure in general lighting and have an average level of 2 lux	-
UK		-	As a minimum requirement, one luminaire in ten of the Stage 1 lighting shall be designated as emergency lighting and maintained by an UPS.	-

Country	Application criteria	Capacity & Spacing	Comment
USA	≥240 m	The emergency illumination level shall be a minimum average maintained value of 10 lux and, at any point, not less than 1 lux. Emergency lights, exit lights, and essential signs shall be included in the emergency lighting system and shall be powered by an emergency power supply.	-
EU	≥500 m	-	Normal, safety and evacuation lighting shall be provided
PIARC	-	• In high traffic tunnels: Minimum safety lighting connected to an UPS. • In low traffic tunnels with no UPS: 1/3 or 1/4 tunnel lights should be fitted with a battery backup. • In heavy traffic tunnels: A separate system of evacuation lights (marker lights, 25 spacing)	-

Note: In the table, *Italics*: Høj [20], <u>underline</u>: KTA [3], normal font: Original guideline.

Emergency lighting helps road users to find appropriate exits and to escape from the tunnel successfully in the event of an emergency. It is essential that this facility should be maintained by an UPS or a generator in case of an electricity power cut.

The minimum length of targeted tunnels does not show a great variation. The length is from 100 m to 500 m. Specific spacing can be found in France (10 m), in Germany (≤25 m) and in Norway (62.5 m). Other countries give a minimum level of lighting.

Korea requires an average of 1 lux at any point regardless of walkway or roadway as a minimum. On the other hand, France requires 10 lux (average) and 2 lux (at any point) as a minimum level of lighting over the roadway and walkways. USA demands 10 lux (minimum average maintained value) and not less than l lux (at any point).

4.6 Smoke extraction ventilation

Assistant firefighting facilities can be defined as equipment which helps fire brigades to perform their work efficiently. This category includes a smoke control ventilation system, a standpipe system and power tool sockets.

4.6.1 Smoke control ventilation

After the catastrophic tunnel fires, e.g., the Mont Blanc tunnel fire and the Channel tunnel fire in recent years, the importance of the smoke control ventilation system has been recognized and their construction and design is consequently given more attention. In general, there are two kinds of ventilation systems which can be installed in road tunnels. One is the longitudinal ventilation system where the air is introduced to or removed from the tunnel roadway at a limited number of points e.g. portals, shafts or special inlet/outlet, resulting in a longitudinal airflow within the tunnel. The other is a transverse ventilation system which distributes uniform fresh air and/or collects uniform ventilated air along the length of the tunnel.

It is not easy to decide which type of ventilation systems should be set up in a certain length tunnel. A variety of check points for example tunnel length, risk evaluation, congestion of traffic and location should be considered carefully when designing effective smoke control.

The requirements of smoke control ventilation in different countries are shown in Table 4.17.

Table 4.17 Smoke control ventilation in different guidelines.

<table>
<tr><th colspan="2">Country</th><th>Requirement or Comment</th></tr>
<tr><td rowspan="2">Korea</td><td>NFSC</td><td>≥1000 m.
Systems shall be linked to fire detection system and shall be able to switch to the smoke control operation. Air supplier and auxiliary equipment exposed to a fire shall be able to operate for more than one hour under 250 °C. When setting the capacity of ventilation, the size of design fires shall be more than 20 MW.</td></tr>
<tr><td>GIST</td><td>• Bi-directional tunnel or congested urban unidirectional tunnels
≤500 m: Natural ventilation
500–1000 m: Mechanical ventilation
≥ 1000 m: Transverse or semi-transverse ventilation
• Non-urban uni-directional tunnel
≤500 m: Natural ventilation
500–1000 m and ≤2 of risk index: Natural ventilation
500–1000 m and >2 of risk index: Mechanical ventilation
≥1000 m: Mechanical ventilation</td></tr>
<tr><td colspan="2">France</td><td>1. Longitudinal ventilation systems.
- Urban uni-directional tunnels
• 300–500 m: Accepted (300–800 m, if controlling the longitudinal air flow is possible)
• ≥500 m: Accepted only with massive extraction systems every 500 m.
(≥800 m, if massive extraction systems are installed every 800).
- Urban bi-directional tunnels: Prohibited.
- Non-urban uni-directional tunnels with heavy traffic
• 500–5000 m: Recommended.
• ≥5000 m : possible with massive extraction.
- Non-urban bi-directional tunnels with heavy traffic.
• 500–1000 m: Accepted with compensatory measures.
• ≥1000 m: Prohibited.
- Non-urban bi-directional tunnels with low traffic.
• 1000–1500 m: Compulsory with compensatory measures
• ≥1500 m: Prohibited (except special circumstances and with compensatory measure)
2. Fully (semi) transverse ventilation systems.
- Urban tunnels: ≥300 m tunnels are accepted.
- Non-urban bi-directional with heavy traffic : ≥500 m tunnels are accepted.
- Non-urban bi-directional with low traffic: ≥1000 m tunnels are accepted
- Non-urban uni-directional with heavy traffic (≥500 m): Longitudianl to be preferred where possible.</td></tr>
<tr><td colspan="2">Germany</td><td>• For bi-directional tunnels or congested uni-directional tunnels.
≤400 m: Natural ventilation.
400-600 m: Longitudinal ventilation can be installed.
600-1200 m: Longitudinal or transverse ventilation systems depending on the risk analysis.
≥1200 m: Ventilation systems whose dampers can open and close.
• For uni-directional non-congested tunnel.
≤ 600 m: Natural ventilation.
600–3000 m: Longitudinal ventilation can be installed.
≥3000 m: Longitudinal ventilation whose inflow capacity has been improved or transverse ventilation systems.</td></tr>
</table>

Country	Requirement or Comment
Japan	≥1500 m For Class AA tunnels, either ventilation system or parallel escape tube should be installed.
Norway	Mechanical longitudinal ventilation is based on the use of impulse ventilator fans. In long tunnels with heavy traffic, or where there are particular restrictions, the use of ventilator shaft may be considered.
Sweden	For fire gas control, longitudinal ventilation should be used and have a capacity to give 3 m/s for fire sizes up to 100 MW.
UK	Class AA, A, B (to be considered for Class C, D) • Mechanical ventilation system. - ≥400 m tunnels - ≥200 m tunnels with steep gradients or those subject to frequent congestion. - Fully transverse ventilation is seldom adopted for new tunnels. - Semi transverse ventilation has frequently been used in the UK tunnels at river crossings.
USA	Installation is possible for ≥300 m tunnels (≥240 m when the maximum distance from any point within the tunnel to a point of safety exceeds 120 m).
EU	• Mechanical ventilation system: >1000 m with a traffic volume >2000 vehicles per lane. - Longitudinal ventilation system: Bi-directional and/or congested uni-directional traffic only if risk analysis is acceptable and specific measures are taken. - (semi) transverse ventilation system: Mechanical ventilation system is necessary and longitudinal ventilation is not allowed.
PIARC	• Natural ventilation: Impossible at this moment to express universal recommendations. • Longitudinal ventilation systems should be used under the following conditions (with exceptions): - Tunnel with uni-directional traffic not designed for queues (non-urban area) - Tunnel with uni-directional traffic designed for queues (urban area) - Tunnel with bi-directional traffic: Only if the risk is acceptable.
UNECE	• Natural ventilation: Short tunnels. The acceptable length depends on whether traffic is uni or bi directional and how heavy it is. • Longitudinal ventilation: Uni-directional tunnels. Under certain circumstances, in short bi-directional tunnels. • Transverse ventilation: Long and heavy traffic tunnels.

Note: In the table, *Italics*: Høj [20], underline: KTA [3], normal font: Original guideline.

The decision of which ventilation system to use depends on the tunnel length (most countries), tunnel category (the UK and Japan), traffic flow type (France, Germany, Korea, EU, PIARC and UNECE), urban/rural location (France and Korea), traffic volume (France, Norway, EU and UNECE), risk of congestion (Germany, Korea, the UK, EU and PIARC), tunnel gradient (the UK), and risk degree (Germany, Korea and PIARC). The minimum requirements for mechanical ventilation are 200 m (the UK), 240 m (USA), 300 m (France), 400 m (Germany), 500 m (Korea), 1000 m (EU) and 1500 m (Japan). In summary, tunnel length or category, traffic flow type and risk of congestion are key criteria when making a decision concerning the type of ventilation system.

4.7 Signage

Generally, signage is developed to give safety information on driving to drivers using the tunnel. This signage can be subdivided into two main types. One aims at prevention and the other mitigation. Prevention signs help tunnel users to pass a tunnel safely by providing information on the speed limits, overtaking restrictions, etc. Mitigation signs inform the tunnel users about an on-going emergency situation and how to respond to the emergency to prevent another accident or expedite escape. In this report, mainly mitigation signs are discussed.

4.7.1 Traffic signals outside the tunnel

The aim of traffic signals outside the tunnel is to stop vehicles entering into the tunnels when an emergency situation is on-going. These are typically placed at the entrance to the tunnel. Traffic lights or mechanical barriers are typical equipment which may be used for this purpose.

The requirements of traffic signals outside the tunnel in different countries are shown in Table 4.18.

Table 4.18 Traffic signals outside the tunnel in different guidelines.

Country		Application criteria	Comment
Korea	NFSC	No reference	-
	GIST	≥1000 m	VMS (Variable Message Sign): 500 m in front of tunnel entrances.
Austria		*Class II, III, IV*	*At each portal.*
France		- Signage for stopping traffic: ≥300 m (50 m in front of each entrance) - Closure device+VMP[a)] · Urban: ≥1000 m[b)] · Non-urban heavy traffic: ≥3000 m[c)] · Non-urban low traffic bi-directional: ≥800 m[d)]	a) VMP means a variable message panel. b) ≥800 m if the tunnels are supervised. c) ≥800 m if there is human supervision. d) If there is human supervision.
Germany		*<300 m tunnels or 300–400 m tunnels and ≤15000 veh/day and ≤80 km/h*	***Minimum equipment: W****arning sign traffic lights, speed limit, overtake restriction etc.*
		300-400 m tunnels and >15000 veh/day and >80 km/h or 400-2000 m and ≤15000 veh/day	***Basic equipment: M****inimum equipment plus an additional variable traffic sign, reference to the traffic radio signal.*
		<2000 m and >15000 veh/day or ≥2000 m	***extended equipment: B****asic equipment plus permanent traffic lights, additional variable traffic signs, variable message sign.*
Japan		≥200 m	-
Norway		Flashing red stop signal: ≥Class B Remote controlled barriers: Class F and ≥Class B[e)]	e) Evaluation on basis of expected frequency of use.

Country	Application criteria	Comment
Sweden	All classes (≥100 m)	Traffic lights and boom (mechanical barrier)
UK	Class AA, A, B, C tunnels (tunnel closure signs/signals). To be considered in Class D.	-
USA	≥90 m	Means to stop traffic from entering the tunnel shall be provided.
EU	>1000 m	Tunnel closing equipment shall be installed before the entrances.

Note: In the table, *Italics*: Høj [20], <u>underline</u>: KTA [3], normal font: Original guideline.

The German guideline describes prevention signage, for example warning traffic lights, speed limits, overtaking restrictions, as well as mitigation signage. On the other hand, in other countries, traffic signs outside the tunnel indicate a means to stop approaching vehicles from entering the tunnel.

The provisions of the countries studied show a significant difference concerning the minimum criteria of targeted tunnels. The minimum lengths vary: all tunnels (Germany), 90 m (USA), 100 m (Sweden), 200 m (Japan), 300 m (France), and 1000 m (Korea and EU). The German guideline classifies all tunnels in three classes depending on tunnel length, traffic volume and speed limits and specifies required equipment for each class. France applies its guideline according to location and traffic volume. The other countries' requirements depend on tunnel length or class only.

4.7.2 Traffic signals inside the tunnel

In this section, mainly signage for stopping traffic and means to control traffic within the tunnel are compared.

The requirements of traffic signals inside the tunnel in different countries are shown in Table 4.19.

Concerning those tunnels to which signage requirements apply, the requirements of traffic signals inside and outside a tunnel are the same in Korea (≥1000 m), and the UK (≥Class C and to be considered in Class D). Other countries show some differences. In Germany, tunnels <300 m are excluded from the installation of inside signals although all tunnels shall be equipped with outside traffic signals. The requirements depend on tunnel length (all compared countries), traffic volume (France, Germany, Sweden, and EU), urban/rural location (France), traffic speed (Germany), the existence of a control center (EU), human supervision (France) and traffic flow type (France).

Table 4.19 Traffic signals inside the tunnel in different guidelines.

Country		Application criteria	Comment
Korea	NFSC	No reference	No reference
Korea	GIST	≥1000 m	LCS (Lane-use Control Sign): 400–500 m Spacing.
France		- Signage for stopping traffic+VMP · Urban: ≥1000 m · Non-urban heavy traffic: ≥3000 m[a)] · Non-urban low traffic bi-directional: 1000 m[b)] - Lane allocation sign · Urban: ≥1000 m[c)] · Non-urban heavy traffic uni-directional: ≥3000 m[c)] · Non-urban heavy traffic bi-directional: ≥800 m[d)]	a) ≥1000 m if there is human supervision. b) only if there is human supervision. c) ≥800 m if there is human supervision. d) ≥800 m if there is human supervision and more than one lane in each direction. Signage for stopping traffic: 800 m spacing. Lane allocation sign: every 200 m in urban and every 400 m in non-urban tunnel.
Germany		*300–400 m tunnels and >15000 veh/day and >80km/h or 400–2000 m and ≤15000 veh/day*	*Variable traffic signs (for length >600 m).*
Germany		*<2000 m and >15000 veh/day or ≥2000 m*	*Permanent traffic lights (every 300–600 m)*
Japan		Class AA Class A (≥3000 m)	They should be installed at emergency stopping lane.
Norway		Changeable signs: ≥Class B[e)] Lane signals: ≥Class E[e)]	e) It is not obligatory but shall be evaluated.
Sweden		Class TB[f)] and TA[g)]	f) manually controlled lane signals. g) as for TB, but also variable message signs (VMS), queue warning system, and equipment for stopping vehicles at least each 1000 m.
UK		≥Class C	Lane control signals should normally be provided (to be considered in Class D).
USA		≥240 m	Means to control traffic within the tunnel and to clear traffic downstream of the fire site shall be provided.
EU		Equipment to close the tunnel is recommended inside all tunnels longer than 3000m, with a control center and a traffic volume higher than 2000 vehicles per lane.	The spacing is ≤1000 m
UNECE		-	Variable message signs, traffic lights and possibly mechanical barriers may be used inside the tunnel.

Note: In the table, *Italics*: Høj [20], underline: KTA [3], normal font: Original guideline.

The minimum distances between signals are 200–800 m (Urban tunnels of France), 300–600 m (Permanent traffic lights, Germany), 400–500 m (Korea), ≤1000 m (EU). The requirements of France, Germany and Korea, and are fixed or approximate target values while the provisions for the EU give maximum figures.

4.7.3 Emergency exit sign

Emergency exit signs are devised to indicate the way to exit or escape facilities. They are usually self-illuminated or permanently lighted by lighting apparatus. The requirements of emergency exit signs in different countries are shown in Table 4.20.

Table 4.20 Emergency exit signs in different guidelines.

Country		Application criteria	Spacing	Comment
Korea	NFSC	No reference	No reference	-
	GIST	≥500 m	≤50 m$^{a)}$	a) At least four between emergency cross passages. They shall be maintained by emergency power supply at least for 60 minutes.
France		≥300 m	-	Signs shall be permanently illuminated.
Germany		<u>≥400 m</u>	<u>≤25 m</u>	It is installed together with emergency lighting 15 W.
Japan		<u>≥Class B</u>	-	<u>At least two emergency exit signs between emergency cross-passages.</u> <u>For ≥Class B and tunnels with no emergency cross-passage: arrow symbols and indication of the distance to the nearest exit.</u>
Norway		Category E, F	-	Also obligatory in other categories if the tunnel is constructed with alternative emergency exits, e.g. interconnections.
UK		≥Class B	50 m (emergency point)	To be considered for Class C and D. At each emergency point within the tunnel, it is desirable to include the distance to the nearest emergency exit in each direction.
UNECE		-	50 m	The two nearest escape exits should be signed on the sidewalls of the tunnel, at a height of 1–1.5 m, with an indication of the distances.

Note: In the table, *Italics*: Høj [20], <u>underline</u>: KTA [3], normal font: Original guideline.

Emergency exit signs are required to be installed in tunnels ≥300 m in France, ≥400 m in Germany, ≥Class B in the UK and ≥500 m in Korea. The maximum distances between signs vary from 25 m (Germany), to 50 m (the UK and UNECE). Korea requires at least four exit signs between emergency cross passages while Japan requires at least two. Norway and the UK have recommended provisions. The comparison in Table 3.20 shows that there is not a great deal of difference between national guidelines.

In Korea, NFSC has not established provisions related to emergency exit signs. However, related provisions can be found in GIST.

4.8 Monitoring equipment

4.8.1 CCTV

CCTV is an acronym for Closed-Circuit Television. It is useful equipment for the tunnel operator to watch the situation of tunnels, check fire locations and size and take necessary action accordingly. In particular, CCTV can show the tunnel operators real, vivid pictures while emergency telephones and push buttons can provide only limited information, i.e., voices and alarms.

The requirements of CCTV in different countries are shown in Table 4.21.

Table 4.21 CCTV in different guidelines.

Country		Application criteria	Spacing and Comment
Korea	NFSC	No reference	-
	GIST	Non-urban and unidirectional tunnel: ≥1000 m. Urban or bi-directional tunnel: ≥500 m	200–400 m
Australia		-	Not longer than 150 m spacing is recommended. CCTV systems should have sufficient zoom facilities.
Austria		*Class III, IV*	*200-300 m and at the portals*
France		- TV and automatic incident detection monitoring · Urban: ≥1000 m · Non-urban: ≥3000 m (≥300 m[a)]) · Non-urban low traffic bi-directional: ≥300 m.	a) If there is human supervision.
Germany		*≥400 m with ≥4000 HGV× km/bore per day*	*75–150 m*
Japan		For tunnel with sprinkler system: Type A CCTV (no zoom-up function)	200 m
		Class AA or Class A (≥3000 m) with sprinkler system: Type B (zoom-up function)	750 m (at emergency bay)
Norway		Category E [b)] and F [b)]	b) CCTV surveillance is only applicable to tunnels with a high capacity usage throughout much of the day.
Sweden		Class TB[c)] and TA[d)]	c) surveillance of alarm points for traffic incidents d) as for TB, but also speed and/or queue detection with automatic alarm for queue
UK		≥Class AA	Inside the tunnel, outside of each portal and on the approaches/exits. It is considered in other class A, B, C, D.
USA		≥240 m	CCTV with or without traffic-flow indication devices shall be permitted to identify fires in tunnels with 24-hour supervision
EU		>3000 m (video monitoring system)	Video monitoring systems and a system able to automatically detect traffic incidents and/or fires shall be installed in all tunnels with a control centre.
PIARC		All important road tunnels that are manned full or part-time (recommendation)	At the portal and inside the tunnel.
UNECE		Under surveillance over 1000 m in length	Video monitoring systems and automatic incident detection should be installed.

Note: In the table, *Italics*: Høj [20], underline: KTA [3], normal font: Original guideline.

The requirements vary depending on the traffic type (Korea), location (France and Korea), traffic volume (France, Sweden, and Germany), surveillance (France, PIARC and UNECE), and the existence of a water mist system (Japan). In Japan, two types of CCTVs have been specified. The nominal lengths of targeted tunnels are 240 m (USA), 300 m (France), 400 m (Germany), 500 m (Korea), 1000 m (UNECE) and 3000 m (EU). Since the Swedish requirements depend on the class, the length of the targeted tunnels depends on the traffic volume. The UK gives recommendations as well as requirements. The spacing between cameras is different in the various guidelines studied: 75–150 m (Germany), 200 m (Type A) and 750 m (Type B, Japan), ≤150 m (Australia), 200–300 m (Austria), and 200-400 m (Korea).

The requirements for CCTV are established in the guidelines of most countries and international organizations included in this study. This indicates that CCTV is universally used and/or recommended as monitoring equipment.

4.9 Emergency power supply

Emergency power supply facilities provide electric power to the safety systems such as ventilation, lightening, information and communication systems etc. in an emergency. Thanks to these facilities, safety systems can do their work regardless of a power cut.

4.9.1 UPS and emergency generator

UPS means an uninterruptible power system. This is one example of power supply facilities and ensures a certain time of power supply before the emergency generators start to produce power.

The requirements of UPS and emergency generator in different countries are shown in Table 4.22.

Table 4.22 UPS and emergency generator in different guidelines.

Country		Application criteria	Comment
Korea	NFSC	≥500 m	Ventilation, lightening and fire hydrant systems shall be supported by an emergency power supply at least 20 minutes.
Korea	GIST	UPS: ≥200 m. Generator: ≥500 m[a)] with ventilation system	a) Where tunnels are bi-directional traffic or urban tunnels. Otherwise, ≥1000 m. UPS should ensure at least 60 minutes. Emergency lightening and emergency exit signs shall be provided with reliable power by an UPS.
Australia		-	A reliable power supply is vital with multiple redundancies and back-up systems is recommended. Signage should be connected to an uninterruptible electrical power source.
Austria		*Class III, IV*	*Following systems must be connected to the emergency power supply:* *- Steering and control system of power supply* *- Ventilation system and emergency lighting* *- Traffic regulation and control system* *- Emergency call and communication system*

Country	Application criteria	Comment
France	≥300 m	UPS shall have an independence time of at least half an hour in the event of failure of the external power supply. • Essential safety equipment which shall be powered by an UPS. - Emergency lighting and marker lights - Lighting of facilities for the evacuation - Signage and marking of safety equipment - Pollution sensors and anemometers - Information systems - Function of monitoring and control rooms - Signaling devices, barriers - CCTV, automatic incident of fire detection - Radio communications relay equipment
Germany	*≥400 m*	*UPS shall be designed for the clearance period of the tunnel (15–60 min.)* *• Essential safety equipment which shall be powered by an UPS.* *- Signage for emergency escape* *- Emergency lighting in case of fire, emergency light* *- Escape route lighting and monitoring systems* *- Illumination of operational rooms, minimum one lamp per room* *- Traffic control, fire alarm, control systems*
Japan	UPS: ≥200 m Generator: ≥500 m	UPS should ensure at least 10 minutes
Norway	≥Category B	In order to ensure that road users are not handicapped by power failure the following equipment shall be connected to continuous power supply equipment (batteries or aggregate): • Surveillance, control • Flashing red stop signal • Priority lighting • Escape route lighting • Emergency telephone • Service signs • Emergency Exit signs • Communication and broadcasting equipment. The emergency power supply shall function for a minimum of one hour's duration with the designed load.
Sweden	All classes	Reserve power should be available for the following function (if needed for the tunnel class in question): emergency lighting, guiding markings, lane and entrance signals and barriers, information signs, control and surveillance systems (incl. CCTV), radio and telephone-based safety equipment, power supply for rescue services.
UK	-	• Essential service loads for UPS (minimum period of time: two hours) - Approximately 10 % of the Stage 1 lighting. - Computer control and fault indication systems. - Sub-surface communications systems including CCTV - Radio Systems and tunnel portal signals/signs. - Fire brigade power tool sockets etc.

Country	Application criteria	Comment
USA	≥240 m	The following systems shall be provided with reliable power for a fire emergency: Lighting, lighting for means of egress and areas of refuge, exit signs, communications, tunnel drainage and fire pump and ventilation during a fire emergency. UPS system or an on-site generator can be used as a source of power.
EU	≥500 m (emergency power supply)	To ensure the functioning of indispensable safety equipment at least at during evacuation of tunnel users.
PIARC	-	Signage for emergency escape and minimum safety lighting shall be powered by an UPS or have a battery backup.

Note: In the table, *Italics*: Høj [20], <u>underline</u>: KTA [3], normal font: Original guideline.

In the case of UPS, minimum running time and the equipment supported by UPS have been the main focus when determining which tunnels are targeted. The nominal tunnel length shows no great difference between the various countries included in this study: 100 m (Sweden), 200 m (Korea and Japan), 300 m (France and USA), 400 m (Germany), and 500 m (EU and Generator of Korea and Japan).

The minimum running time is from 10 minutes (Japan), 15-60 minutes (Germany), 20 minutes (NFSC of Korea), 30 minutes (France), 60 minutes (GIST of Korea and Norway). Most of the countries included in this study require that indispensable safety equipment, for example emergency lighting, signals/signs, and communication systems, shall be supported by the emergency power supply. Hydrant systems and fire pumps are required to be provided with reliable power only in Korea and the USA. Fire brigade power tool sockets are specified as equipment powered by a UPS only in the UK. Japan, Korea and the USA have on-sight generator related requirements.

4.9.2 Fire brigade power tool sockets

Fire brigade power tool sockets are used for the fire brigade to operate a variety of electrical appliance carried to a fire scene by fire fighters. Requirements concerning emergency power supply to such sockets are specified only in some countries.

The requirements of fire brigade power tool sockets in different countries are shown in Table 4.23.

The minimum requirements of the tunnel length are 300 m (France), 400 m (Germany) and 500 m (Korea). Shorter distances between sockets are required in Korea than in France and Germany. In the UK, UPS equipment is required to provide the sockets with permanent power. Other countries do not have related provisions.

Table 4.23 Fire brigade power tool sockets in different guidelines.

Country		Application criteria	Spacing	Comment
Korea	NFSC	≥500 m	<50 m	-
	GIST	≥500 m	<50 m	-
France		≥300 m	200 m	Electricity sockets are to be provided in emergency recesses.
Germany		<u>≥400 m</u>	<u>≤150 m</u>	<u>It should be installed in emergency call station.</u>
UK		-	50 m (emergency point)	Fire brigade power tool sockets shall be permanently connected to the UPS equipment.

Note: In the table, *Italics*: Høj [20], <u>underline</u>: KTA [3], normal font: Original guideline.

4.10 Drainage of flammable liquids

The spill of flammable liquids in a tunnel is more dangerous than outside of the tunnel. The gases from the flammable liquids cannot be exhausted from a tunnel easily or completely and therefore often remain inside the tunnel. These gases and liquids can be ignited, make the road surface slippery and cause a serious accident. For this reason, drainage facilities are important to ensure the safety of tunnels. A typical pumped drainage system for road tunnels is shown in Figure 4.1.

Drainage of flammable liquids is related to the inclination of the tunnel, the existence of a separate drainage system and liquid sump. In this study, the inclination of the tunnel and liquid sump are reviewed.

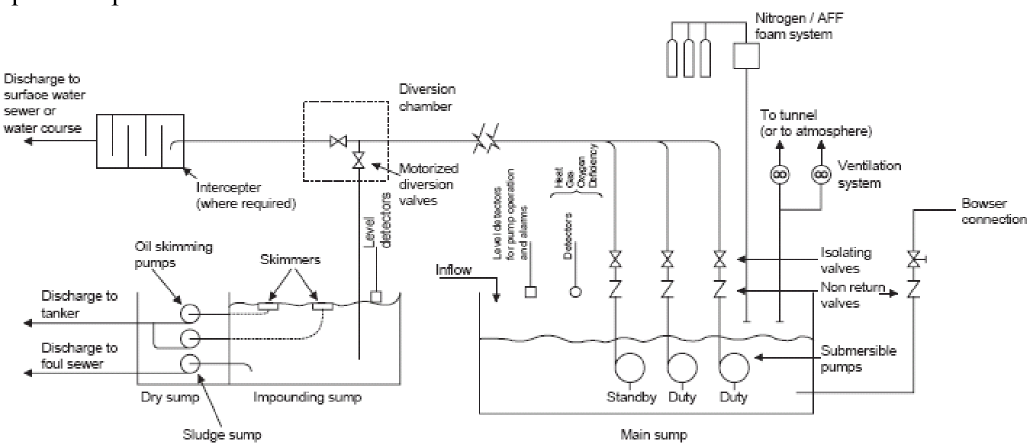

Figure 4.1 Typical pumped drainage system [15].

4.10.1 Inclination (slope) of tunnel

The degree of tunnel inclination should be considered carefully. Tunnels with steep gradients can demand higher ventilation costs due to increased vehicle emissions. In addition, the traffic speeds may be decreased. On the other hand, tunnel inclination helps to drain the spilled substances on the motor way. Desirable maximum gradient shall be subject to a cost-benefit study.

The requirements of the slope in transverse and longitudinal direction in different countries are shown in Table 4.24.

Table 4.24 Inclination of tunnel axis in different guidelines.

Country	Requirement
Korea	Transverse gradient: 1.5–2.0 %.
Austria	*Inclination should be 0.5 % (Transverse gradient)*
France	A minimum transverse gradient of 2 % is to be complied with over the traffic width of the roadway.
Sweden	The cross-fall should be between 1.5 % and 2.5 %.
UK	It is recommended that the normal cross-fall of 2.5 % is provided throughout the tunnel.

Note: *Italics*: Høj [20], underline: KTA [3], normal font: Original guideline.

Requirements concerning transverse gradient can be found in the guidelines of Austria, France, Korea, the UK and Sweden. The minimum transverse gradient is 0.5 % in Austria, 1.5-2.5 % in Sweden, 2 % in France and 2.5 % in the UK.

The provisions relating to the inclination of the tunnel are not provided in NFSC and GIST of Korea. Another Korean standard, "The Standard of Structure and Facilities for Roads" [21], provides requirements for the inclination of road tunnels. It seems that the roads within the tunnels are built in accordance with the "The Standard of Structure and Facilities for Roads". The standards require that transverse gradient shall be 1.5–2.0 %.

4.10.2 Liquid sump

Sumps are normally situated at the lowest point of a sag curve in the tunnel to contain an adequate volume of drainage water and to retain any spillage of flammable or other hazardous liquids in tunnels.

The requirements of liquid sump in different countries are shown in Table 4.25.

The liquid sump is mentioned in most of the guidelines included in this study. The minimum capacities of the liquid sump are: 25m^3/50 m^3 (Austria), 30 m^3 (the UK), 100 m^3 (Germany), and 200 m^3 (France). The requirements in Australia and the USA are descriptive. The directive of EU gives fixed values for targeted tunnels (>500 m).

Table 4.25 Liquid sump in different guidelines.

Country	Requirement
Australia	A drainage system should be provided in tunnels to collect, store, or discharge, or any combination of these functions.
Austria	*A sufficiently dimensioned storage tank must be stationed (25 m^3/50 m^3).*
France	Each section of gutter is to be capable of accepting a volume of 5 m^3 in one minute. The siphons and the main are to be capable of draining a flow of 100 L/s. The drainage system must be capable of recovering at least a minimum total volume of 200 m^3.
Germany	*The volume of a sump must be approximately 100 m^3 (72 m^3 for fire extinction and approximately 30 m^3 spill from a tank)*
Sweden	All tunnels should have roadway inlets at least every 30 m (drainage area ≤250 m^2) In tunnels allowing dangerous goods, roadway inlets should be installed at least every 20 m (drainage area ≤200 m^2). The drainage system should have a capacity to handle a spill of 10 m^3 during two minutes.
UK	Tunnel drainage system: ≥240 m (with some exceptions). The volume to be assumed is 30m^3, which approximates to the total contents of a large tanker vehicle.
USA	A drainage system shall be provided in tunnels to collect, store, or discharge effluent from the tunnel, or to perform a combination of these functions.
EU	For >500 m tunnels (drainage for flammable and toxic liquids is Mandatory with exceptions). Mandatory where transport of dangerous goods is allowed.

Note: In the table, *Italics*: Høj [20], <u>underline</u>: KTA [3], normal font: Original guideline.

4.11 Response of structure and equipment to fire

The tunnel structure and important equipment should be able to endure the fire and maintain their performance for the evacuation of the tunnel users and firefighting of emergency services. Otherwise, economic damage due to the closure of tunnels and the loss of lives may be disastrous.

4.11.1 Structural fire resistance

Related provisions are established in most of countries. However, the specific requirements and criteria are different. The requirements of structural fire resistance in different countries are shown in Table 4.26.

Table 4.26 Structure resistance to fire in different guidelines.

Country	Requirement
Australia	In the event of a fire within the tunnel, the structure and safety equipment should not burn and produce large amounts of toxic gases and smoke. The tunnel structure must not collapse and safety equipment should continue to operate while fire fighting and evacuation is taking place.
Austria	*Intermediate ceilings must have a resistance to fire according to fire class F90 (90 minutes resistance).*
France	- Level N1(CN 120): Structures supporting a roadway or an area which is accessible to pedestrians locate above it. - Level N2(HCM 120): when the structure is required to maintain the stability of another tube. - Level N3(CN 240 HCM 120[a)]): in the case of immersed tunnel. a) it means two separate justifications, one using the standard graph for 240 minutes, the other using the supplemented hydrocarbons fire graph for 120 minutes.
Germany	*By structural measures it shall be prevented that the load bearing reinforcement is heated to more than 300 ºC. The minimum cover for load bearing reinforcement is 6cm* [22]. RABT/ZTV is used as a temperature curve [23].
Norway	Tunnels must be designed for a fire load of 5 MW for AADT <10000, 20 MW for AADT >10000. In tunnels with risk of structural collapse the design fire load must be evaluated separately.
Sweden	Resistance to fire should be verified by testing, calculations or both. Avoidance of spalling should be documented by testing or investigation. If not transports of explosives, gases, or flammable liquids are allowed, a temperature load corresponding to 120 min of the hydrocarbon temperature curve should be used. If transports of anything but flammable gases are allowed, a temperature load corresponding to 180 min of the hydrocarbon temperature curve should be used. If also transports of flammable gases are allowed, a special investigation of the fire load should be performed.
UK	Measures to reduce concrete spalling from concrete ceilings at 150 ºC shall be applied
USA	Regardless of tunnel length, all primary structural concrete and steel elements shall undergo a fire engineering analysis to ensure that the tunnel structure can withstand the anticipated fire severity based on the type of traffic to be permitted.
EU	The main structure of all tunnels (≥ 500 m) where a local collapse can have catastrophic consequences shall ensure a sufficient level of fire resistance.
UNECE	Adequate resistance to fire should be ensured so that, in the case of a fire, users can be evacuated and rescue teams can operate under safe conditions, and extensive loss of property can be avoided.

Note: In the table, *Italics*: Høj [20], underline: KTA [3], normal font: Original guideline.

The prescriptive requirements in the German guideline give the maximum temperature which load bearing reinforcement is allowed to reach and minimum cover for such reinforcement. The Norwegian requirements are described differently, depending on the heat release rate and the volume of traffic. The French guideline requires 120 min or 240 min of structural resistance, depending on the fire graph. In Sweden the structural resistance and avoidance of spalling should be verified in some way. The fire load depends on the type of goods transported in the tunnel. A specified fire curve is mentioned as acceptance criteria in the guidelines of Austria, France, Germany and Sweden. The guidelines of Australia, the USA, the EU and UNECE are descriptive. The concept “structure resistance to fire” is not represented in the guidelines of Korea.

4.11.2 Equipment resistance to fire

In this section, a summary is made of the resistance temperature (the critical surrounding gas temperature) and endurance time for which tunnel equipment and facilities are required to withstand for evacuation and life saving.

The requirements of equipment resistance to fire in different countries are shown in Table 4.27.

Table 4.27 Equipment resistance to fire in different guidelines.

Country		Requirement
Korea	NFSC	Air supplier and auxiliary equipment of ventilation systems exposed to a fire shall be able to operate for more than one hour under 250 °C
	GIST	All electrical and structural components essential to the continued operation of ventilation fans shall, in the event of a fire, be suitable for operating in smoke-laden air at a temperature of 250 °C for 1 hour.
Australia		Consideration should be given to emergency doors, emergency recesses, communication systems, ventilation system and other equipment located between two tunnel tubes, the tunnel and the escape route or located on the walls or ceiling of the tunnel.
Austria		*Cables for emergency lighting must be inflammable and corresponding to F90 (90 minutes functionally).* *Cable for normal lighting, ventilation and door steering must correspond to E30 (30 minutes functionality) and FE180 (180 minutes isolation).*
France		The main arteries ensuring connections between electricity supply points and transmission cables can function under the conditions of Level N3(CN 240 HCM 120. Where fans are installed in order to ensure massive extraction, these must be capable of operating for 120 minutes at a temperature of 200 °C. Extraction fans located at each end of a duct must be capable of operating at a temperature of 200 °C for 120 minutes.
Germany		*Extraction fans and dampers must be designed minimum for resistance to a temperature of 400 °C during 90 minutes.* *Jet fans and electrical connections shall withstand a temperature of 250 °C during 90 minutes and (in some case) up to 400 °C in 90 minutes.*
Norway		For open ducts a distinction is made between cables which supply power to equipment which shall function in a fire situation (Cable class 3), and cables for non-critical equipment (Cable class 2). Cables in Class 3 shall function for a period of 90 minutes in a flame temperature of 750 °C.
Sweden		Installations should endure 250 °C for at least 45 minutes.
UK		Light, lighting diffusers, cables and tunnel linings above shall be non-flammable. Heavy items such as fans, subject to temperatures of 450 °C, should not fall during the fire fighting period. All electrical and structural components essential to the continued operation of ventilation fans shall, in the event of a fire, be suitable for operating in smoke-laden air at a temperature of 250 °C for 2 hours.
USA		Tunnel ventilation fans, their motors, dampers and all related components shall be designed to remain operational for a minimum of 1 hour in an air stream temperature of 250 °C. Materials that are manufactured for use as conduits, raceways, ducts, cabinets, and equipment enclosures and their surface finish materials shall be capable of being subjected to temperatures up to 316 °C for 1 hour.
EU		The level of fire resistance of all tunnel (≥ 500 m) equipment shall aim to maintain the necessary safety functions.

Note: In the table, *Italics*: Høj [20], <u>underline</u>: KTA [3], normal font: Original guideline.

The minimum resistance temperature and time is shown in most guidelines. However, the figures differ significantly: 200 ºC for 120 minutes (ventilation fans, France), 250 ºC for 45 minutes (all installations, Sweden), 250 ºC for 1 hour (all electrical and structural components relating to ventilation fans, Korea), 250 ºC for 1 hour (tunnel ventilation fans etc, USA), 316 ºC for 1 hour (materials manufactured for use as ducts etc, USA), 250 ºC for 2 hour (all electrical components, the UK), 400 ºC for 1.5 hour (fans and electrical connections, Germany) and 750 ºC for 1.5 hour (fire-proof cables, Norway). The guidelines of Australia and EU do not give detailed temperature and duration time requirements.

According to NFSC and GIST, all electrical and structural components for operation of ventilation fans should be able to do their performance at a temperature of 250 ºC for 1 hour. Compared to the requirements of Germany and the UK, there is a significant difference between the European guidelines and their Korean counterparts on the issue of fire resistance temperature and time.

5 Discussion

In this study, requirements concerning different fire safety equipment have been compared for a number of countries and organizations. When all detailed comparison tables are reviewed, some important issues should be highlighted. A list of the most important issues is given below.

- **Most requirements depend on the tunnel length.**. This means that the installation of required facilities for road tunnels are decided mainly based on the length of tunnels. However, some countries consider other criteria as well, e.g., traffic volume is adopted as a key parameters in Japan, Norway, Sweden and the UK. Danger potential is considered in Austria and risk analysis is carried out in Korea. The French guideline is established mainly according to the location of the tunnel, traffic type and traffic volume as well as tunnel length. In conjunction with the criteria given above, risk of congestion, ventilation type, and human supervision can also influence the ultimate decision concerning the application of provisions.

- **The minimum length of tunnel for application of guideline varies from country to country.** The figures are 90 m (USA), 100 m (Japan and Sweden), 150 m (the UK), 300 m (France) and 500 m (Norway and EU). Germany and Korea do not have a minimum value so all road tunnels are potentially applicable. The minimum value is useful as safety facilities may be useless in very short tunnels. There is also a cost-benefit issue.

- **Further study is needed on the relationship between capacity and spacing for firefighting equipment.** In Korea, extinguishers, hydrants and fire department connections have lower capacity than that of other compared countries. However, the installation spacing in Korean guidelines are shorter than that of European countries and USA. It is not known which approach is better or whether these two aspects (i.e., capacity versus spacing) compensate for each other so that the requirements are essentially equivalent.

- **The minimum values of AADT adopted by category systems vary.** They are 100 AADT in the UK and Sweden, approximately 250 AADT in Norway and approximately 500 AADT in Japan. In addition, the methods for calculating AADT are different in the five countries: 10 (Japan), 15 (the UK) and 20 (Korea, Norway and Sweden) years after opening.

- **More attention has been drawn to the installations of fixed fire suppression systems worldwide.** It reported that fixed fire suppression systems have been installed in Australia, Austria, Japan, Korea, Norway, Sweden and USA. In Japan, the use of sprinkler systems is mandated. In Australia, the installation is not mandatory but new tunnels are equipped with sprinkler systems.

6 Specific recommendations for Korea

Comparisons show that some requirements of NFSC need to be updated due to insufficient capacities or the fact that some important safety equipment has not yet been included in NFSC. In this section, the focus is given to specific recommendations for changes to NFSC to make it a reasonable and cost-effective guideline for road tunnels. Some important issues are presented below, as a backdrop to specific recommendations.

- Some fire safety equipment and safety concepts have not been specified in NFSC and GIST. These include:
  - Separated emergency vehicle gallery access
  - Emergency service parking
  - Inclination of tunnel axis
  - Liquid sump
  - Structural fire resistance
- Requirements are provided in GIST but not in NFSC for some equipment, including:
  - Loudspeakers
  - Emergency telephones
  - Parallel escape tube
  - Emergency cross-passages
  - Turning areas
  - Cross passages for rescue vehicle
  - Emergency exit signs
  - Traffic signals inside/outside the tunnel
  - CCTV
- In some cases existing provisions need to be improved or revised. These include:
  - The capacity of hand held extinguishers
  - The discharge volume and pressure of fire hydrants
  - The minimum operation time of emergency power supply
  - The minimum temperature and time of equipment to resistance fire

From the comparisons performed in this report some of the issues mentioned above should be given special attention. Those are described in the following:

Minimum capacity of extinguishers of NFSC should be revised to require two 4.5 kg-extinguisher (5 unit capacity for A class fire and 10 unit capacity for B class fire) as a minimum requirement. PIARC recommends 6 kg-extinguishers at a minimum for portable extinguishers.

There is no provision in NFSC concerning extinguisher removal alarms which would enable tunnel operators to be informed of the use of their equipment should an extinguisher removed. For quick response in tunnel fires, efficient equipment removal alarm systems are necessary.

When considering the relationship between targeted tunnels, spacing, water pressure, flow rate and discharging time, more intensive studies are necessary to optimize the various requirements. One should note, however, that the Korean requirements for water flow rate and pressure do not satisfy the recommendation of PIARC where 1000 L/min as a water flow rate and 0.5 MPa as a water discharge pressure, are stated. Based on this comparison the authors feel that the water pressure, flow rate and maximum water discharging time in the Korean guidelines should be upgraded.

It is certainly worth considering whether detailed provisions related to fixed fire suppression systems should be included in Korean guidelines.

It is imperative that NFSC be updated to come into accordance with GIST which has already strengthened the fire detection related regulations. Further, current provisions of NFSC on fire detection are not specific so they are open to misinterpretation. It is necessary that more detailed requirements, reflecting the tunnel's unique characters such as an existing air flow and difficulties of locating of fire site, are included in future provisions.

There is no reference relating to the loudspeakers in NFSC. Only sirens, activated by an alarm button, are presented. Fortunately, related requirements are made in GIST. It is natural that voice instructions are more helpful to tunnel users than sound signals when they are faced with the emergency situation and do not know what to do. For that reason, it is recommended that provisions relating to loudspeakers be included in NFSC.

The Korean existing requirements for radio communication can be considered to be reasonable compared to those of other countries. Even 200 m long tunnels are recommended to be equipped with wireless communication systems for fire brigade and users.

The minimum length of targeted tunnels for emergency cross-passes in GIST has been revised from 1000 m to 500 m tunnels in 2004. It appears that the changed requirement is appropriate and is expected to contribute to a higher level of fire safety.

There are some differences between NFSC and GIST on how long road tunnels shall be equipped with the emergency lighting; ≥ 500 m in NFSC, ≥ 200 m in GIST. In addition, the minimum operation time of a supplementary power supply is set to 20 minutes in NFSC, while 60 minutes in GIST. A supplementary power supply, for example an UPS or emergency batteries, shall ensure a certain time of operation before the fire brigade arrives at the scene or an emergency generator generates power. For this reason, 20 minutes as a minimum operation time appear to be insufficient to ensure the safety of the tunnel users. The fact that there are differences between NFSC and GIST and that the differences are not logical, may cause confusion among the tunnel designers and operators when they plan and maintain tunnels. For this reason, it is recommended that the targeted length of NFSC should be shortened in alignment with GIST and the minimum operation time should be prolonged from 20 minutes to 60 minutes.

Concerning the minimum length of tunnel for requiring smoke control ventilation, the two guidelines of Korea have different requirements. GIST has been revised in 2004 where the minimum length of application for smoke control ventilation system has been changed from 1000 m to 500 m. However, the related provisions of NFSC remain unchanged and require 1000 m as a minimum. The formulation of NFSC is rather descriptive and does not provide specific information such as tunnel conditions and the type of ventilation.

Drainage systems for dangerous liquid have not been prepared in NFSC and GIST of Korea although there might be other guidelines or standards dealing with this issue. Reviewing Table 4.25, it is clear that European countries have their own provisions involving the liquid sump. It is suggested that Korea introduce this safety concept and set up the related provisions with reference to the ones of the European countries.

It is strange that the concept "structural resistance to fire" is not represented in the guidelines of Korea. Serious tunnel fires are known to cost many lives and properties and stop the tunnels from functioning properly for a considerable amount of time. One reason for this is the structural damage that occurs in the tunnel. In the case of the Mont Blanc tunnel fire in 1999, the tunnel had to be closed for three years. Detailed provisions associated to structural resistance to fires should be included in the Korean guidelines as soon as possible.

The Korean fire authorities should examine these issues and decides what actions should be taken. Suggested recommendations are shown below. Table 6.1 summarizes the reviews presented in each section. It is hoped that this can provide a starting point for the Korean government to develop more advanced fire safety guidelines for road tunnels.

Table 6.1 Suggested requirements of NFSC

Fire Safety Equipment	Existing provisions (NFSC)		Suggested provisions (NFSC)	
	Targetd Tunnel	Capacity & Spacing	Targeted Tunnel	Capacity & Spacing
Hand held extinguisher	All tunnel	Two 3.3 kg (3 unit capacity)	All tunnel	**Two ≥4.5 kg** (5 unit capacity for A class fire and 10 unit capacity for B class fire). **Automatic alarm on extinguishers**
Pressurised fire hydrants	≥1000 m	130 L/min, 0.17 MPa/cm^2 Minimum discharing time: 20 min.	≥1000 m	**Discharging volume and pressure need to be increased. Minimum discharging time: ≥40 min.**
Fixed fire suppression system	No reference	No reference	**Further studies are needed**	
Automatic fire Detection system	≥1000 m	-	**≥500 m**	**-**
Loudspeakers	No reference	No reference	**≥500 m**	**≤50 m**
Emergency telephone	No reference	No reference	**≥500 m**	**≤250 m**
Separate emergency vehicle gallery access	No reference	No reference	**Requirements should be arranged.**	
Emergency services parking	No reference	No reference	**Requirements should be arranged.**	
Emergency lighting	≥500 m	An average of ≥1 lux at any point	**≥200 m**	**Supplementary electricity supply should operate it at least for 60 minutes**

Fire Safety Equipment	Existing provisions (NFSC)		Suggested provisions (NFSC)	
	Targetd Tunnel	Capacity & Spacing	Targeted Tunnel	Capacity & Spacing
Emergency exit sign	No reference	No reference	**≥500 m**	**At least four between emergency cross passage Detailed requirements should be arranged.**
Smoke control ventilation	≥1000 m	No reference	**≥500 m**	**Detailed requirements should be arranged.**
Fire department connections	≥2000 m	≤50 m	**≥1000 m**	≤50 m
UPS and Emergency generator	Ventilation, lightening, exit signs and hydrant system shall be supported by a emergency power supply at least 20 minutes.		**The emergency power supply should be able to last at least 60 minutes.**	
Inclination of tunnel axis	No reference	No reference	**Requirements should be arranged.**	
Liquid sump	No reference	No reference	**Requirements should be arranged.**	
Structure resistance to fire	No reference	No reference	**Requirements should be arranged.**	
Equipment resistance to fire	All electrical and structural components shall be suitable for operating at a temperature of 250 ºC for 1 hour.		**More than 250 ºC and 60 minutes**	

7 Conclusions

In this study, numerous guidelines from countries and organizations have been compared to identify their differences and similarities. Some fire safety equipment has been described frequently or similarly in various guidelines while some are mentioned rarely or differently in different countries. It is hoped that this comparison, will provide meaningful information from which beneficial conclusions can be derived for improvements to future tunnel safety. The aim of this work is to support existing requirements or develop more useful provisions.

Provisions for NFSC have been suggested in Table 6.1 based on comparisons between various guidelines. However, they should be passed through a screening process before they are applied to real tunnels, as they are based on a comparison between guidelines and not on real tests or engineering calculations. The present lack of engineering data for the development of validated tunnel safety guidelines is the main limitation of this study. Further research is required to verify and develop the suggested improvements.

It is practically impossible to construct a perfect tunnel safety guideline, ensuring absolute fire safety in road tunnels. However, we must make every effort to decrease the risks associated with the use of tunnels to the greatest extent possible. It is only through continuous research on this topic that we will ultimately decrease the threat of tunnel fires.

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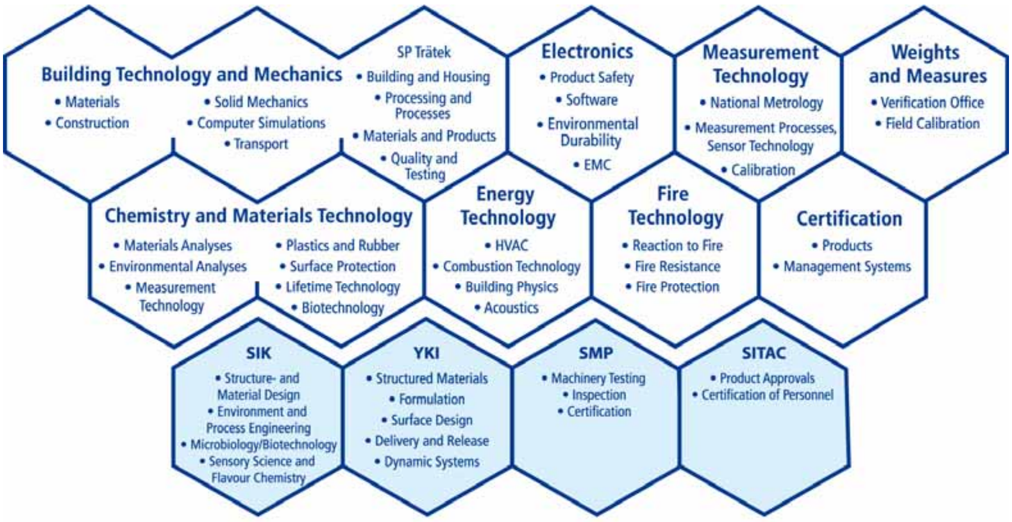

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