Investigation and Analysis on the Vehicle Cross Passages of Highway Tunnels

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Abstract. Vehicle cross passages are critical infrastructure for emergency rescue in highway tunnels but how to use them is disputed in the industry. This paper investigates 9 expressway operation and management companies in China and 292 highway tunnels in their charge through site interviews and questionnaires to understand and analyze traffic routes of general vehicles and rescue vehicles and the use of vehicle cross passages during routine operation & maintenance, traffic accident and fire incident handling by each company. The survey results show: it is difficult for large vehicles to pass through vehicle cross passages due to the small radius of turning circle at the corner, and the influence on traffic safety in the adjacent tube is great. It is not recommended to use vehicle cross passages if traffic in the adjacent tube is not interrupted. The use of vehicle cross passages should be limited to rescue vehicles in initial stage of fire incidents.

1. Introduction
As China’s transport construction industry develops, an increasing number of highway tunnels have been built. According to the Statistical Bulletin on the Development of the Transportation Industry issued by the Ministry of Transport, by the end of 2018 China had 17,738 highway tunnels covering 17,236,100m, including 1058 super long tunnels (length > 3,000m) covering 4,706,600m and 4315 long tunnels (3000m ≥ length > 1,000m) covering 7,421,800m. While providing convenient transport services, tunnels present a grave challenge to emergency response. As a long underground structure with openings on both ends, the tunnel can be entered by rescue personnel and vehicles only from portals on both ends, through which vehicles inside the tunnel must exit[1]. However, an incident often causes traffic congestion inside the tunnel, making it very difficult for rescue vehicles to rapidly reach the incident scene and for vehicles inside the tunnel to evacuate the scene. To overcome this difficulty, a tunnel longer than 1,000m is often designed with vehicle cross passages. A cross passage is a transverse passageway that connects two parallel tubes and allows rescue vehicles to rapidly reach the incident scene or blocked vehicles to quickly move to the adjacent incident-free tube[2].

It plays a vital role in emergency rescue in the event of an incident in the tunnel. However, existing research mostly focuses on analysis mechanical properties during excavation of vehicle cross passages and technical aspects of intersection construction, with a lack of attention to their spacing, width and use[3–9]. In fact, they can play an effective role in routine operation and emergency rescue only with a reasonable design and correct utilization plan. However, disputes exist regarding the design and
utilization of vehicle cross passages, for example, whether they can be used to evacuate general vehicles during an emergency or only used by rescue vehicles [10].

This paper investigates 9 expressway operation and management companies in China through site interviews and questionnaires to analyze and summarize design experience in key parameters of highway tunnels and the use of vehicle cross passages during routine maintenance, traffic and fire incidents.

2. Basic information on tunnels investigated
This paper investigates 9 expressway operation and management companies in China which manage 292 highway tunnels in total. Table 1 lists the number of tunnels, the name and length of the longest tunnel managed by each expressway management company. Among these tunnels, the longest one is provided with vehicle cross passages every 500~818m; 5 ones are provided with vehicle cross passages with an angle of 60° with regard to main tunnel and 3 ones with vehicle cross passages with an angle of 90°. The investigation suggests when the angle between vehicle cross passages and main tunnel is 60°, it is easier for vehicles to pass through the vehicle cross passages.

Table 1. Summary of tunnels investigated

| NO. | Company name                                      | Number\textsuperscript{a} | The longest tunnel managed                                      |
|-----|---------------------------------------------------|---------------------------|----------------------------------------------------------------|
| 1   | Liuzhou Expressway Co. Wuxuan Branch Fuzhou Southeast | 1                         | Ma’an Shan Tunnel, 2784 m, Spacing 876 m, Angle 90°            |
| 2   | Around-the-city Expressway Co., Ltd.                | 10                        | Dongfengshan Tunnel, 2628 m, Spacing 600 m, Angle 60°          |
| 3   | Henan Expressway Luoyang Administrative Office      | 3                         | Yuhuangmiao Tunnel, 815 m, Spacing —, Angle —                 |
| 4   | Zhejiang Jinliwen Expressway Co., Ltd.              | 137                       | Sizhouling Tunnel, 6765 m, Spacing 750 m, Angle 60°           |
| 5   | Jiangxi Jiurui Expressway Co., Ltd.                 | 5                         | Nanyangyi Tunnel, 2345 m, Spacing 600 m, Angle 60°            |
| 6   | Fujian Expressway Co. Longyan Branch               | 16                        | Zengrui Tunnel, 4620 m, Spacing 500 m, Angle 90°              |
| 7   | Chongqing Expressway Co. Northeast Branch          | 66                        | Motianling Tunnel, 7600 m, Spacing 800 m, Angle 60°           |
| 8   | No. 2 Maintenance Station, West Hubei Expressway Administrative Office | 29 | Xianglushan Tunnel, 4023 m, Spacing 750 m, Angle 60°          |
| 9   | Jingzhu Northern Branch, Guangdong Expressway Co., Ltd. | 25 | Dayaoshan No. 1 Tunnel, 4257 m, Spacing 818 m, Angle 90°     |

\textsuperscript{a} Number of tunnels managed  
\textsuperscript{b} Spacing of vehicle cross passages(m)  
\textsuperscript{c} Angle between vehicle cross passage and main tunnel

3. Use of vehicle cross passages during routine maintenance
This paper investigates the use of vehicle cross passages during routine operation and maintenance work, including the opening/closing state, fault rate and causes of fire-resisting rolling shutters at vehicle cross passages and how vehicle cross passages are used during maintenance work. The investigation results show: 55.56% of the management companies said the fire-resisting rolling shutters at vehicle cross passages are fully closed during routine operation while 44.44% open them to a height of 1.5~1.8m. The former claimed keeping these shutters fully closed could prevent polluted air in one tube from entering to the other while the latter thought opening them to some height could enable people to be evacuated in
In the event of an emergency, the shutters cannot be opened due to a fault. Regarding the fault rate of fire-resisting rolling shutters at vehicle cross passages, 22.22% of companies reported a fault occurring once every month; 11.11% reported a fault occurring once every six months; and 66.66% said a fault occurred once every year. 33.33% of faults were caused by communication issues, i.e., the fire-resisting rolling shutters could not be remotely controlled but could be manually opened/closed on-site; 66.67% were due to mechanical issues, i.e., it was impossible to freely open/close the fire-resisting rolling shutters due to deformations or slipping out of track.

Regarding traffic organization during tunnel maintenance, the tunnel management companies surveyed agreed that decisions should be comprehensive based on traffic flow through the tunnel and the length of time the travel lanes will be occupied for the purpose of maintenance. In general, if traffic flow is low and the time for lane occupation is short, it is sufficient to close the relevant tunnel for a short time, typically during wee hours when traffic flow is low, as shown in Fig. 1(a); if the traffic flow is high and the time for lane occupation is long, traffic can be diverted before entering the tunnel and the other tube can be temporarily converted to a bidirectional tunnel, as shown in Fig. 1(b). Considering traffic safety, none of the companies plan to change lanes using vehicle cross passages in the middle of the tunnel, as shown in Fig. 1(c).

![Traffic routes of general vehicles during tunnel maintenance](image)

**Fig. 1** Traffic routes of general vehicles during tunnel maintenance

**4. Use of vehicle cross passages during traffic accident**

This paper investigates possible traffic routes for general vehicles and the principles for using vehicle cross passages in the event of traffic accidents inside the tunnel. The survey results show if the traffic accident does not occupy all travel lanes, the lane with the accident is generally closed and general vehicles are allowed to travel on a single lane, as shown in Fig. 2(a); if the traffic accident occupies all travel lanes, the selection of travel scheme for general vehicles is dependent on the time required to handle the traffic accident and the number of vehicles blocked. If the handling time is short and the number of vehicles blocked small, the tunnel with the accident may be closed until the accident has been handled, as shown in Fig. 2(b); if the handling time is long and the number of vehicles blocked is large, the tunnel with the accident may be closed and general vehicles approaching this tunnel are diverted to the adjacent tunnel which is converted to bidirectional, as shown in Fig. 2(c). Before the adjacent tunnel is converted to bidirectional, temporary lane separation measures such as reflective cone tanks must be placed along its entire length. This will take some time. For this reason and others, the adjacent tunnel is not converted to bidirectional if the accident handling time is short. In addition, all tunnel management companies surveyed said in order to prevent secondary accidents it is not recommended to change lanes utilizing vehicle cross passages, as shown in Fig. 2(d).
In addition, regarding the travel route of rescue vehicles, 77.77% of the companies surveyed said they would give priority to route a, and would consider route b only if rescue vehicles could not reach the accident point because vehicles upstream of the accident point are completely blocked, as shown in Fig. 3; the other 22.22% said they would consider routes a and b at the same time because they deemed it safe for rescue vehicles to enter the tunnel from downstream against the traffic direction as all vehicles downstream of the accident point had evacuated the tunnel when rescue vehicles reached the accident point, with the accident vehicle occupying all lanes and blocking vehicles from the upstream. As with travel routes for general vehicles, none of the companies considered the use of vehicle cross passages for rescue vehicles to arrive at the accident point for traffic safety concerns, as shown in Fig. 3(c/d).

5. Use of vehicle cross passages during fire accident
All the companies surveyed said the tunnel (both up and down traffic) should be closed immediately in the event of a fire to prevent general vehicles entering the tunnel, and notice given through audible and
visual alarm, emergency broadcast and other equipment in the tunnel to vehicles downstream of the accident point to quickly leave the tunnel and occupants of vehicles upstream of the accident point to evacuate the fire tunnel through pedestrian/vehicle cross passages in the tunnel or portals, leaving their vehicles behind. Some people thought blocked vehicles upstream of the accident point may be directed to enter the adjacent tunnel through vehicle cross passages to quickly get out of the tunnel while clearing the road upstream of the accident point for rescue vehicles. In fact, it is very difficult for large vehicles to travel through vehicle cross passages due to the small radius of turning circle at the corner, leading to possible blocking and low efficiency in evacuation. In addition, the mixing of people who get out of vehicles to escape and vehicles being evacuated on the same route might lead to secondary accidents. Evacuation of vehicles through vehicle cross passages requires the fire-resisting rolling shutters at vehicle cross passages be fully opened. This will surely allow fire smoke to enter the non-fire tunnel from the fire tunnel, thus posing a threat to personal safety. Therefore, it is not recommended to fully open the fire-resisting rolling shutters in initial stage of the fire and evacuate vehicles through vehicle cross passages.

In the event of a tunnel fire, selection of travel routes for rescue vehicles shall take into account the location of rescue vehicles, traffic congestion inside the tunnel, configuration of diverting lanes outside the tunnel, etc. The companies surveyed said the recommended travel routes for rescue vehicles are a and b (Fig. 4), depending on whether they come from upstream or downstream of the accident point. When rescue vehicles come from the upstream of the accident point and blocked by other vehicles, they can reach the accident point via route c (Fig. 4). When rescue vehicles come from the downstream of the accident point and no diverting lanes are provided outside the tunnel, they can reach the accident point via route d (Fig. 4). Overall, because a fire accident has more hazardous consequences and wider impacts than a traffic accident, both up and down tunnels shall be closed in the event of a fire accident. For this reason, rescue vehicles can reach the accident point through the adjacent tunnel and vehicle cross passages.

![Fig. 4 Traffic routes of rescue vehicles during a tunnel fire accident](image)

6. Conclusion
This paper investigates 9 expressway operation and management companies in China and 292 highway tunnels in their charge through site interviews and questionnaires to understand and analyze traffic routes of general vehicles and rescue vehicles and the use of vehicle cross passages during routine operation & maintenance, traffic accident and fire incident handling by each company. The survey results are as follows:

1. During routine operation and maintenance of the tunnel, travel routes for general vehicles depend
on the time required for maintenance work. If the time required for maintenance work is short, one tunnel can be closed temporarily during low-traffic hours; if the time required for maintenance work is long, the tunnel where maintenance work is to be done should be closed and the adjacent tunnel converted to bidirectional. Considering traffic safety, none of the companies plan to change lanes using vehicle cross passages in the middle of the tunnel.

(2) In the event of a traffic accident inside the tunnel, the selection of travel routes for general vehicles is dependent on the time for handling the traffic accident and the number of vehicles blocked. Specific travel routes are the same as during tunnel maintenance work. Rescue vehicles should enter the accident tunnel from upstream with traffic direction to the accident point if possible; if the upstream of the accident point is congested, rescue vehicles should enter the accident tunnel from the downstream against traffic direction to the accident point. For travel safety concerns, vehicle cross passages should not be used for lane change because the adjacent tunnel will usually not be closed during handling of the traffic accident.

(3) In the event of a tunnel fire, all companies said the tunnels (including up and down traffic) should be closed immediately and notice given to vehicles upstream of the accident point to quickly get out of the tunnel and occupants of vehicles blocked upstream of the accident point to escape leaving their vehicles behind. Selection of travel routes for rescue vehicles shall take into account the location of rescue vehicles, traffic congestion inside the tunnel, configuration of diverting lanes outside the tunnel, etc. The recommended scheme is to enter the accident tunnel from upstream or downstream of the accident point. Rescue vehicles may also enter the non-accident tunnel and travel through vehicle cross passages to reach the accident point, if necessary.

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