IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received March 10, 2021, accepted March 30, 2021, date of publication April 6, 2021, date of current version April 16, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3071308

Modeling and Verification of the Length of the Entrance and Exit Sections of an Undersea Tunnel

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This work was supported in part by the Foundation for Jiangsu Key Laboratory of Traffic and Transportation Security under Grant TTS2020-08, in part by the Natural Science Foundation of Shandong Province, China, under Grant ZR2020MG021, in part by the Humanities and Social Sciences Research Planning Foundation of Chinese Ministry of Education under Grant 18YJAZH067, in part by the Key Research and Development Project of Shandong Province under Grant 2018GGX105009, and in part by the Natural Science Fund for Colleges and Universities in Jiangsu Province under Grant 18KJA580001.

ABSTRACT At present, there is no standard or research to define the specific length of the entrance and exit sections of an undersea tunnel. In combination with the unique longitudinal slope of the undersea tunnel and the change in the illumination difference, the lengths of the lane change, transition and adaptation sections of the entrance and exit sections of the undersea tunnel were theoretically deduced, and a model for the entrance and exit sections lengths was established. Considering the Qingdao Jiaozhou Bay undersea tunnel as an experimental subject, the accuracy of the model of the entrance and exit section lengths was verified using two methods. The results indicated that the lengths of the entrance and exit sections of undersea tunnels change with changes in the factors such as the illumination, vehicle speed, and slope. In the case of the Qingdao Jiaozhou Bay undersea tunnel, when the vehicle passes the undersea tunnel at a speed of 70 km/h on a sunny day, according to the studied model, the entrance and exit sections of the undersea tunnel are 146.7 m and 157.1 m long, respectively. The entrance and exit section lengths of the undersea tunnel, determined using test method 1 and test method 2 are 151.0m, 153.6m and 161.0m, 148.9m, respectively. The absolute errors between the results of the model and test method 1 and 2 are less than 10%. These findings indicate that the model for the entrance and exit section lengths of undersea tunnels is reasonably accurate.

INDEX TERMS Undersea tunnel, length of the entrance and exit sections, illumination, percentage of eyelid closure, longitudinal slope.

I. INTRODUCTION

An undersea tunnel is a large scale artificial transportation facility for vehicles that is built under the seabed to solve the traffic problems between straits and bays [1]. Undersea tunnels can change the traffic pattern and promote the social and economic development on both sides of the tunnel. Such tunnels can alleviate the problem of land occupation, do not obstruct sea navigation, can facilitate all weather traffic flow, and exhibit a large traffic capacity [2].

In contrast to road tunnels, the submarine section of an undersea tunnel is below sea level, with a limited height, large length, and relatively closed regions. There is not enough natural lighting, and the necessary illumination for driving is provided through artificial lighting [3], [4]. Consequently, the driver undergoes a ‘‘bright-dark-bright’’ visual change process when driving the vehicle through the tunnel during the day [5], [6]. The difference in the illumination inside and outside the tunnel may lead to the ‘‘black hole effect’’ and ‘‘white hole effect’’ in the entrance and exit sections of the undersea tunnel, respectively, and drivers may experience a lag in the visual adaptation, which may affect drivers' driving ability and behavior [7], [8]. Moreover, the road alignment at the entrance and exit of the undersea tunnel is more complicated than that within the tunnel. This unique alignment of the longitudinal slope makes it challenging for drivers to obtain traffic information at the entrance and exit of the undersea tunnel [9], [10]. Under the combined effect of the illumination and longitudinal slope, the driver many exhibit a reduced control of the vehicle, leading to physical

The associate editor coordinating the review of this manuscript and approving it for publication was Xinyue Xu.

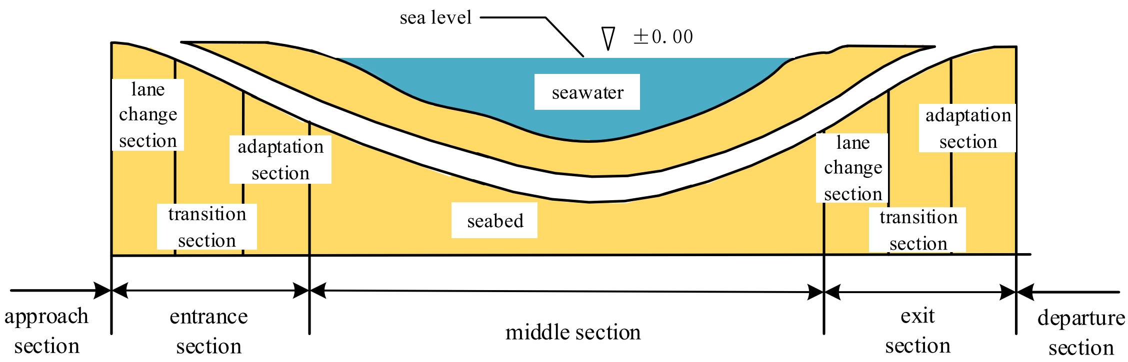

FIGURE 1. Schematic of undersea tunnel section.

and psychological stress, which poses a considerable hidden risk to driving safety [11]-[13]. Because undersea tunnels are strategic transportation facilities, they play a vital role in facilitating urban traffic. The occurrence of a traffic accident may impede the functionality of the undersea tunnel, thereby causing local large scale regional traffic congestion at both ends of the tunnel, which threatens the productivity and daily lives of the residents and the safety of life and property [14], [15]. The rate of and losses associated with traffic accidents in a road tunnel are considerably larger than those for an ordinary road, and accidents more frequently occur at the entrance and exit sections of road tunnels [16]-[18]. As undersea tunnels have been developed only recently and are few in number, research on the entrance and exit sections of the undersea tunnel is lacking. The length of the entrance and exit sections of undersea tunnels is of significance for the operation and management of the undersea tunnels and the related theoretical research. Therefore, this article reports on the verification of the length of the entrance and exit sections of a road tunnel, along with the actual situation of an undersea tunnel. Moreover, the characteristics of the driving environment and traffic participants in the undersea tunnel were examined to verify the length of the entrance and exit sections of the undersea tunnel and establish a model.

II. DIVISION OF ENTRANCE AND EXIT SECTIONS OF THE UNDERSEA TUNNEL

An undersea tunnel is a key branch of road tunnels [19]. However, due to the unique structure of the undersea tunnels, in contrast to that of an ordinary road tunnel, the driving environment is slightly different in terms of the complex longitudinal slope present in undersea tunnels [20]. The path of undersea tunnels enters the seabed from the land, passes under the seabed, and moves outward to the land. Owing to this physical structure, undersea tunnels have an ‘‘U’’ shape [21]–[24]. Therefore, ordinary road tunnels do not have complicated longitudinal slope changes. Due to this physical structure, the road alignment of an ordinary road tunnels appears as a ‘‘horizontal line segment’’ [25]–[28].

In this research, a complete undersea tunnel is divided into the approach section, entrance section, middle section, exit section, and departure section [29], [30]. The exit and entrance sections are divided into lane change, transition and adaptation sections [31]. A schematic of the undersea tunnel division is shown in Figure 1.

III. VERIFICATION AND MODELING OF THE ENTRANCE AND EXIT SECTION LENGTHS

A. VERIFICATION AND MODELING OF THE LANE CHANGE SECTION LENGTH

Because the entrance and exit lane change sections are located outside and inside the undersea tunnel shelters, respectively, the difference in the illuminance before and after the entrance and exit lane change sections is small. Furthermore, because the lane change section is located in the transitional area between the land and coast, the slope of the lane change section changes considerably. Therefore, when verifying the length of the lane change section, the influence of the road slope on the lane changing behavior must be examined.

The purpose of driving on the lane change section is to move from the original lane to a target lane. The process of changing lanes can be divided into the lane change decision making section, execution section and completion section [32]. The process of a vehicle changing lanes is illustrated in Figure 2.

Figure 2 shows that the driving track of the vehicle in the lane change decision making and completion sections is a straight line, while that in the lane change execution section exhibits an ‘‘S’’ shape, connected by two curves with a continuously changing curvature. The running track is shown in Figure 3.

As shown in Figure 3, the lane change execution section can be divided into stages I and II. In stage I, the driver controls the steering wheel such that the vehicle deviates from the straight state and moves to the boundary between lanes A and B. In stage II, the vehicle moves from the boundary between lanes A and B into lane B, and re-enters the straight state. Stages of I and II can be connected by two opposite curves of equal length. Based on the characteristics of the vehicle’s driving track, the transition curve coincides with the track of the vehicle’s centroid, and the minimum radius of

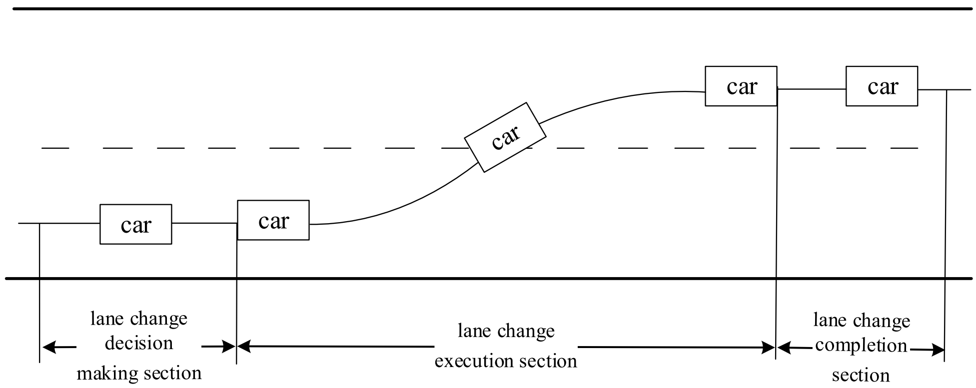

FIGURE 2. Schematic of a vehicle change lanes.

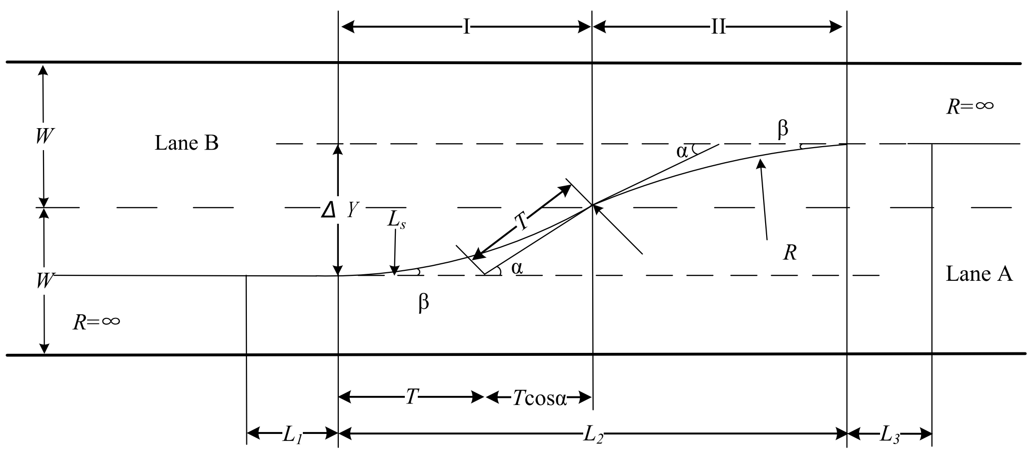

FIGURE 3. Schematic of the vehicle lane changing track.

the curve at the connection is the minimum turning radius of the vehicle at the given speed [33].

The minimum turning radius refers to the minimum radius that can ensure the safe passage of a vehicle through the curve of the road. Specifically, when the vehicle passes through a curve, the friction force (i.e., centripetal force) generated by the vehicle tire and the ground is equal to the centrifugal force. Therefore, the corresponding calculation formula can be obtained through the force analysis of the vehicle at the curve:

$$R = \frac{v^2}{127\,(\mu + i_h)} \tag{1}$$

where R is the radius of the cur (m); v is the vehicle speed (km/h); μ is the sideways force coefficient; and i_h is the superelevation.

Furthermore, when vehicles change lanes, they exhibit not only lateral displacement but also longitudinal displacement. As shown in Figure 3, suppose L_2 and Δy represent the longitudinal and lateral displacement of the vehicle in the lane change execution section, respectively, according to the geometric relationship, the following formulas can be obtained.

$$L_2 = 2T(1 + \cos\alpha) \tag{2}$$

$$\Delta y = w \tag{3}$$

$$T = (R + p)\tan\frac{\alpha}{2} + q \tag{4}$$

$$p = \frac{L_s^2}{24R} \tag{5}$$

$$q = \frac{L_S}{2} - \frac{L_S^3}{240} \tag{6}$$

$$\beta = \frac{\alpha}{2} = \frac{L_S}{2R} \tag{7}$$

$$l = 4L_s = vt \tag{8}$$

where T is the tangent length (m); w is the lane width (m); q is the tangent increment (m); p is the inward extension (m); L_s is the transition curve length (m); β is the transition curve angle; α, l, and t represent the tangent angle of the center point, driving track length, and vehicle driving time (s) for the lane change execution section, respectively.

The length of the lane change execution section can be derived using the aforementioned calculation formula, as shown in formula (9), as shown at the bottom of the next page:

The total length of the lane changing section is

$$D_1 = L_1 + L_2 + L_3 \tag{10}$$

TABLE 1. Luminance reduction coefficient.

Design traffic volume N (veh·(h·In)$^{-1}$)		Design speed V (km·h^{-1})				
Traffic volume in one direction	Traffic volume in two directions	20–40	60	80	100	120
≥1200	≥650	0.012	0.022	0.035	0.045	0.070
≤350	≤180	0.010	0.015	0.025	0.035	0.050

Note: When the traffic volume has an intermediate value, the corresponding value is obtained through linear interpolation

$$L_1 = vt_1 \tag{11}$$

$$L_3 = vt_3 \tag{12}$$

where L_1 and t_1 denote the lane change decision making section length (m) and reaction time (s), respectively; L_3 and t_3 denote the lane change completion section length (m) and reaction time (s), respectively.

B. VERIFICATION AND MODELING OF THE TRANSITION AND ADAPTATION SECTION LENGTH

According to ***the design specification of highway tunnels*** (JTG D70/2-2014, in China) [34], the luminance at the entrance of an ordinary road tunnel is

$$L_{th1} = k \times L_w \tag{13}$$

$$L_{th2} = 0.5k \times L_w \tag{14}$$

where L_{th1} and L_{th2} represent the luminance of the transition and adaptation sections (cd·m^{-2}), respectively; k is the luminance reduction coefficient, and its values are listed in Table 1. L_{w} is the luminance outside the hole (cd·m^{-2}); if no measured data are available, the value of this parameter can be considered according to Table 2.

Considering the effect of the longitudinal slope at the entrance and exit of the undersea tunnel on the driver, the luminance of the entrance and exit sections of the undersea tunnel can be defined as

$$L_{th1} = k \times L_{\mathrm{w}} \times \eta \tag{15}$$

$$L_{th2} = 0.5\, k \times L_{\mathrm{w}} \times \eta \tag{16}$$

$$L = E \times r \tag{17}$$

where η is the longitudinal slope correction coefficient; L is the luminance (cd·m^{-2}); E is the illumination (lux); r is the reflection coefficient.

According to the reference [34], under ordinary circumstances, the maximum allowable longitudinal slope of a road tunnel is 3%. Because undersea tunnels must cross the seabed, the associated longitudinal slope is generally larger than 3%. Considering the actual longitudinal slopes of the Qingdao Jiaozhou Bay undersea tunnel and Tokyo Bay undersea tunnel, which are in operation, to facilitate practical operation, the maximum allowable longitudinal slope of the undersea tunnel was set as 4%. Consequently, η can be calculated using formula (18).

$$\eta = \begin{cases} 1 + \dfrac{i}{4\%}, & \text{entrance section} \\ 1 + \dfrac{0.5i}{4\%}, & \text{exit section} \end{cases} \tag{18}$$

where i is the longitudinal slope (%).

Considering the driver's visual characteristics at the entrance and exit sections, the calculation formula for the length of the transition and adaptation sections is as shown in formulas (18) and (19), respectively:

$$D_2 = \frac{1}{2}\left(1.154D_s - \frac{h-1.5}{\tan 10^\circ}\right) \times \eta \tag{19}$$

$$D_3 = \frac{1}{2}(1.154D_s - \frac{h-1.5}{\tan 10^\circ}) \times \eta + T_s \times 3.6v_0 \tag{20}$$

$$D_S = d_1 + d_2 + d_0 = \frac{v_1 \times t_0}{3.6} + \frac{v_1^2}{254\mu_1} + d_0 \tag{21}$$

where D_2 is the transition section length (m); D_{s} is the stopping sight distance (m); D_3 is the adaptation section length (m); T_{S} is the visual adaptation time (s); v_0 is the design speed of the undersea tunnel (m/s); d_1 is the reaction distance (m); d_2 is the braking distance (m); d_0 is the safety distance (m); v_1 is the driving speed (km·h^{-1}); t_0 is the driver's reaction time (s); μ_1 is the longitudinal friction coefficient between the road surface and tire.

When a driver drives the vehicle through the entrance and exit sections of the undersea tunnel, due to the difference in the illumination inside and outside the undersea tunnel, a certain amount of time is required for the driver's vision to be restored, which is termed as the visual adaptation time [35].

In this research, a real vehicle experiment was performed at the Qingdao Jiaozhou Bay undersea tunnel. An eye tracker

$$L_2 = 2\left\{\left[\frac{v^2}{127(\mu+i_h)} + \frac{127(\mu+i_h)}{384}\right]\tan\frac{127(\mu+i_h)}{8} + \frac{vt}{8} - \frac{16129(\mu+i_h)^2t^3}{15360v}\right\}(1+\cos\frac{127t(\mu+i_h)}{4v}) \tag{9}$$

TABLE 2. Luminance outside the hole ($cd \cdot m^{-2}$).

Sky area percentage	Direction of the hole/background outside the hole	Design speed V (km·h^{-1})				
		20–40	60	80	100	120
35–50%	South facing hole	-	-	4000	4500	5000
	North facing hole	-	-	5500	6000	6500
25%	South facing hole	3000	3500	4000	4500	5000
	North facing hole	3500	4000	5000	5500	6000
10%	Dark background	2000	2500	3000	3500	4000
	Bright background	3000	3500	4000	4500	5000
0%	Dark background	1500	2000	2500	3000	3500
	Bright background	2000	2500	3000	3500	4000

Note:
1 The sky area percentage refers to the percentage of the sky area in the 20° field angle.
2 The east and west facing holes adopt the intermediate values of the south and north facing holes, respectively.
3 When the sky area percentage has an intermediate value, the corresponding value is obtained through linear interpolation.

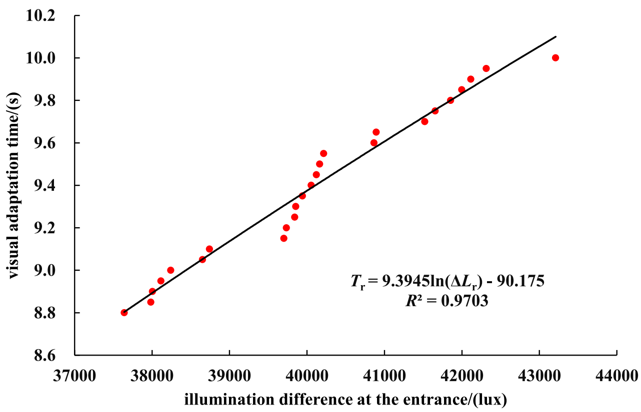

FIGURE 4. Curve of the drivers' visual adaptation time at the entrance of the undersea tunnel.

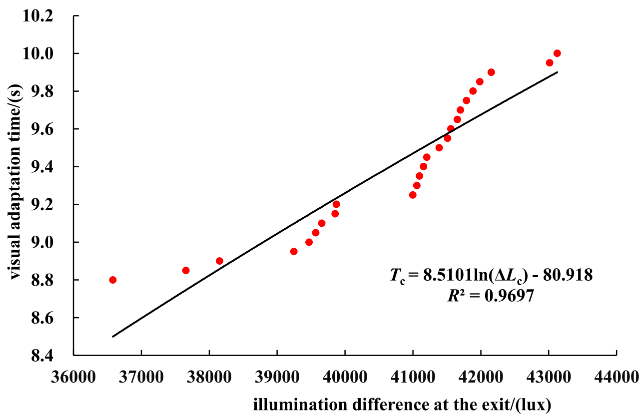

FIGURE 5. Curve of the drivers' visual adaptation time at the exit of the undersea tunnel.

was used to measure the percentage of eyelid closure for the driver, and an illuminometer was used to measure the difference in the illuminance at the entrance and exit. Considering the percentage of eyelid closure as the characteristic indicator of the visual adaptation time, the time period from the relatively large fluctuation of the percentage of eyelid closure to the restoration of a stable state was deemed as the visual adaptation time.

Through the statistical analysis of the relevant data obtained from the experiment, the fitting curve between the driver's visual adaptation time and the difference in the illumination inside and outside the tunnel is shown in Figure 4 and Figure 5.

According to Figure 4 and Figure 5, the calculation formula for the fitting curve of the visual adaptation time and illuminance difference of the driver at the entrance and exit of the undersea tunnel can be expressed as in formulas (22) and (23), respectively:

$$T_r = 9.3945 \ln(\Delta L_r) - 90.175 \tag{22}$$

$$T_c = 8.5101 \ln(\Delta L_c) - 80.918 \tag{23}$$

where T_r and T_c represent the visual adaptation time for the entrance and exit sections (s), respectively; ΔL_r and ΔL_c denote the illumination difference at the entrance and exit sections (lux), respectively.

According to these calculation formulas, the model to calculate the length of the entrance and exit sections of the undersea tunnel can be obtained, as shown in formulas (24) and (25), respectively:

$$D_r = \lambda D_1 + D_2 + D_3, \quad \lambda \in \{0, 1\} \tag{24}$$

$$D_c = \lambda D_1 + D_2 + D_3, \quad \lambda \in \{0, 1\} \tag{25}$$

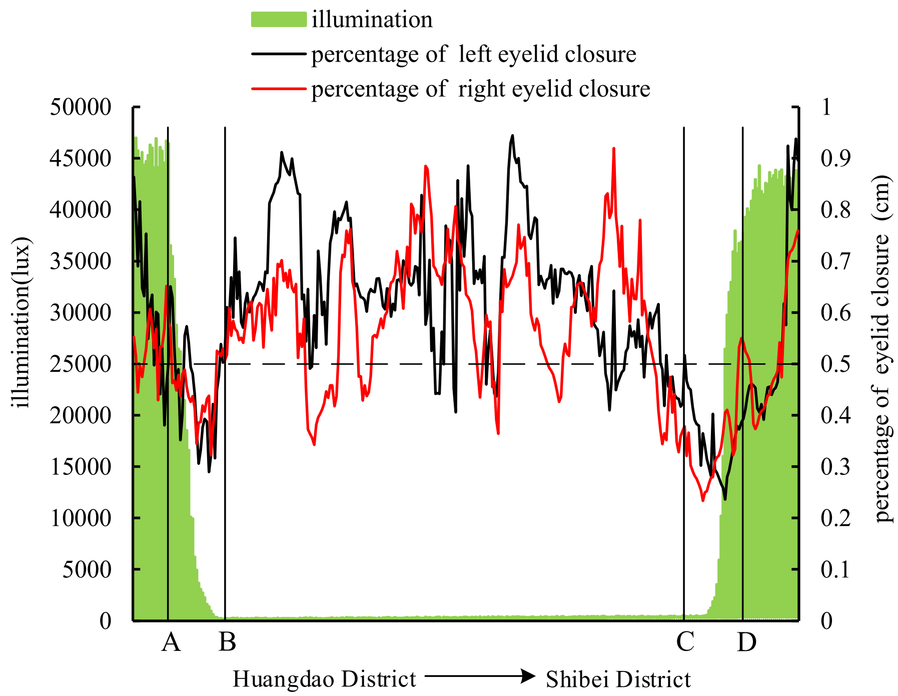

FIGURE 6. Illumination and percentage of eyelid closure in the undersea tunnel sections.

where D_r and D_c denote the length of the entrance and exit sections of the undersea tunnel (m), respectively; λ represent the lane changing coefficient, with a value of 0 or 1. When $\lambda = 0$, the driver enters the entrance or exit without changing the lane, and when $\lambda = 1$, the driver changes lanes at the entrance or exit.

IV. MODEL VALIDATION

To verify the rationality and accuracy of the calculation model of the entrance and exit section lengths of the undersea tunnel, the Qingdao Jiaozhou Bay undersea tunnel was used as an experimental site, and the model was verified using two methods. Qingdao Jiaozhou Bay undersea tunnel has a total length of 7.8 km, of which the cross-sea section is 4.1 km, and the deepest section is 82.8 m below sea level. It has 3 lanes in each direction, and the design speed and maximum speed limit for each area of the undersea tunnel is 80 km/h [36].

A. TEST METHOD 1

The length of the entrance and exit sections of the undersea tunnel was verified considering the change in the visual characteristics of the driver, in terms of the percentage of eyelid closure. In general, the percentage of eyelid closure refers to the iris coverage when the upper and lower eyelids are closed, and its value is between 0 and 1. A value of 0 means that the upper and lower eyelids do not cover the iris, and a value of 1 means that the iris is completely covered by the upper and lower eyelids. The closure degree of the eyelid can reflect the attention and tension states of the driver.

During a sunny daytime period, the driver passed the Jiaozhou Bay undersea tunnel at a usual speed of 70 km/h. The percentage of eyelid closure and illumination of the undersea tunnel were recorded when the driver passed through the undersea tunnel, and the results were analyzed. The corresponding results are shown in Figure 6.

In Figure 6, points A and B are the start and end points of the undersea tunnel entrance and exit sections, respectively. In section A-B, the percentage of eyelid closure of the left and right eyes is low, and its value first decreases and later increases, indicating that the driver is focused and nervous when entering the entrance section of the undersea tunnel. After a brief period of adaptation, the driver's nervousness gradually decreases and returns to the normal state at point B. Thus, point B can be regarded as the end point of the entrance section of the undersea tunnel. Similarly, point C is the starting point of the exit section of the undersea tunnel. Through actual measurement, the length l_{A-B} is 161.0 m, and l_{C-D} is 151.0 m.

When the parameters in the model to verify the length of the entrance and exit sections of the undersea tunnel change, the length of the entrance and exit sections of the undersea tunnel vary accordingly. Specifically, in the direction from the Huangdao District to the Shibei District, the entrance and exit of the Qingdao Jiaozhou Bay undersea tunnel are south and north facing holes, respectively, with the average longitudinal slope of the entrance and exit sections being 3.9% and 3.4%, respectively. Therefore, $\eta_c = 1.44$, and $\eta_r = 1.98$. We assume that the driver enters the undersea tunnel transition section in the same lane and keeps driving in

TABLE 3. Basic information of the drivers.

variable	average	standard deviation	range	skewness	kurtosis
age	33.56	6.300	24–43	-0.021	-1.131
driving age/(year)	4.40	2.230	1–12	1.206	1.826
driving mileage (ten thousand kilometers)	0.51	0.275	0.3–1	0.105	-0.844
visual acuity	4.80	0.117	4.6–5.0	0.844	-0.908
physical condition		satisfactory			

the original lane through the undersea tunnel entrance and exit sections, i.e., $\lambda = 0$; the driver's reaction time is $t = 2.0$ s; the driving speed $s = 70$ km/h; the friction coefficient $\mu_1 = 0.5$; the illuminance difference at the entrance and exit of the undersea tunnel $\Delta L_c = \Delta L_r = 40000$ lux; the design speed of the undersea tunnel $v = 80$ km/h. According to calculation formulas (24) and (25), the length of the entrance and exit sections of the Qingdao Jiaozhou Bay undersea tunnel is 146.7 m and 157.1 m, respectively.

Considering the result obtained using test method 1 as the true value, the relative error of the result obtained using the model is

$$\partial = \frac{100\%\Delta}{L} \tag{26}$$

where Δ is the absolute error, i.e., the difference in the results obtained using test method 1 and the model. L is the result of test method 1. According to formula (26), the relative error in the length of the entrance and exit sections of the undersea tunnel, obtained by the model, is 2.4% and 2.8%, respectively. The relative error in the length of the entrance and exit sections of the undersea tunnel is less than 5%, which demonstrates that the model is accurate.

B. TEST METHOD 2

We used the driver's perception of the length of the entrance and exit of the undersea tunnel to verify the accuracy of the model of the entrance and exit section lengths of the undersea tunnel. The experiment involved 26 drivers, including 21 males and 5 female drivers. The basic information is presented in Table 3.

Before the start of the experiment, the drivers were trained to clarify the meaning of the "exit" and "entrance" sections of the undersea tunnel and to familiarize them with the experiment process and purpose. From the traffic accident statistics of the whole undersea tunnel, there are more traffic accidents at the entrance and exit sections. One of the main reasons is that the illumination inside and outside the tunnel is quite different, and the "black hole effect" at the entrance and the "white hole effect" at the exit are more serious. The undersea tunnel has 24-hour artificial lighting and the illumination of the tunnel is stable at 80-100 lux. The illumination outside the tunnel can reach 45000-50000 lux on sunny days. The greater the illumination outside the tunnel, the more serious the "black hole effect" at the entrance and the "white hole effect" at the exit of the undersea tunnel, and the greater the threat to traffic safety. In fact, for the entrance and exit of the undersea tunnel, the harsh environment is a sunny day with high illumination. Therefore, in order to ensure the practicability of this study, the sunny day with better weather was selected for the experiment. During the experiment, the driver passed through the Jiaozhou Bay undersea tunnel at an ordinary speed of 70 km/h without changing lanes within the undersea tunnel [37]. When the driver sensed the critical points between the entrance and middle sections of the undersea tunnel and those between the middle and exit sections of the undersea tunnel, he/she reported them to the assistant experimenter, who was the copassenger, in real time. The assistant experimenter used a stopwatch to record the time and general position of the participant at the critical point. After the experiment, according to the time recorded by the stopwatch, the video of the driving recorder was viewed frame by frame and matched with the actual positions in the undersea tunnel to obtain the length of the entrance and exit of the undersea tunnel, verified by perception. The experimental results are shown in Table 4.

It can be seen from Table 4 that among the 26 drivers, the 3rd, 4th, 9th, 16th and 25th are female drivers. The results show that in the group of "length of entrance of undersea tunnel", the P value between male and female drivers is 0.58, so there is no significant difference between male and female drivers. The results show that in the group of "Length of exit of undersea tunnel entrance", the P value between male and female drivers is 0.18, so there is no significant difference between male and female drivers, and gender has no effect on the results. In addition, the number of male drivers with driver's license in China is about 2.7 times that of female drivers with driver's license [38]. In fact, in China, male drivers are more active than female drivers, that is to say, male drivers actually drive more cars. According to

TABLE 4. Results of the length of the entrance and exit of the undersea tunnel, as perceived by the drivers.

Number	1	2	3	4	5	6	7	8	9	10	11	12	13
Gender	Male	Male	Female	Female	Male	Male	Male	Male	Female	Male	Male	Male	Male
Length of entrance of undersea tunnel (m)	146	191	152	139	137	98	152	138	156	152	144	141	143
Length of exit of undersea tunnel entrance (m)	160	149	148	145	157	157	166	147	154	157	151	170	148

Number	14	15	16	17	18	19	20	21	22	23	24	25	26
Gender	Male	Male	Female	Male	Male	Male	Male	Male	Male	Male	Male	Female	Male
Length of entrance of undersea tunnel (m)	156	158	155	158	158	137	142	148	148	154	154	158	149
Length of exit of undersea tunnel entrance (m)	143	143	150	159	165	174	137	164	155	147	147	147	158

TABLE 5. Statistics of the length of the entrance and exit of the undersea tunnel, as perceived by the drivers.

Parameter / Length	average	mode	maximum value	minimum value	standard deviation	95% confidence interval
Entrance of the undersea tunnel (m)	148.9	158	158	137	7.3	(145.8, 152.0)
Exit of the undersea tunnel (m)	153.6	147	170	143	7.7	(150.3, 157.8)

statistics, the number of male drivers passing through the Qingdao Jiaozhou Bay undersea tunnel is about 4.3 times that of female drivers. The proportion of male and female drivers in this study is basically consistent with this statistical proportion.

To reduce the error and improve the accuracy of the experimental results, the maximum and minimum values in each set of data were removed, and the experimental data after the removal were analyzed. The results are shown in Table 5.

Table 5 indicates that the lengths of the entrance and exit sections of the undersea tunnel obtained using the model are within the 95% confidence interval of the values measured using the perception method, thereby demonstrating the high accuracy of the model to verify the entrance and exit section lengths of the undersea tunnel. Considering the average value of test method 2 as the true value, calculation formula (26) can be used to indicate that the relative errors in the length of the entrance and exit sections calculated using the model are -5.5% and 4.5%, respectively. The absolute value of the relative error of the length of the entrance and exit sections of the undersea tunnel is less than 10%, thereby demonstrating the accuracy of the model.

V. CONCLUSION AND DISCUSSION

This research considered factors such as the longitudinal slope and illumination of an undersea tunnel. Through the derivation and calculation of the entrance and exit section length of the undersea tunnel, as well as experimental verification, the following conclusions were obtained:

(1) A model for the lengths of the entrance and exit sections of the undersea tunnel was established.

(2) The accuracy of the model was verified experimentally.

(3) On a sunny day, the length of the entrance and exit sections of the Qingdao Jiaozhou Bay undersea tunnel could be considered as 150 m.

From a theoretical viewpoint, the length of the entrance and exit sections of undersea tunnels changes dynamically, and the specific value changes with the change in the slope, speed and illumination. Therefore, based on the distribution range of velocity and illuminance, researchers must examine the range of the entrance and exit section lengths of undersea tunnels considering a given slope.

In order to get a more scientific length of the entrance and exit sections of an undersea tunnel, the following issues need to be further studied:

(1) The studied length model for the entrance and exit sections of an undersea tunnel is only suitable for large-depth underpass tunnels like undersea tunnels, and is not suitable for horizontal tunnels without longitudinal slope changes.

(2) In the transition and adaptation section, the study only considers the impact of longitudinal slope on the driver, not the cross slope.

(3) There is no distinction between experimental drivers in the study. Drivers of different professions, ages and driving ages may have different perception of longitudinal slope and illumination changes. Therefore, it is necessary to make further research on different driving groups.

(4) Vehicle speed is one of the important factors that determine the length of the entrance and exit sections of an undersea tunnel. The ''vehicle speed'' in this study refers to the average speed of all vehicles passing through the entrance and exit sections of an undersea tunnel. The management department can calculate the corresponding length of the entrance and exit sections of an undersea tunnel based on the calculation model of this study and the average speed of the entrance and exit sections of an undersea tunnel. It should be noted that the length of the entrance and exit sections of an undersea tunnel obtained in this study is based on the normal driving behavior and driving physiology of most drivers, and the abnormal conditions are not considered, such as speeding, visual impairment, etc.

(5) Gender is one of the factors that affect the results of the experiment. Limited by time and economic cost, this study only uses a small number of experimental drivers to verify the length of the entrance and exit sections of an undersea tunnel. In addition, due to the limitation of the total sample size and the proportion of male and female drivers passing through the Jiaozhou Bay undersea tunnel, the number of female drivers in this study is relatively small. Therefore, it is necessary to use a larger sample size to verify the length of the entrance and exit sections of an undersea tunnel.

ACKNOWLEDGMENT

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