State of the road tunnel safety technology in Japan

H. Mashimo
Public Works Research Institute, Independent Administrative Institution, Tsukuba, Japan

ABSTRACT: As more and more tunnels have been constructed to develop new road network through mountainous ranges or to avoid environmental problems in urban areas, safety in road tunnels has been becoming a major issue. Establishment of tunnel safety measures is the most important task for all those who are engaged in road tunnel design, construction, operation or safety. Based on the past experiences of serious accidents involving fires, efforts to improve safety in road tunnels have been made by establishing technical standards with technological progress and improving emergency facilities in Japan. This paper describes the state of the road tunnel safety technology in Japan.

1. INTRODUCTION

Japan is a country surrounded by sea on all sides, consisting of an arc-shaped chain of islands. About 70% of its land is steep mountainous with great geological variation. Tunnels play an important role in developing new road networks and the number of road tunnels in Japan has continually increased rapidly over many years as shown in Figure 1. This is because of recent developments of road networks through mountainous ranges, and also because of the reduction of tunnel construction costs. In addition, with improving construction technology, tunnels have been adopted as an increasingly cost-effective engineering solution to traverse urban areas with minimum local environment impact. As of April 2000, Japan had road tunnels in 8,189 locations, with a total length of 2,575km.

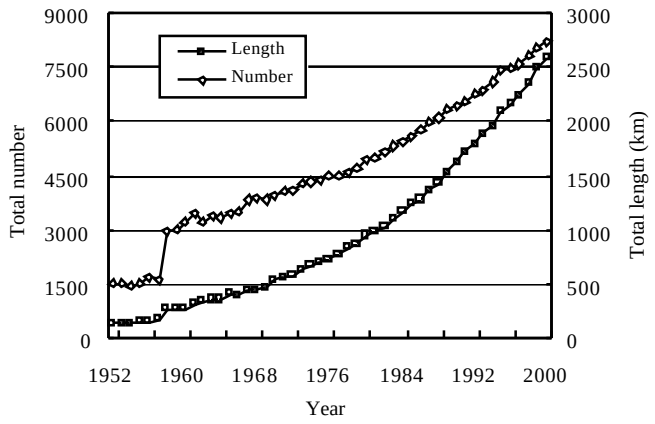

Figure 1. Increases in total number and length of road tunnels

In the past, we have suffered some serious accidents involving fires in road tunnels with the increase of road tunnels and absorbed the lessons from these past accidents. To improve safety in road tunnels, we have made efforts at establishing safety measures by establishing and revising technical standards in accordance with technological progress, improving emergency facilities, establishing a joint operation system with the police and the fire brigade, and promoting information campaigns aimed at tunnel users.

In this paper, the latest measures and technology to ensure safety in road tunnels including planning, design and operation of emergency facilities, and fire resistance of tunnel structure in Japan are presented.

2. SAFETY CONCEPT OF THE ROAD TUNNEL

Generally fewer accidents occur in tunnels than on open roads. However, if an accident occurs in a tunnel, the impact is often much greater than on open roads. The consequences can be extremely destructive and dangerous, especially in the event of a fire, because the enclosed space hinders the dissipation of heat and smoke. In addition, access limitations for fire-fighting and rescue operation, difficulty in ensuring safe escape route of the tunnel users from an enclosed space increase the severity of the accident seriously. Fires in tunnels not only endanger the lives of tunnel users, they can also cause the damage to the tunnel structure with the very prejudicial consequences on the capital represented by the tunnel. In view of this, it is essential to prevent accidents in tunnels and provide adequate measures for tunnel users to escape or be rescued by fire brigade.

The measures of ensuring safety in road tunnels fall into two categories: reduction of the probability of an accident and reduction of the consequences of events such as accidents and fires. The former con-

sists of tunnel design, traffic regulations, facilities installed in a tunnel, such as ventilation system, lighting system and interior finish, and maintenance. The latter consists of installing emergency facilities in road tunnels and constructing fire-resistant tunnel structures.

3. MEASURES TO REDUCE THE PROBABILITY OF AN ACCIDENT

3.1 *Tunnel Design*

Many elements of tunnel design such as cross section, alignments, drainage, road surface and shape of portal have an important influence on tunnel safety.

In particular, the design of the vertical and horizontal alignment is an important factor in decreasing the frequency of accidents. Horizontal alignments of road tunnels should be either linear or radially large in principle to ensure the safe visual perception, and vertical alignments should incline as gently as possible within a range where the discharge of water in tunnel is not prevented.

Lay-bys for emergency parking in case of vehicle breakdown will also reduce the probability of an accident. In Japan, lay-bys are generally provided at intervals of between 500 and 1,500m in long tunnels.

3.2 *Traffic Regulations*

Speed reductions and prohibition to overtake are considered to be one of the most cost-effective measures to decrease the frequency and severity of accidents, provided that they can be enforced rigidly. Overtaking is generally prohibited in bi-directional tunnels with one lane in each direction.

The restriction of dangerous goods transport through a tunnel is an important factor when dealing with fire safety in road tunnels. In Japan, the transport of dangerous goods through underwater tunnels (or tunnels similar to) and tunnels longer than 5,000m shall be restricted, taking account of the catastrophic consequence such as tunnel flooding, and the difficulties to evacuate tunnel users and carry out rescue operation in long tunnels when an accident such as an explosion of hazardous material occurs.

3.3 *Ventilation System, Lighting System, Interior Finish and Maintenance*

Since a tunnel is enclosed structure and the illuminance there is lower than in open roads, a satisfactory visual environment has to be created to allow drivers to pass through tunnels safely and comfortably. For this purpose, ventilation system, lighting system and interior finish are provided in road tunnels depending on tunnel length, traffic flow volume and design speed.

1) Ventilation system

The objective of ventilation system is to dilute or remove harmful substances contained in exhaust gas from vehicles, in order to prevent the harmful substances from injuring the health of tunnel users and maintenance personnel and to maintain good visibility in tunnels. In Japan, CO, which adversely affects human body, and soot, which is detrimental to the visual environment are targeted for road tunnel ventilation. Ventilation system is divided into four basic systems: longitudinal ventilation, transverse ventilation, semi-transverse ventilation, and combinations of these. Recently, the adoption of longitudinal ventilation systems has spread widely.

2) Lighting System

The objective of tunnel lighting system is to secure safe and smooth passage of traffic in tunnels. Lighting system is designed to give a certain road luminance taking into account design speed, type of traffic and tunnel structure. Lighting system is composed of fundamental lighting, entrance lighting, exit lighting and connecting roads lighting. The level of luminance at the entrance lighting is higher than that of the fundamental lighting. This is because of the resolution of visibility problems, particularly when driving from a very luminous outside environment into the much darker tunnel environment. In general, road tunnels are equipped with entrance and fundamental lighting, while other lightings are provided depending on traffic flow volume, tunnel length, meteorological conditions outside and so on.

3) Interior finish

The objectives of interior finish are:

- To secure visual information such as identification of alignment and obstacles by means of the difference in luminance between walls and road surfaces under tunnel lighting
- To ensure traffic safety by enabling drivers to confirm the position from the tunnel walls
- To make the interior presentable by preventing wiring, piping, and the like from being exposed and to avoid causing discomfort to drivers

Interior finish is provided depending on tunnel length, traffic flow volume, type of road and so on.

4) Maintenance

Poor maintenance results in reduced safety for tunnel users. Therefore, a reliable maintenance is necessary for reducing the probability of an accident. The maintenance of tunnels carried out periodically by qualified specialists in Japan is divided into two categories: one is the inspection of tunnel structures such as lining, portals, interior boards, ceiling slabs and drainage facilities; and the other is inspecting and maintenance of facilities including ventilation system, lighting system and emergency facilities in order to remain these systems functional. Tunnel maintenance work includes cleaning surface, cleaning attachments to the road such as interior boards and tiles on the sidewalls, cleaning drainage facilities and cleaning tunnel lighting.

4. REDUCTION OF THE CONSEQUENCES OF AN ACCIDENT BY EMERGENCY FACILITIES

4.1 *Principles*

In the case of an accident in a tunnel, and in particular, in the case of a fire, the essential point to ensure safety is that the early detection of a fire and the early transmission of information on it to tunnel users, can lead to reduction of the consequences that fire has on the tunnel users and the tunnel structure. The fact that a fire can be generally easily extinguished immediately after it breaks out should be also considered. The following elements should be therefore taken into consideration when providing a tunnel with emergency facilities:

- Early detection of an accident and a fire
- Early alarm transmission and control of traffic
- Evacuation of tunnel users to safe space
- Extinction of a fire at initial stage

In Japan, "Installation Standards for Road Tunnel Emergency Facilities" has been established on the basis of these elements and the standard defines the criteria governing the installation of the emergency facilities including planning, design and operation.

4.2 *Planning of Emergency Facilities*

Every tunnel has its own unique characteristics. Tunnels vary in length, cross section, profile, traffic control, and traffic flow volumes, among other characteristics. They may be constructed at varying depths under ground or water. It is desirable to consider these characteristics when planning the emergency facilities arrangement on each tunnel, but it is impossible to arrange the necessary emergency facilities for each specific tunnel considering all these characteristics.

In Japan, to arrange emergency facilities, tunnels are categorized into the five classes as shown in Figure 2 in relation to the tunnel length and the traffic flow volume. This classification was determined by the probability of accidents and fires based on the past experiences. Long tunnels with a high design speed such as a national expressway, or tunnels with bad perspective owing to especially winding horizontal or vertical alignment should be ranked in the upper class than the standard.

Emergency facilities as shown in Table 1 should be installed in tunnels depending on the tunnel class.

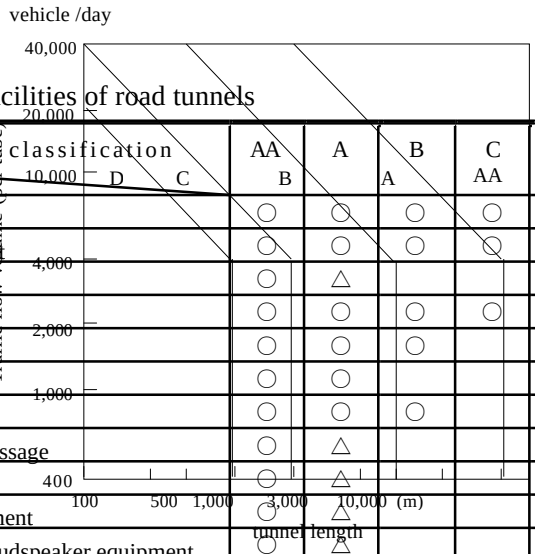

Figure 2. Tunnel classification

Table 1. Standard of emergency facilities of road tunnels

Emergency facilities		Tunnel classification: AA	A	B	C	D
Information and alarm equipment	Emergency telephone	○	○	○	○	
	Pushbutton type information equipment	○	○	○	○	
	Fire de tector	○	△			
	Emergency alarm equipment	○	○	○	○	
Fire extinguishing equipment	Fire extinguisher	○	○	○		
	Fire plug	○	○			
Escape and guidance equipment	Guide board	○	○	○		
	Smoke exhaust equipment or escape passage	○	△			
Other equipment	Hydrant	○	△			
	Radio communication auxiliary equipment	○	△			
	Radio re-broadcasting equipment or loudspeaker equipment	○	△			
	Water sprinkler system	○	△			
	Observation equipment	○	△			

Note: In the table, ○ indicates that the equipment should be installed as a rule, and △ indicates that the equipment should be installed as required.

4.3 *Types and Details of Emergency Facilities*

4.3.1 *Information and Alarm Equipment*

Information equipment alerts the tunnel operator, the fire brigade or the police, and alarm equipment informs drivers inside and outside the tunnel of an accident or a fire.

1) Emergency telephone

Tunnel users can inform the tunnel operator, the police or the fire brigade about the situation in the tunnel and can be informed of the steps to be taken in a given situation by emergency telephones (Figure 3). The phones should be installed at intervals of not more than 200m, at a height of 1.2-1.5m on sidewalls of the tunnel. Emergency telephones are one of the most frequently used equipment of all information equipment.

Figure 3. Emergency telephone

2) Pushbutton type information equipment

Persons involved in or discovering an accident can inform the tunnel operator of occurrence of the accident by pushing the button. This equipment should be installed at every 50m, at a height of 0.8-1.5m on sidewalls of the tunnel for easy operation.

3) Fire detector

Fire detectors should not be influenced by the emission of pollutants from vehicles and ventilation air blowing. They should therefore be the beam types that catch the wave length peculiar to the fire at initial stage. Among the beam types, glittering two-wave-length type (Figure 4) and CO_2 sympathetic vibrations type are used with confidence in many tunnels. They are mounted on sidewalls at a height suitable for fire detection but still easy to maintain and inspect. Intervals should be arranged considering the fire detection ability and the discharge sections of water sprinkler system.

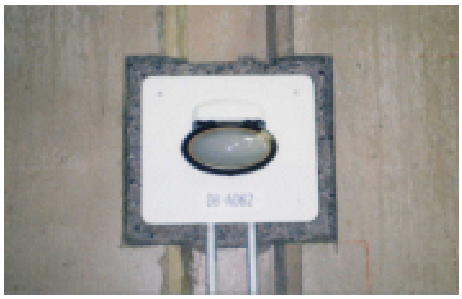

Figure 4. Fire detector

4) Emergency alarm equipment

Emergency alarm equipment can be used to notify the abnormality promptly to tunnel users in the tunnel and approach zone or to prevent vehicles from entering the tunnel in case of an accident. This system is composed of entrance information boards at tunnel entrances (Figure 5) and in-tunnel information boards in lay-bys in tunnel (Figure 6).

Figure 5. Tunnel entrance information board

Figure 6. In-tunnel information board

4.3.2 *Fire Extinguishing Equipment*

Fire extinguishing equipment is composed of fire extinguishers and fireplugs. They should be easy of use for an unskilled person who can fight the fire until the professional fire-fighters arrive.

1) Fire extinguisher

Fire extinguishers can be used to extinguish a fire at initial stage and its ease of operation is important for general use. They should be selected for use on both oil and electric fires, and should not generate gases harmful to the human body. They should be placed at every 50m on sidewalls at a height for easy operation. Each fire extinguisher boxes should include a pair of fire extinguishers and be combined with fireplug (Figure 7).

Figure 7. Fire extinguisher / plug / hydrant

2) Fire plug

Fire plugs can be used to fight the fire at initial stage along with fire extinguishers. They should be easy to operate for the general public even when they have no experience. It is desirable to install the type that discharges water as soon as a valve opens. Though water-type fire plugs are installed in most tunnels, foam-type fire plugs are installed in some of them. They should be installed at every 50m on sidewalls at a height for easy hose removal in a fireplug box.

4.3.3 *Escape and Guidance Equipment*

Escape and guidance equipment can be used to facilitate evacuation of tunnel users by providing evacuation information and securing the evacuation environment. This equipment is composed of guide board, smoke exhaust equipment and escape passage.

1) Guide board

Guide boards (Figure 8) indicate escape routes, that is, the distances and direction to the emergency exits and its presence. The guide board plate should be internally lighted, if necessary.

2) Smoke exhaust equipment

In the event of a fire, smoke exhaust equipment prevents or limits the dissemination of smoke and toxic gases. Usually, the tunnel ventilation system is used as smoke exhaust equipment.

In longitudinal ventilation system using the jet

Figure 8. Guide board

fans, it should be designed to work inversely to ventilation airflow, and electronic wiring should be fireproof. In transverse ventilation system or semi-transverse ventilation system which is designed to extract smoke, duct cooling equipment should be installed to prevent thermal damage to the ventilator.

3) Escape passage

Typical escape passages are:

- Evacuation tunnel built beside and along the main tunnel (Figure 9)
- Cross passageways which connect the main tunnel and the evacuation tunnel, or two adjacent main tunnels
- Emergency exits of urban tunnels to escape from the tunnel to the open

Factors to be considered when planning escape passage are tunnel length, type of traffic, traffic flow volume, type of ventilation system and topography.

In the tunnel with cross passageways, cross passageways should be placed at approximately every 700-800m for two adjacent unidirectional tunnels and approximately every 300-400m for bi-directional tunnels. Auxiliary equipment for escape passage should provide the necessary illumination to ensure the evacuation environment.

Doors should be capable of stopping the propagation of smoke or gases and be fireproof. They are therefore duplicated in some cases. They should be easily opened and automatically closed.

Figure 9. Evacuation tunnel

4.3.4 *Other Equipment*

Besides above-mentioned equipment, other equipment is provided as emergency facilities in order to supplement information and alarm equipment, fire extinguishing equipment, and escape and guidance equipment, and to facilitate fire-fighting operation especially in the tunnels with very long length or heavy traffic flow volume.

1) Hydrant

Hydrants can be used by fire fighters for fire-fighting operation inside the tunnel.

Although hydrants should be installed at both entrances, they should also be installed in lay-bys in tunnels and near the entrance of escape passages, if necessary.

2) Radio communication auxiliary equipment

Radio communication auxiliary can be used for communication with the outside of the tunnel by the fire brigade engaging in rescue or fire-fighting operation in the tunnel.

3) Radio re-broadcasting equipment

An induction antenna is installed in the tunnel so that radio broadcasting can be received in it. A tunnel operator can break in on these radio frequencies and provide tunnel users with information and safety instruction through their car radio in case of an emergency.

4) Loudspeaker equipment

Tunnel operators can provide instructions to drivers who have left their vehicles or to all tunnel users via this equipment in case of an emergency.

5) Water sprinkler system

A water sprinkler system discharges fine particles of water from water spray heads in order to prevent fire from spreading, support fire-fighting operation (Figure 10). The water discharge section should be over 50m long considering that the area of fire coverage would be 20-30m.

Figure 10. Water sprinkler system

6) Observation equipment

A close-circuit television system (CCTV) can be used to confirm information from other alarm systems such as emergency telephones, detect any accidents and obtain the information necessary to take the appropriate actions in case of an emergency. Under normal circumstance, traffic conditions are monitored for traffic control via CCTV. Cameras should be placed at appropriate intervals so that they can cover the whole length of the tunnel and the areas around the portals.

If possible, CCTV should be linked with other information equipment such as emergency telephones, pushbutton type information equipment, and fire detectors in order to turn the camera toward an accident or a fire.

4.4 *Operation of Emergency Facilities*

4.4.1 *Preliminary to Effective Operation*

As described above, high-grade emergency facilities are installed to reduce the consequences of accidents and fires in tunnels in Japan. In the case of an accident in a tunnel and particularly in the case of a fire, it is of most importance to operate these facilities as soon as possible and correctly. For this purpose, some indispensable preliminaries should be implemented.

1) Periodical exercise

For tunnels longer than 1,000m and shorter tunnels with heavy traffic volume, exercises on site should be carried out jointly with the police, the fire brigade and other organizations concerned once or more a year. This exercise includes the following actions:

- Testing of fire detection and alarm transmissions
- Evaluation of tunnel operator, police and fire brigade response time
- Confirmation of instructions on operation of ventilation system and more general instructions relating to the response to a fire
- Exercise of extinction of fire-fighting and rescue operation

2) Information Campaign

In order to acquaint tunnel users with the emergency facilities available, how to use them and the proper tunnel user behaviour in tunnels, information campaigns such as distributing leaflets and posters, displaying fire extinguishing equipment in parking areas should be organized and implemented.

3) Preparation of manual

Manual including the following items should be prepared:

- Quickest methods of transmitting alarms to the control room and reliable information to the intervention teams regarding the severity and location of the fire
- Programs to operate the various emergency facilities

- Instructions to be issued by emergency alarm equipment and cut-in radio re-broadcasting with respect to the behaviour of tunnel users
- Confirmation of the information from tunnel users

4) Establishment of cooperation with relevant organizations

Since tunnel operators alone can never manage a disaster in a tunnel, agreed command and management of operation between the various organizations involved, such as the police and the fire brigade, is indispensable. The cooperation with relevant organizations should be therefore established.

4.4.2 *Operation Procedures of Emergency Facilities*

In the event of a fire in tunnels, the highest priority must be detection and ability of tunnel users to rescue themselves. Emergency facilities should be worked out in line with this principle. To detect a fire in tunnels, several kinds of equipment is provided and operation of all equipment after detecting a fire is organized into an efficient system.

If the first alarm on a fire comes from fire detectors, pushbutton type information equipment or lifting of a fire extinguisher, the ventilation system, the pumps for hydrants and fire plugs, are automatically started up, and lighting system in the tunnel is set to maximum levels. Entrance information board also is activated to prohibit the entry of subsequent vehicles, except in tunnels with CCTV. On the other hand, in case of the first alarm from an emergency telephone, these necessary actions are taken manually according to the contents of the information.

After confirming the situation and recognizing a fire via CCTV or the like, the following actions are taken:

- Prohibiting the entry of subsequent vehicles by means of the entrance information board (in tunnels equipped with CCTV)
- Calling upon the police and the fire brigade
- Broadcasting a instruction for evacuation from the tunnel
- Starting up the water sprinkler system

5. FIRE RESISTANCE OF TUNNEL STRUCTURE

The objectives for fire resistance of tunnel structures are:

- To make evacuation or protection of tunnel users possible
- To make rescue and fire-fighting operations possible and ensure their safety
- To limit damage to tunnel structure and equipment, and to surrounding buildings

It is generally acceptable that repairs are necessary after a large fire, but not that whole tunnel is lost. Therefore, the need for special fire-resistant protection must be examined taking account of an economic balance between extra costs for additional fire-resistant protection, and costs of repairs and consequences of a traffic disruption after a possible fire.

The need for fire-resistant protection of the main structure depends to a great extent on the type of construction and on the role of the specific structure.

In Japan, most of the road tunnels have been constructed in rock by the New Austrian Tunnelling Method (NATM) or the conventional tunnelling method using steel supports and lagging. In the tunnel with two lanes constructed by the NATM, unreinforced concrete lining with a thickness of 30cm was normally installed inside the tunnel. In the tunnel constructed by the conventional tunnelling method, unreinforced concrete lining with a thickness of more than 45cm was used as the main structure of the tunnel.

For these tunnels, no special fire-resistant protection has been provided, because a local collapse of concrete lining caused by a fire will generally have much smaller consequences on safety and property of the rock tunnels and it will be repaired more easily and in a short time. In fact, a wide range of technical investigation on the disastrous fire accident of Nihonzaka tunnel, which wrecked 173 vehicles and continued to burn during four days, shows that the mechanical properties of the tunnel lining, on which numerous spalling appeared, were scarcely affected and the whole tunnel stability was not affected by the fire at all.

On the other hand, a few road tunnels driven by the shield tunnelling method are now under construction in urban areas where the ground is composed of soft ground with high water table. Until now, a tunnel driven by the shield tunnelling method has been usually installed with secondary concrete lining inside the segments lining for the purpose of corrosion protection, alignment adjustment, waterproofing interior lining and vibration protecting. However, with the progress of technology that can substitute the secondary concrete lining's function, such as seg-

ment seal materials and improvement of accuracy in the construction execution, secondary concrete lining is going to be omitted in these tunnels in view of the economy. In these tunnels, fire-resistant protection measure to prevent the failure, such as the installation of fire-resistant insulating boards on the segments surface, will be applied, because a collapse of the segments may be very difficult to repair in a high water bearing soft ground.

A few immersed tunnels have also been constructed under sea or rivers in Japan. In immersed tunnels, the need for special fire-resistance protection to prevent the tunnel flooding due to a local collapse during a fire has been decided taking into account many factors such as the type of traffic allowed in the tunnel (whether vehicles transporting dangerous goods are allowed or not), the type of structure and material, the strategy for fire-fighting.

6. CONCLUSION

Efforts to improve road tunnel safety have been made based on the lessons learned from past accidents involving fires in Japan.

The accident consequence shows that the highest priority has to be given to securing safe escape route for self-rescue of tunnel users, particularly in the case of a fire. Building escape passages can be the most effective and certain measures from this point of view and much more consideration has been given to building escape passages when planning emergency facilities for long tunnels in Japan. However, safety in road tunnels is not simply a question of installing emergency facilities and operating them efficiently. It also depends to a great extent on the behaviour of tunnel users in case of an emergency. It is therefore important to note that road users should be constantly made aware of correct behaviour in road tunnels through education and information campaigns.

There is no such thing as absolute safety in road tunnels even though we must make every effort to reduce the risks to the greatest extent possible. Further research is therefore required to improve road tunnel safety.