Study on Minimum Clear Distance between Tunnel Exit and Expressway Mainline Toll Station

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Abstract. The mainline toll station and tunnel are the important parts of the expressway system. The rationality of the clear distance affects the traffic capacity and safety. Based on the characteristics and the implementation status of expressway construction, combined with the relevant standards and research results at home and abroad, the clear distance between tunnel exit and mainline toll station has been defined and divided into the light adaptation distance, the traffic signs recognition distance, the operation distance and the lane confirmation distance. On the basis of analysing various constraints, the research has been carried out to establish a calculation model for the clear distance between the tunnel exit and the mainline toll station. It is proposed that under the secondary service level of the 4-lane expressway, under the design speed of 120km/h, the general value of the clear distance between the tunnel exit and the mainline toll station should be greater than 750m; when it is limited by terrain and route corridors, the minimum clear distance should be no less than 600m. It provides a valuable reference for the design and management of tunnels and mainline toll stations.

1. Introduction

In recent years, the highway infrastructure construction is still relatively large in China. On the basis of completing the construction of the national main trunk line, the focus will be further shifted to the construction of western regions, tourist areas and intercity highways. Therefore, there are a lot of construction in the mountainous areas. Due to the limitation of the complex route corridors, mountainous terrain and geological conditions, the proportion of tunnels in highway design in these places is very large. Therefore, there will be a situation where the tunnel exit and the mainline toll station are arranged at a small distance. In this case, there is a problem that the driver cannot recognize the sign and make the braking measures in time, the safety of the entrance of the mainline toll station is greatly affected, resulting in traffic accidents and casualties.

The current standard in China--"Design Specification for Highway Alignment" (JTG D20-2017), does not make the corresponding provision for the distance setting between the tunnel exit and the mainline toll station of the expressway. Therefore, which value of the clear distance can be used brings the confusion to many designers. At this stage, many researchers at home and abroad have conducted in-depth research on the clear distance between the tunnel exit and the interchange. The designer's choice of the clear distance between the tunnel exit and the mainline toll station is mainly based on the clear distance between the tunnel exit and the interchange. There is less literature on this aspect, and it is still in a blank state.
In foreign countries, Patrick TW Broeren et al. determined the clear distance between the tunnel exit and the interchange based on traffic flow characteristics and average risk theory, including the weaving length of ramp terminal, the distance required by the driver to identify the location of tunnel exit and to accommodate the difference between the light inside and outside the tunnel. In China, Zhao Y.F. et al. studied the clear distance from the light adaptation at the exit of the tunnel, the identification of the interchange exit location, the need to identify the traffic sign and to operate the vehicle, etc. The clear distance between the expressway tunnel exit and the interchange of the interchange also need to ensure the traffic safety. Liao Junhong et al. used the simulation technology to quantitative analyse the clear distance from the perspectives of traffic safety, traffic capacity, driver response time and vehicle operation time requirements, and proposed the interchange interchange under the condition of limited conditions. The recommended value of the clear distance between the tunnel exit and the expressway interchange under limited condition is proposed. Sun Mingling et al. calculated the clear distance from the perspectives of vehicle speed, traffic volume, driver's operation behaviour and lane change behaviour, obtained the recommended minimum value of the distance between the tunnel exit and the interchange of the two-lane highway under different geographical conditions. According to the research method of the clear distance between the tunnel exit and the interchange, based on the driving process of the driver exiting the tunnel exit and entering the mainline toll station, aiming the special situation of the expressway mainline toll station immediately after the tunnel, this paper reasonably extrapolates the minimum clear distance between the tunnel exit and expressway mainline toll station.

2. Analysis of driving process between tunnel exit and expressway mainline toll station

Since there is less literature on the clear distance between the tunnel exit and the mainline toll station, there is no uniform and clear definition of this concept definition. Based on the clear distance between the tunnel exit and the interchange, combined with the study of Ouyang J.H et al., the definition of the clear distance between the tunnel exit and the mainline toll station is proposed. It is defined as the distance that the driver maintains the safe and comfortable driving from the tunnel exit to the starting point of the transition section of the mainline toll station, after going through the process of the light adaptation, the traffic signs recognition, the operation and the lane confirmation. And the above process should be in good climatic conditions, actual road conditions and traffic conditions. The calculation model of the clear distance between the tunnel exit and the mainline toll station is based on the most unfavourable situation that the driver experienced after driving out of the tunnel exit. That is, in the case of unfamiliar road conditions, the driver drives out of the tunnel from the innermost lane and undergoes a process of light adaptation, the traffic signs recognition, the smooth deceleration and braking, and the lane confirmation, finally, the driver drives to the beginning of transition of the toll station. Therefore, the driving process between the tunnel exit and the expressway mainline toll station can be divided into the following four stages.

Light Adaptation Process. When the human eye suddenly changes from a darker environment to a brighter environment, it takes a while to see the objects in the bright environment. This is called the light adaptation. Due to the difference in light intensity between inside and outside the tunnel, the driver has to undergo a period of light adaptation at tunnel exit.

Traffic Signs Recognition Process. After the driver has experienced the light adaptation process at tunnel exit, the next step is to identify the front traffic sign, judge the information and make decisions. In this process, it is necessary to consider whether the traffic sign is occluded, and whether the setting position of the traffic sign satisfies the distance requirement for drivers.

Operation Process. When the driver completes the identification of the front mainline toll station, the brake operation process is then entered, so that the driver reduces the vehicle from a higher speed to the lower speed required to enter the toll station. In this process, the reaction time of the driver's brake operation and the time of each brake stage should be considered.

Lane Confirmation Process. The driver has to make a decision before entering the transition section of the toll station: which toll gate to line up. First, the driver collects the queuing information of the
toll station through the eyeball, then transmits the information to the cortical centre through the retinal nerve, finally analyses and makes decisions through the cortical centre.

3. Analysis of minimum clear distance between tunnel exit and expressway mainline toll station

According to the analysis of driving process, the driving process between the tunnel exit and the expressway mainline toll station can be divided into four stages. Based on this, the calculation model for the minimum clear distance between the tunnel exit and the expressway mainline toll station is as following Equation (1):

\[ L_0 = L_1 + L_2 + L_3 + L_4 \]

In this equation, \( L_0 \) is the minimum clear distance between tunnel exit and expressway mainline toll station(m). \( L_1 \) is the demand distance for light adaptation at tunnel exit(m). \( L_2 \) is the demand distance for traffic signs recognition(m). \( L_3 \) is the demand distance for braking operation(m). \( L_4 \) is the demand distance for lane confirmation(m).

The composition of the minimum clear distance between the tunnel exit and the mainline toll station is shown in the Figure 1 below:

![Figure 1. Composition of Minimum Clear Distance between Tunnel Exit and Mainline Toll Station](image)

### 3.1. Demand Distance for Light Adaptation at Tunnel Exit

When the driver leaves the tunnel exit at night, there is no obvious difference of illumination intensity in and out of the tunnel, so that the light adaptation is not too strong to affect the driving. Therefore, the obvious light adaptation process mainly occurs during the day. "Traffic Engineering" pointed out that the visual disturbances generated at the tunnel exit is about 1 second. Meanwhile, it is pointed out that if there is strong light in the field of view, the colour is not uniform, which will cause discomfort to the human eye, and then form visual disturbances, which will reduce the visual acuity. The degree of the reduction depends on the illumination intensity, the angle between sight and light, the brightness around the light source, the adaptability of the eye and so on. It takes about 3 seconds to adapt the light from dark environment. Therefore, based on the principle of safe driving, this paper takes 3 seconds as the driver's light adaptation time for research. The demand distance for light adaptation at tunnel exit is calculated, as shown in Table 1 below.

| Design Speed(km/h) | Demand Distance for Light Adaptation at Tunnel Exit(m) |
|--------------------|------------------------------------------------------|
| 120                | 100                                                  |
| 100                | 84                                                   |
| 80                 | 67                                                   |

### 3.2. Demand Distance for Traffic Signs Recognition

After the driver exits the tunnel and undergoes the light adaptation process, it should be able to identify the notice of the mainline toll station in time and completely read, judge the information and make the decision. Based on the traffic safety, the demand distance should meet the requirements from identification to make the decision. In the analysis of the demand distance between the tunnel exit and the interchange, the corresponding calculation model has been proposed for the demand distance for traffic signs recognition. The calculation equation is as following Equation (2):
\[ L_2 = \frac{V}{3.6} t_1 + \frac{H^2 + \left(\frac{B}{2}\right)^2}{\tan \left(\frac{\Theta}{2}\right)} \]  \hspace{1cm} (2)

In this equation, \( V \) is design speed (km/h), \( t_1 \) is the time for recognizing and identifying the traffic sign(s). \( H \) is the elevation difference between the traffic sign and the sight of driver. \( B \) is the distance from the view point of driver to the middle of the single cantilever traffic sign (m). 7.5m is taken in this paper according to two lanes. \( \Theta \) is the vision field of driver. When the driver reads the sign, it is better to move the visual axis by 5°. \( \Theta = 5° \) is taken in this paper.

According to the calculation model above, the demand distance for traffic signs recognition under different design speeds is obtained, as shown in Table 2:

| Design Speed (km/h) | Demand Distance for Traffic Signs Recognition (m) |
|---------------------|-----------------------------------------------|
| 120                 | 151                                           |
| 100                 | 131                                           |
| 80                  | 112                                           |

3.3. Demand Distance for Braking Operation

After the fully recognized of the traffic sign information, the driver enters the braking operation process. In this process, the response time and the implementation time of the braking operation must be considered. Therefore, the calculation formula for the demand distance of braking operation is as following Equation (3):

\[ L_3 = L_{31} + L_{32} \]  \hspace{1cm} (3)

In this equation, \( L_{31} \) is the demand distance for the response of driver (m) and \( L_{32} \) is the demand distance for the implementation of driver (m).

3.3.1. Demand Distance for Response of Driver. In "Traffic Engineering", under the laboratory conditions which the response time is measured by the shining of light, the average response time of the right foot from the depressed accelerator pedal to the brake pedal is 0.59s. In the actual situation, the mainline toll station sign is set at 2 km in advance, and the driver has already had psychological expectations for the existence of the toll station. The demand distance for response of driver is calculated as following Equation (4):

\[ L_{31} = \frac{V}{3.6} t_f \]  \hspace{1cm} (4)

In this equation, \( V \) is design speed (km/h) and \( t_f \) is response time (s).

According to the calculation model above, the demand distance for response of driver under different design speeds is obtained, as shown in Table 3:

| Design Speed (km/h) | Demand Distance for Response of Driver (m) |
|---------------------|-----------------------------------------------|
| 120                 | 20                                           |
| 100                 | 16                                           |
| 80                  | 13                                           |

3.3.2. Demand Distance for Implementation of Driver. After the driver passes the braking response process, the driver will enter the braking implementation process. According to the driver's driving behaviour, it is assumed that the desired speed to the toll station entrance is reached after only once deceleration operation. The factors affecting the distance of braking implementation process are the braking acceleration, the initial speed, and the desired speed after deceleration. According to the kinematics principle, the demand distance for implementation of driver can be obtained as following Equation (5):
In this equation, \( \alpha \) is the braking acceleration (m/s\(^2\)). \( V_1 \) is the initial speed (km/h), the value is the speed at which the vehicle exits the tunnel exit, it is assumed as the design speed of the tunnel. \( V_2 \) is the desired speed after deceleration (km/h).

For the value of the braking acceleration \( \alpha \) and the desired speed after deceleration \( V_2 \) in the Equation (4), based on the research of Ouyang J.H et al., this paper makes a brief refinement as follows.

Based on the research at home and abroad, about 90% of drivers will take braking measures with acceleration greater than 3.4 m/s\(^2\) when accidents are found in front of the road which need to stop. Therefore, 3.4 m/s\(^2\) is taken as the braking acceleration when calculating the stopping sight distance. However, if this acceleration is used for braking, the driver can clearly feel the discomfort caused by the sharp deceleration. Design Specification for Highway Alignment clearly stipulates that the highway should be able to ensure a certain comfort for the passenger. Considering the physical and mental feelings of the driver and passengers, this paper proposes the grading standards for acceleration, as shown in Table 4.

| Braking Acceleration (m/s\(^2\)) | Physical and Mental Feelings |
|----------------------------------|-----------------------------|
| \( \leq 1.48 \)                  | Best                        |
| 1.48-2.46                       | Good                        |
| \( \geq 2.46 \)                  | Bad                         |

Table 4 divides the physical and mental feelings into three levels. In order to meet the consistent quality of service, it is advisable to use the indicator of “best”, so \( \alpha = 1.48 \) m/s\(^2\).

The desired speed is the safe speed that must be achieved by the braking deceleration before the vehicle enters the entrance of the toll station. the vehicle in order to smoothly transit from the main line to the toll station, a transition section needs to be provided between the toll station and the main line. considering the driving safety, the speed and the transition rate of the transition section have the negative correlation with the traffic safety. In the "Design Guide for Japanese Expressways" (1987), the gradual rate of the transition section is set to be less than 1/3, the gradual rate of the transition section in china is generally 1/5-1/8. The equation for calculating the gradual rate \( K \) based on the trajectory of the vehicle is as following Equation (6):

\[
K = \frac{\Delta W}{S} = \frac{V_h}{V_2}
\]

In this equation, \( \Delta W \) is vehicle lateral displacement width (m). \( S \) is longitudinal distance in the forward direction when the vehicle changes lanes (m). \( V_h \) is vehicle traverse speed (m/s), \( 1 \) (m/s) is taken in this paper. \( V_2 \) is vehicle longitudinal speed (m/s), this speed is the same as the desired speed after deceleration \( V_2 \).

Therefore, the desired speed after deceleration \( V_2 \) is as following Equation (7):

\[
V_2 = \frac{3.6 V_h}{K}
\]

In summary, the formula of the demand distance for implementation of driver \( L_{32} \) can be converted into the following Equation (8):

\[
L_{32} = \frac{(V_1 \alpha)^2 - 12.96}{383.3616 \alpha^2 K^2}
\]

According to the calculation model above, demand distance for implementation of driver under different design speeds is obtained, as shown in Table 5:

| Design Speed(km/h) | Demand Distance for Implementation of Driver (m) |
|--------------------|-----------------------------------------------|
| \( \frac{1}{5} \) | \( \frac{1}{6} \) | \( \frac{1}{7} \) | \( \frac{1}{8} \) |
3.4. Demand Distance for Lane Confirmation

The confirmation distance of the vehicle entering the interchange is given in [9], which means the safe distance that the vehicle maintains a free flow state after entering the outer lane and confirming the exit ramp, usually 100m is taken in the research. According to the driver behavior analysis, before the vehicle enters the entrance of the main line toll station, the lane confirmation process is usually completed in the safe distance section before the entrance. Based on this, 100m is taken as the demand distance for lane confirmation in this paper.

4. Value of minimum clear distance between tunnel exit and expressway mainline toll station

According to the analysis above of the demand distance for light adaptation at tunnel exit, traffic signs recognition, braking operation and lane confirmation, the recommended value of minimum clear distance between the tunnel exit and the expressway mainline toll station at different design speeds can be obtained. As shown in Table 6:

| Design Speed(km/h) | 120 | 100 | 80 |
|-------------------|-----|-----|----|
| Demand Distance for Light Adaptation at Tunnel Exit(m) | 100 | 84 | 67 |
| Demand Distance for Traffic Signs Recognition (m) | 151 | 131 | 112 |
| Demand Distance for Response of Driver (m) | 20 | 16 | 13 |
| 1/5 | 367 | 252 | 158 |
| 1/6 | 363 | 249 | 155 |
| 1/7 | 359 | 244 | 150 |
| 1/8 | 354 | 239 | 145 |
| Demand Distance for Lane Confirmation(m) | 100 | 100 | 100 |
| Minimum Clear Distance(m) | 738 | 583 | 450 |

Considering that the distance between the tunnel exit and the mainline toll station is generally on the downgrade section, the vehicle is easy to exceed the speed limit when driving out of the tunnel. Therefore, it is recommended that regardless of the design speed of the expressway, the distance between the tunnel exit and the mainline toll station should be the clear distance under the design speed of 120km/h, that is, under the secondary service level of the 4-lane expressway, the clearance between the tunnel exit and the mainline toll station should be greater than 750m under normal circumstances; when it is limited by terrain and route corridors, the minimum clear distance should be no less than 600m considering the setting of the 500m advance sign of the mainline toll station.

5. Conclusions

Based on the characteristics and the implementation status of expressway construction in China, the relevant standards and researches at home and abroad, the minimum clear distance between tunnel and expressway mainline toll station was put forward. under the study of the light adaptation distance, the traffic signs recognition distance, the operation distance and the lane confirmation distance. Analysis result shows that under the secondary service level of the 4-lane expressway, the general value of the clear distance between the tunnel exit and the mainline toll station should be greater than 750m; when it is limited by terrain and route corridors, the minimum clear distance should be no less than 600m.
In addition, the further research should focus on some aspects needed to improve in this paper. For example, the research of this paper is based on the good weather condition. When the weather changes, the response time of driver and the value of the vehicle braking coefficient in the braking model need to be further studied.

It is worth noting that if the distance between the tunnel exit and the mainline toll station is too small, the expressway itself is already a potential accident-prone section. Therefore, the clear distance between the tunnel exit and the mainline toll station should first be selected with reference to the relevant specifications. The minimum clear distance above will be considered when the conditions are indeed limited. At the same time, for the selection of the minimum clear distance, the traffic safety evaluation should be carried out for the project characteristics, the possible adverse traffic safety factors should be systematically analysed. It is also necessary to strengthen the design of traffic safety facilities, optimize tunnel lighting, and strengthen monitoring and management to minimize traffic accidents and accident losses.

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