Configurations of tunnel deceleration area

Yanhong Zhang¹²³,*, Yunlong Fan¹²³, Jianbin He¹²³, Jialei Tian¹²³, Xiangnan Ma¹²³, Weiyuan Yuwen⁴ and Yuanxin Tan⁴

¹ China Highway Engineering Consulting Corporation, Beijing 100089, China
² Research and Development Center of Transport Industry of Technologies, Materials and Equipments of Highway Construction and Maintenance Ministry of Transport, Beijing 100089, China
³ Research and Development Center on Highway Pavement Maintenance, CCCC, Beijing 100089, China
⁴ Pavement Structure and Materials lab, Tsinghua University, Beijing 100084, China

*Corresponding author. Email: 240009199@qq.com

Abstract. The deceleration area of the tunnel has always been the place where accidents occur frequently. Recently published statistics on tunnel accidents showed that 42 percent of which are rear-end collisions. The main reason lies on the luminance difference between the inside and the outside parts of the tunnel. The inside part of the tunnel is much darker than that of the outside part, which results in a “sight shock” and shortage of clear sight for drivers at the tunnel portal. If the tunnel deceleration area is not long enough and the vehicle is at a high speed, rear-end collisions will most likely occur at this area. Therefore, it is important to design the deceleration area of the tunnel in order to avoid rear-end collisions. This paper explains the cause of rear-end collision at deceleration area from the principles of physics and physiology. The mathematical relations among the speed, time and distance of trucks and cars entering the tunnel are given from the mathematical point of view. Finally, this paper puts forward the design idea and reasonable suggestions for the configuration of tunnel deceleration area.

Keywords: tunnel, deceleration area, rear-end collision.

1. Introduction

With rapid growth of the number and mileage of tunnels, China has become the country with the largest number of tunnels, the most complex construction situation and the fastest mileage growth in the world [1]. Statistics show that in the 1950s, there were only more than 30 highway tunnels in China, with a total length of about 25km. By 1979, the number of highway tunnels in China has reached 374, with a total mileage of more than 52km. By the end of 2000, the number of highway tunnels in China has reached 1972, with a total mileage of more than 835.1km. By the end of 2012, the number of highway tunnels in China had reached 10022, with a total mileage of 8.053 million meters, which was about 9.6 times that of the end of 2000 [2].

Recently published statistics on tunnel accidents showed that 42 percent of which are rear-end collisions. When the vehicle enters the tunnel, the driver is generally required to reduce speed, pay attention to the relevant signs at the tunnel entrance, and drive according to the specified speed limit.
requirements. If the driver does not pay attention to the sign board at the tunnel entrance, or even if he does not drive according to the regulations, it may cause accidents due to illegal behaviors such as speeding, overtaking at will, parking, etc. If the distance between the front and rear vehicles is wrong, the vehicle can’t stop in time in case of emergency, which may lead to rear-end collision\(^{[3-13]}\). Among the errors involving drivers, perception errors account for 42%, judgment errors account for 36%, operation errors account for 8%, and others account for 14\(^{[14]}\). The proportion of perception error is the first, which shows that the reliability of driver's information perception stage is particularly important. The results show that the proportion of traffic information transmitted by drivers' sensory organs is about 80% of vision, 14% of hearing, 2% of touch, 2% of taste and 2% of smell. Visual information is the first, and the reliability of visual perception is an important content of driver traffic characteristics research\(^{[15]}\). The highway tunnel group section has dense tunnels and short spacing. Several tunnels are connected by a short bridge or subgrade. The light environment at the entrance and exit of the tunnel changes rapidly, and the driving environment changes frequently in a short time and space, which has a great impact on the driver's psychology and physiology and has prominent safety risks\(^{[16]}\). When passing through the tunnel group section, drivers experience a process of alternating light environment mutation. Due to the limitation of their own physiological functions, the psychological and physiological self-regulation is intensified, and the rapid transformation of visual "light and dark adaptation" appears, which makes the tunnel group section become the sensitive area on the expressway, and traffic accidents occur frequently\(^{[17]}\). The problem of driver's adaptation to light and shade caused by the great difference of ambient illumination inside and outside the tunnel entrance becomes the main cause of the accident\(^{[18,19]}\).

2. Methods
First of all, this paper introduces the dark adaptation process of drivers when they enter the tunnel from the bright place from the perspective of physics. Then it explains the normal reaction and driving behavior of drivers in the tunnel. Then, from the physiological point of view, the adaptation mechanism of human eyes in bright and dark places is explained. Finally, the mathematical relationship between the speed, time and distance of truck and car before and after entering the tunnel is given. Based on the mathematical relationship above, this paper puts forward the reasonable configuration of the deceleration area of the tunnel, and puts forward reasonable suggestions for the design of the deceleration section.

2.1. Dark adaptation
When entering the tunnel, drivers need some time to get used to the sudden luminance change. This phenomenon is called dark adaptation. In other words, dark adaptation is the process from entering the dark environment to the state where the drivers are used to the dark environment and have clear sight of the surroundings. The section of dark adaptation is shown in figure 1.
2.2. Drivers’ driving behavior in the tunnel
According to the sight receptor’s working mechanism, drivers cannot see objects clearly when suddenly entering a dark environment from a bright environment. And the situation gets worse as the change of luminance gets larger. In this case, drivers usually would take measures to decelerate the vehicles subconsciously. If the tunnel deceleration area is not long enough and the driving speed is too high, the rear-end collision will most likely happen.

At the portal of the tunnel, drivers usually operate a large deceleration for the sudden luminance change according to psychology. As drivers adapt to the environment gradually, the deceleration will decrease. After adapting to the inside environment and having the clear sight completely, drivers would stop decelerating and begin to accelerate until the vehicle is running at a proper speed.

2.3. Red-light effect
There are two main receptors on the retina, which are cone cells and rod cells. Cone cells play the main role in bright areas while rod cells in the dark. Cone cells are more sensible to the change of radiance than rod cells. As red light is long-wave light, rod cells lack the recognition of red light. If there is something, such as goggles, filtrating the light and making only red light get into eyeshot, rod cells will not be stimulated by light and will have a low sight threshold. When entering the dark environment where the light waves remain a low level, rod cells have the best receptivity by only decreasing the sight threshold a little, thus effectively reducing people’s time spent on adapting to darkness.

2.4. Driving characteristics of trucks and cars in the tunnel
Extensive investigations show that drivers would adjust the speed continuously in reflection of their psychological change resulting from the luminance distinction between the inside and the outside of the tunnel. According to Code for design of Road tunnel JTG D70-2004, we can find the regularity of speed changes for cars and trucks in tunnels.

According to the speed curve shown above, the process of the change of speed can be divided into several stages, both for trucks and cars. Each stage can be fitted by some function.

**Trucks**
The total process of the trucks adapting to the tunnel environment can be divided into four stages according to the distance from the tunnel portal: $110 \geq s \geq 0, 125 \geq s > 110, 490 \geq s > 125, 750 \geq s > 490$. Unit: m
The relationship between speed and distance in process 1 ($110 \geq s \geq 0$) can be shown in the Figure 2. A quadratic function can be used to fit the curve of process 1. The speed may then be computed as:

$$v = 5.4E - 0.5s^2 - 0.0182s + 16.114 \quad (2.1)$$
In this process, the deceleration is decreasing smoothly, from nearly -0.3 m/s² to -0.09 m/s². The trend of the change of deceleration fits in with the human psychology. People usually take some intensified measures to adjust to an unexpected environment. As drivers gradually adapt to the surroundings, they will finally get back to the original state.

The result of a mathematical integration of the equation (1) which can be used to describe the distance of the trucks from the tunnel portal is:

\[ s = 168.5186 - 519.6238 \tan(-0.02806t + 0.31361) \]  

(2.2)

In equation (2.2), \( t \) represents the time of trucks in process 1.

The relationship between speed and distance in process 2 (125 ≥ \( s \) ≥ 110) can be shown as a line in Figure 2. A linear function can be used to fit the curve. The speed may then be computed as:

\[ v = -0.0944s + 25.167 \]  

(2.3)

The result of a mathematical integration of the equation above which can be used to describe the distance of the trucks from the tunnel portal is:

\[ (0.02519 - 0.55785)1581.45 - 708.726 \]  

(2.7)

In equation (2.7), \( t \) represents the time of trucks for process 3.

After totally adapting to the tunnel, the drivers can have a clear sight. In other words, the tunnel would be considered safe for drivers. They will begin to accelerate to the normal driving level.

The relationship between speed and distance in process 3 (490 ≥ \( s \) ≥ 125) can be shown as a curve in Figure 2. A quadratic function can be used to fit the curve. The speed may then be computed as:

\[ v = -1.1E - 0.5s^2 + 0.0096s + 12.329 \]  

(2.6)

The result of a mathematical integration of the equation (2.6) which can be used to describe the distance of the trucks from the tunnel portal is:

\[ 0.02519 - 0.55785 \]  

(2.9)

In equation (2.9), \( t \) represents the time of trucks for process 4.

Similar to the deceleration process, when totally adapting to the tunnel, drivers would increase their driving speed substantially. A function of which the speed is the derivative can be described as:

\[ v = s' = 14.4111e^{0.0033t} \]  

(2.10)
The equation reflects the speed increases exponentially, which fits in with the analysis of the drivers’ psychology.

II Cars

The critical condition happens when the car driver takes measures to apply the brake the instant the process of dark adaptation is finished. Then the car finally meets the trucks at the same speed. When the car’s dark adaptation is finished, the car’s speed just falls to the lowest. Subsequently it begins to brake instead of entering the process of accelerating. So it is necessary for us to know the function about the speed changes of cars during the cars’ dark adaptation.

![Figure 3. Speed changes of cars after entering the tunnel portal.](image)

The curve in blue in Figure 3 shows the relationship between speed and distance in the process of dark adaptation for cars. A quadratic function can be used to fit the curve. The speed may then be computed as:

\[
v = 2.1E - 07s^3 - 1.1E - 04s^2 - 1.4E - 03s + 2.3E + 01 \quad (2.11)
\]

The result of a mathematical integration of the equation above which can be used to describe the time of the cars is:

\[
t = -15.0547 \arctan(1.30683 - 0.00296893s) + 6.36473 \log(356.527 + s) - 3.18236 \log(307197 + (-880.336 + s) s + 16.6228 \quad (2.12)
\]

The equation shows the direct relationship between the time and distance during the dark adaptation for cars. On the whole, with distance being farther, the time will be longer. It is not linear, for during the dark adaptation drivers would take different decelerations according to the extent they have adapted to the surroundings. Generally, the deceleration changes greatly at the beginning. As time goes by, the change will be smooth until the deceleration reaches 0.

Calculating process of length of tunnel deceleration area:

In order to calculate the length of tunnel deceleration area, we should first get some basic statistics about trucks and cars using functions recommended above.

Using equation (2.2) and (2.4), we can get the duration of process 1 for trucks is \( t_1 = 7.18s \) and the duration of process 2 for trucks is \( \Delta t_2 = 1.07s \). Then the total time from the beginning of process 1 to the end of process 2 can be worked out as:

\[t_1 + \Delta t_2 = 8.25s\]

Similarly, the time of process 3 for trucks, which is the definite integrator of equation (7), can be worked out as . Thus the total time from the beginning of Process 1 to the end of Process 3 is:

\[t_3 = 25.87 + 8.25 = 34.12s\]

Similar to the calculation process of trucks, we can also get some basic statistics for cars. According to equation (2.12), when the dark adaptation for cars is ended, cars will get to the lowest speed and the whole time for the dark adaptation is \( t_d = 15.52s \). From the curve, we can directly read that the driving
distance of cars from the tunnel portal to the end of dark adaptation is $S_d=320$ m and the initial speed entering the tunnel for cars is $V_1 =23.06$ m/s. Then we may use equation (11) to work out that the cars’ final speed at the end of dark adaptation is $V_2 =18.61$ m/s.

Moreover, in general, when drivers take an emergency brake, the deceleration of car-emergency braking is $a=4.5$ m/s$^2$.

Then we can use the basic statistics above to calculate the length of tunnel deceleration area. The process of the calculation of length of tunnel deceleration area can be described as follows.

By setting the emergency braking time for the car, such as 1s, for the car, it is easy to get the braking distance as $S_b$, the final speed of the truck $V_f$ and the braking time for the car $t_b$, considering the process of the car’s braking is at a constant deceleration. Because the car and the truck are in the same position finally, the total driving distance for trucks from the tunnel portal can be worked out as

$$S_{truck} = S_b + S_d$$  \hspace{1cm} (2.13)

It is easy to justify that when the car finally meets the truck, the truck is just in process 3. So according to equation (2.6), we can work out the final speed of the truck. Similarly, according to the distance-time function for trucks, we can calculate the time of the truck driving from the end of process 2 to the final state $t_3'$.

The total time of this process, from the beginning of the truck driving into the tunnel to the final state of the car and the truck being in the same position in the tunnel with the same speed, can be worked out as

$$t_{total} = t_1 + t_2 + t_3'$$  \hspace{1cm} (2.14)

Thus the time for the car driving outside the tunnel can be worked out as
\[ t_s = t_{\text{total}} - t_d - t_b \] (2.15)

At the critical state the speeds of the car and the truck are the same, that is \( \dot{v} = 0 \). So we need to adjust the braking time and repeat the calculating process continuously until \( \dot{v} = 0 \). Thus the time for the car driving outside the tunnel \( t_s \) worked out is just what we want and can be used to calculate the final length of tunnel deceleration area we are searching for. And the final solution is:

\[ S_s = t_s \times V_1 \] (2.16)

Based on the statistics and the analysis above, the final result we get is \( S_s = 139.6 \text{m} \).

At the portal of the tunnel, drivers usually operate a large deceleration for the sudden luminance change according to psychology. As drivers adapt to the environment gradually, the deceleration will decrease. After adapting to the inside environment and having the clear sight completely, drivers would stop decelerating and begin to accelerate until the vehicle is running at a proper speed.

3. Results

Based on the calculation and analysis above, it is of great importance to set the deceleration area in the tunnel portal area, thus instruct drivers to keep a proper distance from the front vehicle. The length of the deceleration area should be set according to the analysis results.

Dark adaptation is caused by the change of the chemical substances in the human receptors. Red light can reduce the time for dark adaptation effectively, whose working process has been explained above. We can adapt to the dark environment much more easily if we are under the red-light environment. If the adaptation time is reduced, then the rear-end collision is less likely to happen under the same situation. These are pieces of effective information for designers to improve the tunnel equipment design in order to reduce the risks of rear-end collisions.

To simulate the red light environment, it is suggested setting a red plastic shelter in the tunnel portal area right before the tunnel portal. The red plastic shelter will infiltrate light and provide the red light environment. The shelter should extend along the road so the simulated environment can last for a while before red light take effect and the drivers will feel much more comfortable. Except for the red plastic shelter, red lightings can be set at the tunnel portal to strengthen the red-light effect. With the decrease of time for drivers to adapt to the dark environment in the tunnel, the same length of tunnel deceleration area will be much safer than before. Meanwhile drivers will feel more comfortable. The final design is presented below.

![Figure 5. Improved design of tunnels with red plastic shelter at the tunnel portal.](image)

When considering the effect of the red environmental simulation, the adaptation time for car drivers can be reduced from 15.52s to 10s, which is a conservative estimate. Then repeating the calculating process above, we can work out that the new length of tunnel deceleration area \( S_s \) can be reduced to 117.63m.

4. Discussion

This paper starts from the speed-distance angle of truck and car passing through the tunnel. Through formula calculation, the shortest setting length of deceleration section is 139.6m. If the red plastic shelter is set, drivers adapt to the dark environment more quickly when entering the tunnel and the length of deceleration section can be further shortened to 117.63m. This paper studies the rear-end collision
between truck and car for the reason that the speed difference between truck and car is the biggest when entering the tunnel. So we don't need to consider the rear-end collision between truck and truck, car and car.

5. Conclusions
If the tunnel deceleration area is not long enough and the vehicle is at a high speed, the risk of rear-end collisions will be very high. There is not an exact regulation providing the minimum tunnel deceleration area for driving. Although there have been some measures to improve the tunnel safety, such as strengthening lighting, it is not economic and will lead to large amount of power consumption.

Based on the analysis in this study, the safe distance for the most unfavorable case is recommended to be 139.6m without taking any special improvement. In the perspective of physiological theory, it will be helpful to set red plastic shelter and thus alleviate the dark environment influence and improve the degree of safety and comfort.

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