CURRENT STATE OF ROAD TUNNEL SAFETY IN JAPAN

H. Mashimo
Public Works Research Institute, Incorporated Administrative Agency, Tsukuba, Japan
mashimo@pwri.go.jp

T. Mizutani
Advanced Construction Technology Center, Tokyo, Japan
mizutani@actec.or.jp

ABSTRACT

With the increase of road tunnels, we have experienced many serious accidents involving tunnel fires, and have learned many lessons from these accidents. Specifically after the tragic fire accident of the Nihonzaka Tunnel in 1979, we have made every effort to improve safety in road tunnels; such as reviewing the concept of road tunnel safety, revising technical standards, improving emergency facilities, establishing cooperation with police and fire brigades, and promoting education and drills for road users.
This paper presents lessons learned from our past experiences and the national safety standard to ensure road tunnel safety in Japan. Moreover, some issues under discussion in Japan, such as safety in urban tunnels with very long length and large-scale tunnels, and operation and management of water sprinklers, are introduced.

KEY WORDS

TUNNEL SAFETY / EMERGENCY FACILITIES / URBAN TUNNEL / LARGE-SCALE TUNNEL / WATER SPRINKLER

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 land with great geological variation. Tunnels play important role to develop new road network and the number of road tunnels in Japan has continually increased over many years as shown in Figure 1. This is because of the recent development of road network through mountainous ranges, and also because of the reduction of tunnel construction cost. 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 2001, Japan had road tunnels in 8,331 locations with a total length of 2,653km.
In the past, we have suffered some serious accidents involving fires in road tunnels with the increase of road tunnels and learned the lessons from these past accidents. To improve safety in road tunnels, we have been making efforts to establish safety measures by formulating and revising technical standards in accordance with technological progress, improving emergency facilities, establishing a joint operation system with the police department and fire brigade, and promoting education and drills among road users.
In the first part of this paper, the national safety standard that defines the planning, design and operation of emergency facilities in road tunnels in Japan is introduced.

This paper further introduces the future directions to be taken for the safety of long urban tunnel (Tachimori et al. 2002), large-scale tunnels - the use of water sprinklers and its effects, as well as its operation guidelines - under the theme, tunnel safety. Recently, long urban tunnels containing many junctions or large-scale tunnels with three-lane and full shoulders are being planned in Japan. Therefore, it is needed to verify the applicability of the national safety standard to these unprecedented tunnels and establish more comprehensive safety system, comprising traffic management, fire and smoke control, in collaboration with the police department and fire brigade. Operation and management of water sprinklers is also the issue under discussion. Water sprinkler is aiming to control fire and arrest the spread of the fire. It is regarded as an effective tool to prevent damage caused by the fire. In Japan, on the contrary to the general practice abroad, water sprinkler is widely installed according to the tunnel classification. It is used because it can cool down the area where fire started and its surroundings, and can further control fire and provide support for fire fighting.

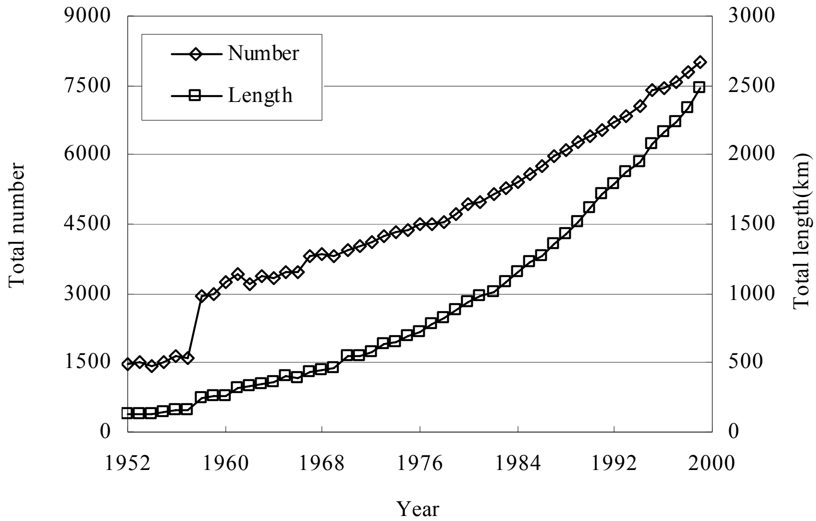


Figure 1. Increase in total number and length of road tunnels

2. NATIONAL SAFETY STANDARD OF EMERGENCY FACILITIES ON ROAD TUNNELS

2.1. Lessons learnt from Nihonzaka Tunnel fire accident

In Japan, the criteria governing the installation of the emergency facilities including planning, design and operation is defined in National Safety Standard of Emergency Facilities on Road Tunnel. The first standard was issued immediately after the fire accident occurred inside the Suzuka Tunnel in 1967, by the Ministry of Construction (currently, Ministry of Land, Infrastructure and Transport). However, this standard could not prevent the disaster at Nihonzaka Tunnel and it became necessary to revise the standard.
The fire accident of the Nihonzaka Tunnel on the Tomei Expressway broke out at 6:40 pm on 11July 1979. It was due to the rear-end collisions of four lorries and two vehicles, however, it led to a huge catastrophe causing seven death and destroying 173 vehicles (Figure 2). The concept of tunnel safety in those days were limited and emergency facilities formed a basis for guarding against fires and preventing damages from spreading, however, the standard was not articulated.

From the experience learned at the Nihonzaka Tunnel, the National Safety Standard was revised in 1981 taking into full account the following four points and the results of full scale fire tests; early detection/prompt reporting (by means of alarm/warning signal), prompt fire control by passengers, prompt alert to other vehicles and prompt evacuation, bearing in mind saving human lives as a top priority. As for the hard aspect, standard was reinforced for emergency facilities such as information boards inside tunnels, radio communication auxiliary and fire resistant cables for traffic signals and lighting circuits. As for the soft aspect, the standard was reinforced by joint drill with fire brigade and police department, increasing user's awareness of safety, and by upgrading guide boards indicating evacuation routes, radio re-broadcasting equipment (capable of interrupting the radio frequencies) and loudspeaker equipment which can audi-visually reach road users.

Figure 2. Nihonzaka Tunnel fire accident

2.2. 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.

For furnishing emergency facilities, tunnels are categorized into the five classes as shown in Figure 3 in relation to the tunnel length, the traffic flow volume and characteristic features. This classification was determined by the probability of accidents and fires based on the past experiences. Long tunnels with a high design speed on national expressways, or tunnels with bad perspective owing to especially winding horizontal or vertical alignment should be ranked higher than standard level.

Emergency facilities as shown in Table 1 should be installed in tunnels according to the tunnel class. Figure 4 shows an example of tunnel equipped with all emergency facilities set by the tunnel classification AA.

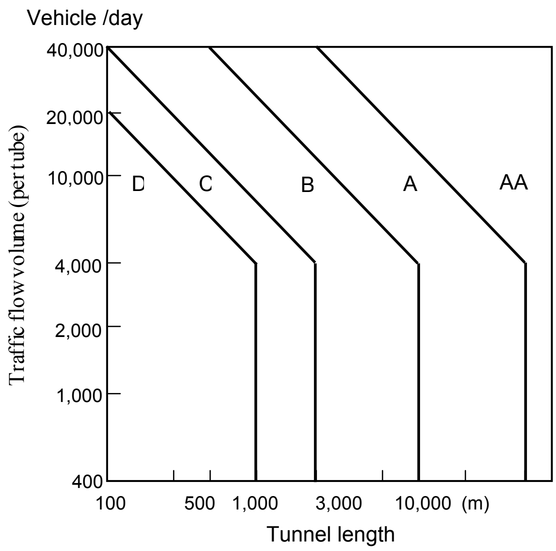
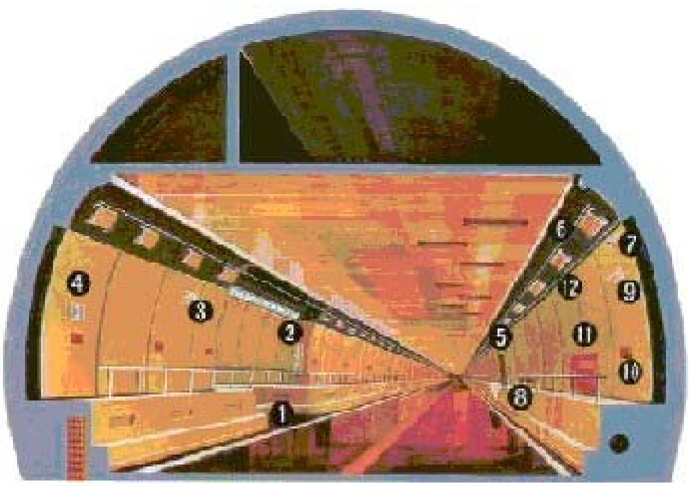


Figure 3. Tunnel classification

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 detector	□ ›	□ ¢			
	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 (CCTV)	□ ›	□ ¢			

Note: In the table, □ ›indicates that the equipment should be installed as a rule, and □ ¢indicates that the equipment should be installed as required.



□Emergency parking bay (at intervals of 750m)
□Adjustable speed limit sign
□CCTV (at intervals of 200m)
□Emergency telephone (at intervals of 200m)
□Evacuation tunnel (at intervals of 750m)
□Radio communication auxiliary equipment
□Loudspeaker
□Inspection gallery
□Visibility meter
□Automatic fire detector (at intervals of 25m)
□Fire hydrant (at intervals of 50m)
□Sprinkler head (at intervals of 5m)

Figure 4. Example of tunnel equipped with emergency facilities of tunnel classification AA

2.3. Types of emergency facilities

Emergency facilities stipulated in the standard are composed of information and alarm equipment, fire extinguishing equipment, escape and guidance equipment and other 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.
Fire extinguishing equipment is composed of fire extinguishers and fireplugs. They should be user-friendly enough for an unskilled passenger who needs to fight the fire until the professional fire-fighters arrive.
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. 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. Typical escape passages are:

- Evacuation tunnel built beside and along the main tunnel
- Cross passageways that 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.
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.

2.4. Operation of emergency facilities

2.4.1. Preliminary to effective operation

As described in the previous section, 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 properly operate these facilities as soon as possible. For this purpose, some indispensable preliminaries should be implemented.

1) Periodical drill

For tunnels longer than 1,000m and shorter tunnels with heavy traffic volume, on-site drill should be jointly carried out with the police, fire brigade and other organizations concerned more than once 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
- Drills on fire control and rescue operation

2) Education and drills for road users

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

3) Preparation of manual

Manuals including the following items should be prepared:

- Quickest methods for transmitting alarms to the control room and reliable information to the intervention teams regarding the severity and location of the fire
- Programs to operate various emergency facilities
- Information for tunnel users given by emergency alarm equipment and radio re-broadcasting equipment
- Confirmation of the report from tunnel users

4) Establishment of cooperation with relevant organizations

Tunnel operators alone cannot manage a disaster in a tunnel. Cooperative management among various organizations such as the police office and fire brigade is indispensable.

2.4.2. Operation procedures of emergency facilities

The highest priority is the early detection of a fire accident and the rescue of tunnel users. Emergency facilities should be worked out in line with this principle. Several types of information and alarm equipment are provided. Operation of the relevant equipment after the first report from tunnel users is as follows.

If the first report comes from fire detectors, pushbutton type information equipment or lifting of a fire extinguisher, the ventilation system, the pumps for hydrants and fire plugs, will be automatically activated, and lighting system in the tunnel is set to the maximum level. Entrance information board is also activated to prohibit the entry of subsequent vehicles in tunnels without CCTV.

On the other hand, in case of the first report from an emergency telephone, the above actions are taken manually according to the contents of the information.

After confirming breakout of fire by CCTV or the like, the following actions will be 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 the water sprinkler system

3. ISSUES UNDER DISCUSSION IN JAPAN

3.1. Safety of urban tunnels

Recently, long urban tunnels containing many junctions (including entrances and exits) are being planed on urban expressways, represented by The Shinjuku Tunnel (a total length of 11km) of the Metropolitan Expressway. Safety issues in case of fire are particularly vital for urban long tunnel projects since the urban tunnel comprises many junctions and has heavy traffic, and is often subject to traffic congestion. It is required to ensure the safety of users by effectively and efficiently applying emergency facilities employing new technologies. It is further necessary to reinforce the linkage of each element, encompassing traffic management, fire and smoke control, collaboration with the police department and fire brigade.

In the event of fire outbreak, in addition to fire and smoke control to withdraw fume, measures has to be taken to improve the evacuation routes. Appropriate information must be offered to guide people to safe areas through emergency exits. The Shinjuku Tunnel is provided with all emergency facilities laid down by the tunnel classification □ AA to ensure safer emergency exits and evacuation routes that are accessible on foot. Consideration is being given to the operation of facilities designated to improve the evacuation routes through the earliest possible detection of fire outbreak, accurate assessment of the situation, and effective operation of smoke exhaust facilities and guide evacuees to safer refuge areas. In addition, a tunnel design is planned to permit rapid access of the fire fighting services to the site. This may include crossing connection between tubes in the tunnel to permit fast rescue and fire-fighting operations for the fire brigade.

The above countermeasures include:

1) Provision of emergency exits and galleries

Emergency exits are placed at less than 350 meters intervals, which is accessible within 10 minutes on foot after the drivers recognize the fire. Location of emergency exits and galleries are determined taking into account the tunnel structure (Figure 5).

2) Provision and operation of smoke exhaust ventilation system

As the Shinjuku Tunnel employs the transversal ventilation, ventilation duct runs all along the tunnel. Fire and smoke control has been studied to ensure a safe evacuation environment in case of fire under congestion by effectively using the ventilation duct to exhaust smoke from the tunnel section affected fire and sending fresh air from the neighboring sections. It enables the smoke to be kept in the upper layer near the ceiling (Figure 6).

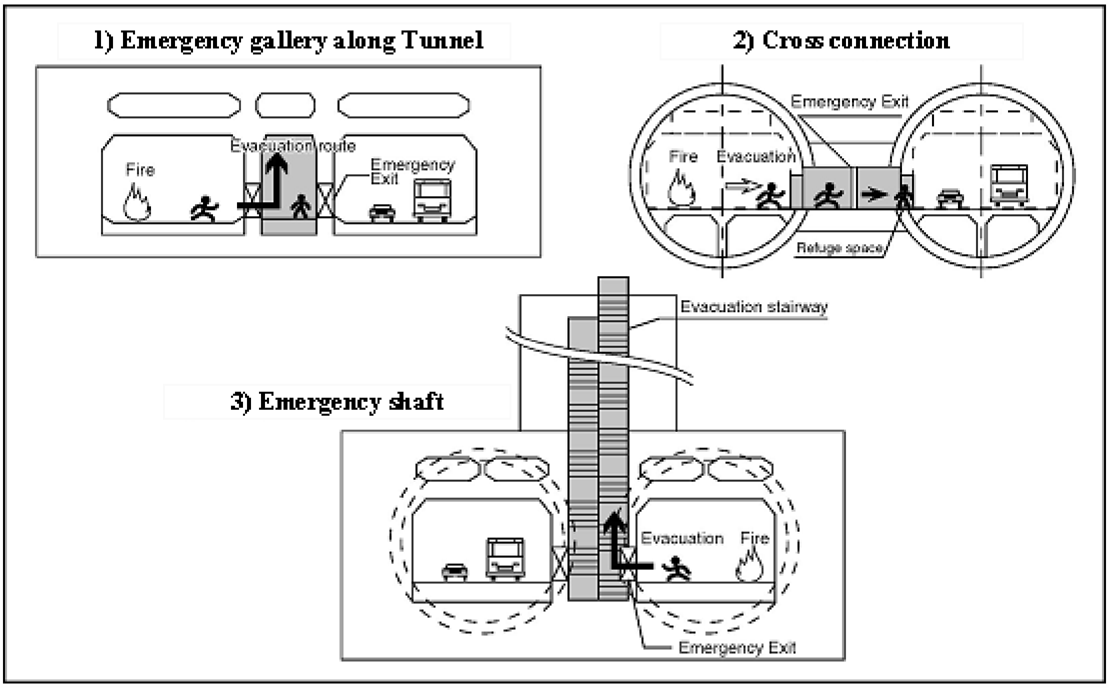


Figure 5. Examples of evacuation type

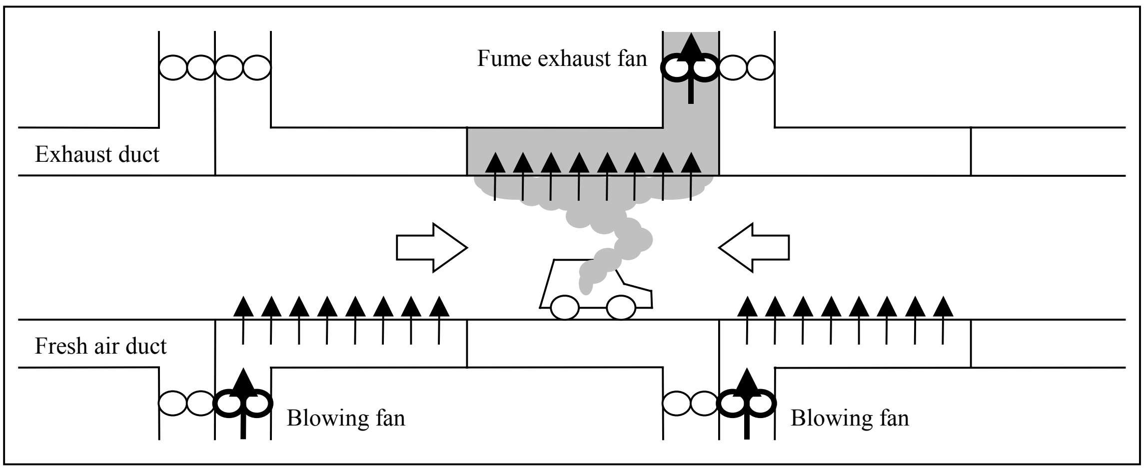


Figure 6. Proposed smoke exhaust control system

3.2. Safety of large-scale tunnels

The new Tomei Meishin Tunnel, currently under construction, is a three-lane tunnel featuring full shoulders with a pavement width of 15.0m, interior width of 16.9m and height of 8.5m. Its 116m^2 inner section is double the size of the conventional two-lane tunnel.
In order to verify the feasibility of application of the national safety standard for two-lane tunnels to this three-lane tunnel, a tunnel fire test was conducted at the Third Shimizu tunnel (1,100m) on the Second Tomei Expressway in March 2001. The fire test was conducted on 10 cases utilizing 4 (8MW) and 9 (20MW) m^2 gasoline pans and a motor coach (20MW) (Figure 7).
The following results, which were unique to large-scale tunnels, were attained by comparing the data acquired from the experiments in the past and the distribution data on interior temperature, pressure and smoke, acquired from this test:

- Compared with two-lane tunnels, rise in temperature was lower inside three-lane tunnels
- Smoke descended (with 4m^2 gasoline pan under wind speed 0m/s) near the road surface at a point 300m away from the fire source at down wind 20 minutes after ignition. Therefore, three-lane tunnel is advantageous in ensuring evacuation time.
- As the ceiling area is more spacious inside the three-lane tunnel, the reverse flow of smoke (with 4m^2 gasoline pan under wind speed 2m/s) at upwind did not descend to the road surface, thus ensured clear visibility for evacuation. With respect to the smoke control system, as in the case of two-lane tunnels, there should be no problem as far as the wind speed inside tunnels is more than 2m/s, same applies at the time of congestion.
- Nevertheless, the smoke concentration level is higher near the road surface, faster the sprinklers are operated; shorter the fire spreads, and lower the temperature can be kept at downwind,

This test demonstrated that the evacuation environment was easier to attain in large- scale tunnels, and further proved the applicability of current national safety standard of two-lane tunnels to the New Tomei-Meishin three-lane tunnels.
From now on, results attained from this test will be further examined together with fire simulations to upgrade the operation methods of emergency facilities for tunnels.

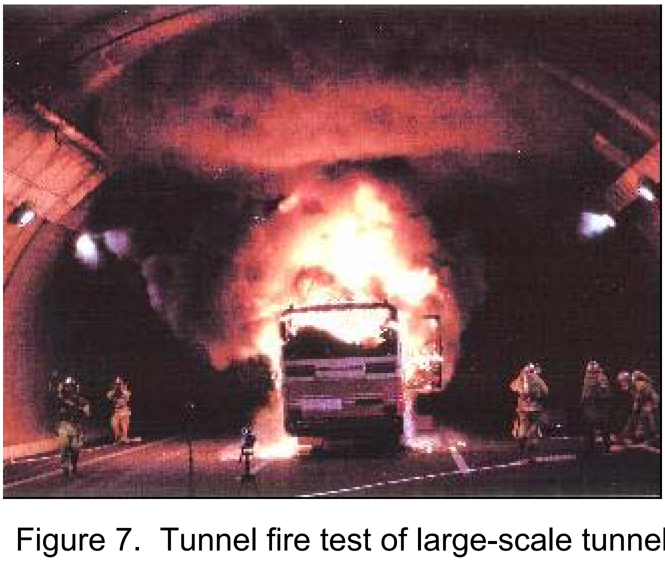


Figure 7. Tunnel fire test of large-scale tunnel

3.3. Operation and management of water sprinkler in urban expressway tunnel

3.3.1. Operation and management of water sprinkler system

Water sprinkler systems shown in Figure 8 have been installed in tunnels in Japan since the latter half of the 1960s. Its use has been studied through experiences learnt from several fire accidents and experiments inside the tunnel. Consequently, water sprinkler system was proven to be effective in controlling fire and restraining the spread of fire. On the other hand, it could push down the smoke and suffocate evacuees and deteriorate evacuation environment. With this view, it is required to use water sprinklers by assessing the overall situations on fire, smoke and evacuees.

Water sprinkler system was first introduced to the Metropolitan Expressway in its Tokyo Port Tunnel in 1976. At present, these are installed and operated in nine tunnels of the Metropolitan Expressway. Although emergency facilities inside the tunnel are not in frequent use, they are crucial in case of emergency, therefore, daily maintenance is most important. The Metropolitan Expressway's tunnel is closed to traffic once a year for an overall inspection of emergency facilities inside tunnels to keep up its function by testing water sprinklers and foam hydrants combined with fire detectors and alarm push buttons.

In the past, water sprinkler was operated only after the evacuation was completed to prevent from making the evacuation environment deteriorate. However, it had a tendency to procrastinate the discharge of water. When the fire accident occurred in May 1998, it took longer to bring fire under control due to delaying the operation of water sprinkler system. As a result, the spread of fire could not be arrested promptly. Therefore, since 1998, the operation manual of water sprinkler was modified and it could be applied as soon as the flame is detected even for small fire.

Figure 8. Water sprinkler system

3.3.2. Operation manual of water sprinkler in case of fire

In case of fire, the traffic control system plays a key role to cope swiftly with the situations. In order to assess traffic conditions constantly and ensure safety of drivers, the Metropolitan Expressway carries out 12 patrols a day and clears traffic accidents and broken-down cars. The Traffic Control Centre monitors road traffic 24 hours. Once the fire is detected, the Centre immediately contacts the fire brigade who is in charge of the affected area and launches actions according to the Tunnel Fire Manual. A fire drill is conducted once a month to reinforce the traffic control operation at the Metropolitan Expressway Public Corporation.

3.3.3. Effect of water sprinkler under the current operation

The effect of water sprinkler was verified from one of the most prominent examples using water sprinkler that occurred due to a lorry accident in 1999. In this case, the fire itself was eventually extinguished by the fire brigade. However, it took 17 minutes for the fire brigade to arrive at the site due to distance between the fire station and the tunnel. As water sprinklers were operated before their arrival, water discharge was completed within 17 minutes and it resulted in extinguishing the fire in 34 minutes since the outbreak. Therefore, it is considered that the water sprinkler is highly effective in arresting the spread of fire and supporting fire control activities.

3.3.4. Issues of water sprinkler operation hereafter

Five out of six fire accidents in the past involved passenger cars and small lorries and are relatively small in scale, thus evacuees were not suffocated by smoke. Also, in the previous case of 1999, as the fire was extinguished in 34 minutes, the evacuation environment was not deteriorated. It is fortunate that most of these accidents did not cause severe damages. It is due to the length of most of the tunnels being relatively short, and is less than 2km. Another reason is that the accidents occurred at off-peak hours while the traffic flow was smooth enough.

Nevertheless, Shinjuku Tunnel that is now under construction forms an 11km-long tunnel. In the event of an unprecedented large fire, it will be crucial to determine when to operate water sprinklers while at the same time ensuring the evacuation environment. It is to become a major issue to be tackled in operating water sprinklers.

4. CONCLUSION

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

The highest priority for safety in case of tunnel fire is to secure safe escape routes for self-rescue of tunnel users. Several types of structures are applied for safe escape routes, such as cross passageways, evacuation tunnels, emergency exits and carriageway itself. The type of safe escape routes should be determined considering the situation of the tunnel.

On the other hands, smoke control system of these safe escape routes is very important to ensure their evacuation environment, especially in carriageway. The system should be planned and designed very carefully.

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 drills.

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.

REFERENCES

Tachimori,T., Sangu,M., Tajima,H. & Tazawa,S. (2002) Safety facilities for urban expressway tunnels. International seminar on tunnel and road technology, Beijing.