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Research paper

Calculation model and analysis for lay-by spacing in highway tunnel

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Abstract: Tunnel lay-by spacing is directly related to traffic safety and engineering investment. Nevertheless, its mechanism is not clear, and the rationality of the exiting norms with respect to tunnel lay-by spacing needs to demonstrate. A calculation model for tunnel lay-by spacing was derived by considering the headway and the physical kinematics of the two vehicles chasing and encountering. With it, the influence of various parameters on lay-by spacing were analysed and the rationality of the model were discussed through comparing with existing norms. Results shows longitudinal gradient rate, daily average traffic flow, rolling resistance coefficient, posted speed limit are significant to determine the lay-by spacing, and the most important parameter is longitudinal gradient rate. Existing tunnel lay-by spacing norm values are not reasonable enough, either too strict or too loose. These findings provide scientific support for how to select tunnel lay-by spacing value, which can improve tunnel traffic safety and make engineering investment reasonable.

Keywords: calculation model, highway tunnel, influence analysis, lay-bys spacing

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1. Introduction

A highway tunnel can effectively shorten the distance between two places and improve transportation efficiency, but the characteristic of its semi-enclosed tubular structure also makes it prone to bottlenecks once vehicles break down within the tunnel. To solve this problem, some section of tunnel will be expanded as lay-by to provide a temporary inspection or waiting area for break-down vehicles, avoiding obstruct traffic and even traffic accidents caused by remaining on the carriageway, which can ensure tunnel traffic smooth and safe.

Lay-by will change the geometric dimensions of tunnel cross section, making the lining structure more complicated [1] and increasing ventilation [2]. In 2012, a serious traffic accident with 28 dead and 24 injured occurred at the end wall of lay-by within the Sierre tunnel in Switzerland, which caused some scholars to study the anti-collision effect of the type and length of the anti-collision facilities at the end wall of lay-by [3,4]. For the lay-by spacing (Fig. 1), it is directly related to traffic safety and engineering investment. As to the spacing is too large, several rear-end collision occurred [5] due to break-down vehicle cannot drive off the carriageway. If the spacing is too small, it means more lay-bys needed and will directly increase the ventilation, excavation, etc. investment. Therefore, the lay-by spacing value should be safe and reasonable.

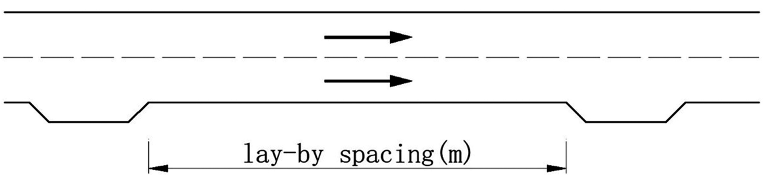

Fig. 1. Sketch of tunnel lay-by spacing

There were few studies concerning tunnel lay-by spacing, existing were almost national tunnel norms. PIARC mentioned principal provision that lay-by should according to the volume of traffic, the mode of operation, uni- or bidirectional, the statistical rate of breakdowns to determine [6]. Cai [7] analyzed and compared the lay-by spacing value from the perspective of ventilation and engineering investment. Wang [8] proposed that the approximate reasonable lay-by spacing could be calculated by using the coasting distance of break-down vehicle and the distance required, under manpower, to move the vehicle to lay-ty. In 2004, the E.U. Bulletin stipulated that for a new two-way tunnel longer than 1500 m, the traffic volume in each lane was greater than 2000 vehicles and no emergency lane was provided, lay-by should be set at a distance not exceeding 1000 m [9]. Both Italy and Spain complied with the technical requirements of the bulletin [10]. While France and Norway had further exceeded the technical requirements. French tunnel norm recommended that lay-bys should be set every 800 m for tunnels over 1000 m in length [11]. Norwegian tunnel norm set 500 m of lay-by spacing for tunnel category E/F, of which were uni-bidirectional and daily average traffic flow (*AADT*) above than 10000 veh/d [12]. Two related technical documents [13, 14] were commonly used in the design of highway tunnels in various states within the United States [15], the documents covered lay-by while did not specify its spacing. Chinese tunnel norm posited that uni-bidirectional tunnel lay-by spacing unsuited to greater than 750 m and could not exceed 1000 m [16]. Japanese tunnel norm proposed that lay-by should be spaced 500 to 1500 m apart [17, 18]. The above-mentioned norms are based on national conditions and the engineering experience of various countries, and no further relevant supporting scientific research.

Tunnel lay-by spacing is directly related to traffic safety and engineering investment, its value should be reasonable to balance traffic safety and investment. We established a calculation model for tunnel lay-by spacing which based on the single-vehicle coasting distance calculation model, combining with the headway and the physical kinematics of the two vehicles chasing and encountering. Furthermore, according to engineering calculation conditions, the corresponding lay-by spacing values under most longitudinal gradient rate (i) were calculated. The influence of various parameters on the lay-by spacing were analyzed and the rationality of the model were discussed through comparing with existing norms values. Those works could provide scientific support for the rational layout of the tunnel lay-by and ensure traffic safety and investment reasonable.

2. Methods

2.1. Single-vehicle coasting distance calculation model

Li [19] derived the single-vehicle coasting distance calculation model on flat road (shown in Eq. (2.1)), which used to obtain wind resistance coefficient, rolling coefficient and other parameters about vehicle by combing with vehicle coasting test result.

$$D = \frac{m}{C_D A\rho} \cdot \text{In} \frac{\dfrac{C_D A\rho V_0^2}{2} + fmg}{\dfrac{C_D A\rho V_t^2}{2} + fmg} \tag{2.1}$$

where: D – vehicle coasting distance, m, m – vehicle mass, kg, C_D – air resistance coefficient, A – windward area, m^2, that was, the vehicle projected area in the direction of driving, ρ – air density, kg/m^3, V_0 – initial speed of vehicle in the coasting period, m/s, V_t – running speed of vehicle in the coasting period at the time t, m/s, f – rolling resistance coefficient, g – acceleration due to gravity, m/s^2.

2.2. Establishment calculation model for tunnel lay-by spacing

Wang [8] proposed that tunnel lay-by spacing should consider the coasting distance of vehicles and manoeuvrable distance. Given rear-end accidents on mountainous expressway has become a big problem that arouses much social concerns [20], and the poor visual environment and challenging driving experience within tunnel, we didn't consider manoeuvrable distance which would endanger personal safety due to undetected or misjudged of the subsequent vehicles.

Eq. (2.1) was used as single-vehicle coasting distance calculation model, if it was directly used as lay-by spacing model as Wang [8] proposed, the break-down vehicle was regarded as a separate entity and only considered the dynamic energy dissipation, ignoring the traffic safety impact caused by the dynamic distance relationship between the break-down vehicle and subsequent vehicle. That was, the break-down vehicle would be overtaken by the subsequent vehicle during its coasting period, which would easily induce rear-end collisions. What's more, unlike field test, it could not obtain the break-down vehicle's speed at the time of subsequent vehicle overtake it. Therefore, more work needed to derive based on Eq. (2.1).

Headway was the time interval between two consecutive vehicles passing through the same section [21]. To simplify the calculation of the headway, we assumed that $AADT$ were evenly distributed on each lane, thus, the average headway of each lane calculated as Eq. (2.2).

$$\Delta t = \frac{86400 \times N \times L}{AADT} \tag{2.2}$$

where: Δt – the average headway of each lane, s, N – 1 (uni-bidirectional tunnel) or 2 (bidirectional tunnel), L – the number of uni-bidirectional lanes.

From the motion logic of the two vehicles, when the subsequent vehicle overtook the break-down vehicle, the difference between the distance driven by the subsequent vehicle and coasting distance of the break-down vehicle was equal to the initial separation distance between the two vehicles, as shown in Eq. (2.3).

$$V_S t_c - D_B = \Delta t V_{B0} \tag{2.3}$$

where: V_S – the subsequent vehicle speed, m/s, t_c – the coasting time of break-down vehicle till overtook by the subsequent vehicle, s, V_{B0} – the initial speed of break-down vehicle, m/s, D_B – the coasting distance of the break-down vehicle, m.

To obtain D_B, it was necessary to determine t_c first. Seen from Eq. (2.4) that the coasting phase of the break-down vehicle was variable deceleration, its deceleration changes with running speed. Therefore, the classic physical motion calculation formula could not be employed to solve the problem.

$$a = -\frac{F}{m} = \frac{-\left[\frac{1}{2} C_D A \rho V_t^2 + mg(f+i)\right]}{m} \tag{2.4}$$

where: a – acceleration in vehicle driving direction, m/s^2, i – road longitudinal gradient rate, F – force in vehicle driving direction, N.

According to physical kinematics and derivative arithmetic, the acceleration was the derivation of speed versus time, thus, Eq. (2.5) and Eq. (2.6) could be obtained.

$$a = -\frac{\frac{C_D A \rho V_t^2}{2} + mg(f+i)}{m} = \frac{\mathrm{d}V}{\mathrm{d}t} \tag{2.5}$$

$$-\frac{\mathrm{d}t}{m}=\frac{\mathrm{d}V}{\dfrac{C_D A\rho V_t^2}{2}+mg(f+i)} \tag{2.6}$$

The break-down vehicle coast from time 0 to time t_c, and its speed corresponding ranges from V_{B0} to V_{Bt}, then integrated both ends of Eq. (2.6), as shown in Eq. (2.7).

$$\int\limits_{v_{B0}}^{v_{Bt}}\frac{\mathrm{d}V}{\dfrac{C_D A\rho V_t^2}{2}+mg(f+i)}=-\int\limits_{0}^{t_c}\frac{\mathrm{d}t}{m} \tag{2.7}$$

where: V_{Bt} was the break-down vehicle speed at time of t_c, m/s.

After integrating the equations could get:

$$t_c=\arctan\frac{\sqrt{2mg(f+i)C_D A\rho}\,(V_{B0}-V_{Bt})}{2mg(f+i)+C_D A\rho V_{B0}V_{Bt}}\sqrt{\frac{2m}{C_D A\rho g(f+i)}}. \tag{2.8}$$

Substituting Eq. (2.8) into Eq. (2.3) could obtain a formula which only contained the unknown variable V_{Bt}, combining it with Eq. (2.1) as shown Eq. (2.9) could obtain lay-by spacing. Taking $V_{Bt}=0$ if $V_{Bt}<0$ calculated from Eq. (2.9a), which meant the subsequent vehicle did not overtook the break-down before it was stopped. If $V_{Bt}\geq 0$, substituting it into the Eq. (2.9a).

$$\begin{aligned} V_S\sqrt{\frac{2m}{C_D A\rho g(f+i)}}\arctan\frac{\sqrt{2mg(f+i)C_D A\rho}\,(V_{B0}-V_{Bt})}{2mg(f+i)+C_D A\rho V_{B0}V_{Bt}} \\ =\frac{m}{C_D A\rho}\cdot\ln\frac{C_D A\rho V_{B0}^2/2+(f+i)\cdot mg}{C_D A\rho V_{Bt}^2/2+(f+i)\cdot mg}+\Delta t V_{B0} \end{aligned} \tag{2.9a}$$

$$S=D_B=\frac{m}{C_D A\rho}\cdot\ln\frac{C_D A\rho V_{B0}^2/2+(f+i)\cdot mg}{C_D A\rho V_{Bt}^2/2+(f+i)\cdot mg} \tag{2.9b}$$

where: S – the tunnel lay-by spacing, m.

The derivation process of lay-by spacing calculation model reflected that the scientific essence of lay-by spacing in tunnel was the coasting distance corresponding to the vehicle dynamic energy dissipation, which under the influence of headway, longitudinal gradient rate and the wind resistance change caused by the variable deceleration speed.

3. Results

3.1. Application lay-by spacing calculation model

Assuming the calculation condition was unfavorable, that was, the break-down vehicle was large-sized vehicle with a relatively slow speed, and the subsequent vehicle was

Table 1. Calculation parameters of the break-down vehicle

Calculation parameter	Value	Remarks
A	$6\ m^2$ [a]	–
C_D	0.8 [a]	–
f	0.014[a]	good asphalt or concrete pavement
m	35000 kg [b]	–

Note: [a]The values come from Yu [22], [b]The value comes from China Automotive Technology and Research Center Co., Ltd [23].

passenger vehicle with a fast speed. The parameters needed by Eq. (2.9) were shown in Table 1.

According to "Specifications for design of highway tunnels section 1 civil engineering" [16], i ranged from –3% to 3%.

Based on the operating speed model provided in the "Specifications for highway safety audit" [24], the operating speeds of passenger vehicle and large-sized vehicle in tunnel calculated respectively as V_s = 20.28 m/s, V_{B0} = 19.97 m/s which according to the posted speed limit 80 km/h.

According to the index of highway technical grade in the "Design specification for highway alignment", $AADT$ = 15000/5000/2000 veh/d [25]. Additionally, considering most highway tunnels in China, N took as 2.

3.2. Comparative results

Compared lay-by spacing values of calculation from Eq. (2.9) with various countries or institutions norms, the comparison result was presented in Fig. 2 and critical data listed in Table 2.

Compared with the Norwegian tunnel design norm [12], the lay-by spacing values calculated by the model were larger than it (namely 500 m) in the conditions of i < 2.6%, $AADT$ = 5000/2000 veh/d or i < 2.5%, $AADT$ = 15000 veh/d.

Compared with Chinese and Japanese tunnel norms [16, 17], the lay-by spacing values calculated by the model were larger than it (namely 750 m) in the conditions of i < 1.2%, $AADT$ = 5000/2000 veh/d or i < 1.0%, $AADT$ = 15000 veh/d.

Compared with French tunnel norm [11], the lay-by spacing values calculated by the model were larger than it (namely 800m) in the conditions of i < 1.0%, $AADT$ = 5000/2000 veh/d or i < 0.8%, $AADT$ = 15000 veh/d.

Compared with the E.U. bulletin [9], the lay-by spacing values calculated by the model were larger than it (namely 1000m) in the conditions of i < 0.5%, $AADT$ = 5000/2000 veh/d or i < 0.2%, $AADT$ = 15000 veh/d.

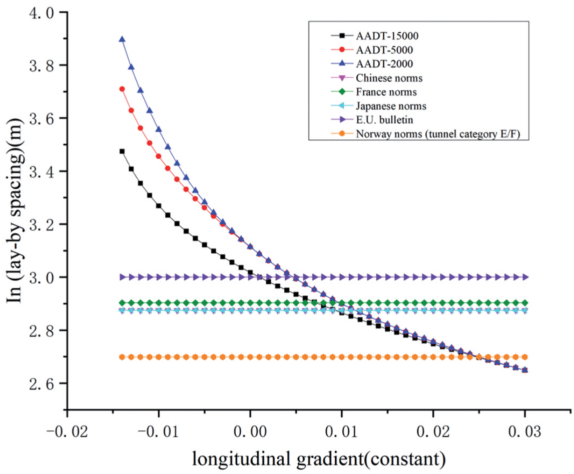

Fig. 2. Lay-bys spacing comparison between calculation model result and the specified values

Table 2. Comparison results of key data

Categories S (m) i	*AADT*-15000	*AADT*-5000	*AADT*-2000	Chinese norms	France norms	Japanese norms	E.U. bulletin	Norway norms (tunnel category E/F)
0.026	486.42	488.06	488.06	750	800	750	1000	500
0.025	497.62	**500.07**	**500.07**	750	800	750	1000	**500**
0.024	**509.22**	512.68	512.68	750	800	750	1000	**500**
0.012	692.08	735.17	735.17	750	800	750	1000	500
0.011	712.40	**762.77**	**762.77**	**750**	800	**750**	1000	500
0.01	733.83	792.52	792.52	750	800	750	1000	500
0.009	**756.48**	**824.70**	**824.70**	**750**	**800**	**750**	1000	500
0.008	780.46	859.60	859.60	750	800	750	1000	500
0.007	**805.91**	897.59	897.59	750	**800**	750	1000	500
0.005	861.86	984.65	984.65	750	800	750	1000	500
0.004	892.76	**1034.85**	**1034.85**	750	800	750	**1000**	500
0.002	961.62	1152.41	1152.41	750	800	750	1000	500
0.001	**1000.22**	1221.85	1221.85	750	800	750	**1000**	500
0	1042.12	1299.59	1300.23	750	800	750	1000	500

Note: Bold indicates that lay-by spacing calculated by the model was just larger than someone country' norm value and highlights the corresponding longitudinal slope rate.

4. Discussion

4.1. Lay-by spacing comparison of calculated values and normative values

When the road is downhill ($i < 0.0\%$), the lay-by spacing values calculated by model were all larger than the various countries norms in the three calculation conditions of $AADT = 15000/5000/2000$ veh/d, which due to accelerated by gravity, the break-down vehicle could coast a longer distance before the subsequent vehicle overtook. Furthermore, when $i \leq 0.0\%$, the lay-by spacing corresponding to $AADT = 2000$ veh/d and $AADT = 5000$ veh/d became different. The reason was that in the condition of $AADT = 5000$ veh/d and $i \leq 0.0\%$, the break-down vehicle would be keep coasting until overtook by the subsequent vehicle.

In Norway, the tunnel $AADT \geq 15000$ veh/d was classified as category F. It can be seen from the Table 2 that lay-by spacing calculated by the model were all larger than that of Norwegians, (500 m) in the condition of $i < 2.5\%$. As i could be set from –3% to 3% in Chinese highway tunnel, which reflected the stricter Norwegian tunnel norm requirements for most longitudinal gradient rate conditions. The tunnel 10000 veh/d $\leq AADT < 15000$ veh/d was classified as category E, and if the tunnel length is over 2.5 to 12.5 km, the corresponding $AADT$ gradually decreases from 10000 veh/d to 7500 veh/d. Taking $AADT = 7500$ veh/d to calculation by the model, the comparison result was shown in Fig. 3. From it, the lay-by spacing calculated by the model were larger than that of Norwegians, (500 m) in the condition of $i < 2.6\%$, which also reflected the stricter Norwegian tunnel norm requirements.

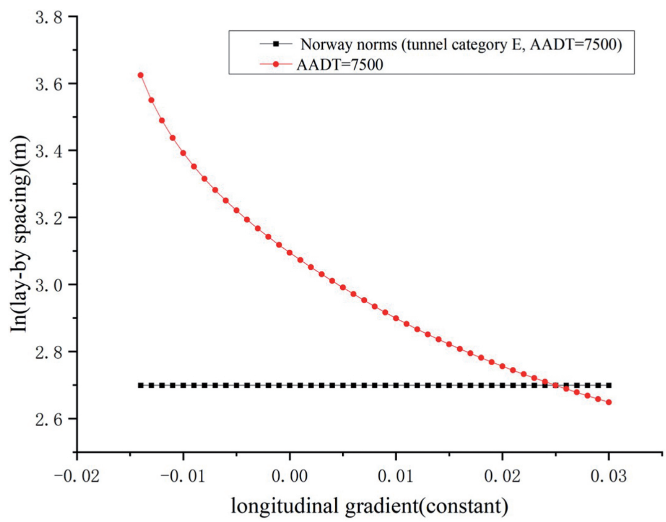

Fig. 3. Lay-by spacing comparison of calculation model result and Norway norm values

4.2. Parameters influence on lay-by spacing

Except i, the other parameters were a single value or several values, so twenty values of five parameters were added (seen in Table 3) to analyze the influence of each parameter on the lay-by spacing.

Table 3. New values of parameters

Parameter	m^a (kg)	A^b (m^2)	f^b	$AADT^c$ (veh/d)	Posted speed limit^c (km/h)
Values	28000	4.8	0.0112	6000	64
	31500	5.4	0.0126	6750	72
	38500	6.6	0.0154	8250	88
	42000	7.2	0.0168	9000	96

Note: [a]According to China Automotive Technology and Research Center Co., Ltd [23], the maximum limit mass for large-sized vehicle is 49000 kg, so the four values are taken every 3500 kg within the limit and choosen 35000 kg (Table 1) as the center.
[b]The values are taken at a certain interval within a reasonable range of which comes from Yu [22].
[c]The values are taken at a certain interval from the actual traffic situation.

Substituting the above values into Eq. (2.9) to obtain lay-by spacing values corresponding to each longitudinal slope rate condition, and then analyzed the influence of each parameter on the lay-by spacing through regression analysis by SPSS software. The results were shown in Table 4.

Table 4. Regression analysis of parameters influence on lay-by spacing

Independent variable	Unstandardized coefficients		Standardized coefficients	Sig.	Adjusted R Square
	B	Standard error	Beta		
(Constant)	1407.747	470.752		0.003	0.702
i	–58009.744	1162.254	–0.831	0.000	
m	0.006	0.007	0.014	0.395	
A	–32.875	38.834	–0.014	0.397	
Δt	–41724.505	16764.869	–0.041	0.013	
$AADT$	–0.038	0.007	–0.085	0.000	
Posted speed limit	14.102	2.913	0.081	0.000	

From Table 4: i, *AADT*, f, posted speed limit were significant to determine the lay-by spacing, where the first three independent variables had a negative effect on the lay-by spacing value, and the last independent variable had a positive effect. Furthermore, m and A were not significant to determine the lay-by spacing. i was the most important parameter affecting the lay-by spacing, follow by *AADT*, posted speed limit, f, which reflected lay-by spacing selection should focus on i, being inconsistent with the findings of various countries norms.

5. Conclusions

Highway tunnel lay-by spacing is closely related to traffic safety and engineering investment. From the perspective of vehicle driving logic, we establish a lay-by spacing calculation model and compare with the existing tunnel design norms. The main findings are as follows:

1. The first calculation model for highway tunnels lay-by spacing is established. i, *AADT*, f, posted speed limit are significant to determine the lay-by spacing, and the most important parameter is i.
2. As to the gravitational acceleration along the road, the lay-by spacing values calculated by model are all larger than the various countries norms in tunnel downhill section, which means exiting tunnel norms about lay-by spacing could increase to save engineering investment without affecting traffic safety. Except Norway, the lay-by spacing values calculated by model are all smaller than the various countries norms under the condition of $i > 1.1\%$, which means exiting tunnel norms about lay-by spacing should be stricter to improve traffic safety.

The research results provide scientific support for tunnel lay-by spacing selection. The related conductor, especially the designer, can calculate and determine the specific spacing value combine with the actual engineering parameters (such as i, *AADT*, main types of vehicles through the tunnel, etc.), avoiding engineering investment loss or potential traffic safety hazards by a single fixed value.

In the next stage, research can be carried out in conjunction with changes of vehicles' speed in the tunnel and the rate of traffic accidents to further optimize tunnel lay-by spacing.

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References

[1] L.J. Chen, B. Liang, "Seismic dynamic response analysis of intersection zone of emergency parking area with main tunnel in high–intensity earthquake region", *Railway Engineering*, 2014, no. 7, pp. 51–54; DOI: 10.3969/j.issn.1003-1995.2014.07.15.

[2] P. Weisenpacher, L. Valasek, "Computer simulation of airflows generated by jet fans in real road tunnel by parallel version of FDS 6", *The International Journal of Ventilation*, 2021, vol. 20, no. 1, pp. 20–33; DOI: 10.1080/14733315.2019.1698164.

[3] R. Kunc, S. Omerovic, M. Ambroz, I. Prebil, "Comparative study of European tunnel emergency-stop-area-wall protection measures", *Accident Analysis and Prevention*, 2014, vol. 63, pp. 9–21; DOI: 10.1016/j.aap.2013.10.020.

[4] E. Tomasch, S.F. Heindl, G. Gstrein, W. Sinz, H. Steffan, "Assessment of the effectiveness of different safety measures at tunnel lay-bys and portals to protect occupants in passenger cars", *Infrastructures*, 2021, vol. 6, no. 6; DOI: 10.3390/infrastructures6060081.

[5] QQ News, "Break-down vehicle stagnated in tunnel for 20 minutes". [Online] Available: https://new.qq.com/ [Accessed: 13. Nov. 2021].

[6] R.T.O. Committee, *Road tunnels manual-strategy and general design*, *Technical report*. PIARC, 2019.

[7] D.G. Cai, F. Ye, "Arrangement of lay-bys of long and big highway tunnel", in *National Conference on Highway Tunnels*. Taiyuan, China, 2003, pp. 182–185.

[8] S.P. Wang, "An analysis of freeway tunnel emergency parking strip effect on traffic safety", M.A. thesis, Chongqing Jiaotong University, China, 2013.

[9] *Directive 2004/54/EC of the European parliament and of the council of 29 April 2004 on minimum safety requirements for tunnels in the Trans-European Road Network*. Official Journal of the European Union, L 167/39, April 30, 2004.

[10] T.C.R.T. Operation, *Lay-bys and protection against lateral obstacles – Current practices in Europe*, *2016R16EN – Technical Report*. PIARC, 2016.

[11] *CETU dossier pilote des tunnels*. Standard France, 1990. ISBN 2.11.084737-9.

[12] *Road tunnels*. Standard Norway, 2004. ISBN 82-7207-540-7.

[13] *NFPA 502-2020 Standard for road tunnels, bridges, and other limited access highways*. Standard USA, 2020.

[14] C.J. Hung, J. Monsees, N. Munfah, J. Wisniewski, *Technical manual for design and construction of road tunnels-civil elements, FHWA-NHI-0-034 – Technical Report*. NHI, 2009.

[15] K. Thompson, *Best practices for roadway tunnel design, construction, maintenance, inspection, and operations*, *NCHRP Project 20-68A – Technical Report*. NCHRP, 2011.

[16] *JTG 3370.1-2018 Specifications for design of highway tunnels section 1 civil engineering*. Standard China, 2018.

[17] Kyushu Local Development Bureau, *The essentials of civil engineering design part iii road part 3-chapter design*. Tokyo Kyushu Local Development Bureau Press, 2011.

[18] H. Mashimo, "State of the road tunnel safety technology in Japan", *Tunneling and Underground Space Technology*, 2002, vol. 17, no. 2, pp. 145–152; DOI: 10.1016/S0886-7798(02)00017-2.

[19] X.H. Li, "Mathematical calculation of the coasting distance", *Changhe tech*, 1990, no. 2, pp. 15–17.

[20] Y.G. Wang, X.Y. Luo, "Analyzing rear-end crash severity for a mountainous expressway in China via a classification and regression tree with random forest approach", *Archives of Civil Engineering*, 2021, vol. 67, no. 4, pp. 591–604; DOI: 10.24425/ace.2021.138520.

[21] Y. Naito, T. Nagatani, "Effect of headway and velocity on safety–collision transition induced by lane changing in traffic flow", *Physica A: Statistical Mechanics and its Applications*, 2012, vol. 391, no. 4, pp. 1626–1635; DOI: 10.1016/j.physa.2011.09.020.

[22] Z.S. Yu, *Automobile theory*. China Machine Press, 2018.

[23] *GB1589-2016 Limits of dimensions, axle load and masses for motor vehicles, trailers and combination vehicles*. Standard China, 2016.

[24] *JTG B05-2015 Specifications for highway safety audit*. Standard China, 2015.

[25] JTG D20-2017 *Design specification for highway alignment*. Standard China, 2018.

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