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EFFECTS OF TRANSITION CURVES AND SUPERELEVATION ON THE CRITICAL STATES OF TRUCK ROLLOVERS ON SHARP CURVES

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Abstract. Sharp curves are vulnerable sections for rollover accidents. This study was conducted to investigate the effects of transition curve and superelevation on the critical speed and critical braking distance of truck rollovers. Using different transition types (spiral, Bloss and Grabowski curve) and different superelevation values (6%, 120 m transition length and 8%, 160 m) as variables, experiments of constant speed driving and hard braking were simulated and conducted by Trucksim. Conclusions regarding the influence of these road design factors on the stability of vehicles were then proposed. Grabowski curve allowed for the maximum critical rollover speed. The difference in critical rollover speed between different transition types was only determined by the length of the transition section. Simply extending the length of the transition section increased the critical rollover speed of spiral curve, at the same time decreasing the critical speed of Bloss and Grabowski curve. Hard

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braking experiments showed completely different characteristics. As the initial speed increased, only spiral curve became safer. Increasing superelevation made the braking behaviour of the vehicle more dangerous and fraught with uncertainties due to different target speed, starting curvature and changing superelevation. Based on these findings, a number of useful recommendations for drivers and road designers were put forward.

Keywords: driving stability, rollover, superelevation, transition curve, traffic safety.

Introduction

Among roadway networks, horizontal curves are one of the most accident-prone sections. The police statistics of road traffic crashes indicate that the proportion of traffic accidents on curves remains high all year round, with alarming numbers of injuries, fatalities, and property losses. Among the top 10 high-risk highway segments announced by the traffic police in Yunnan, China, nine are related to sharply curved sections, which witnessed a total of 45 serious traffic crashes resulting in 41 deaths and 37 serious injuries during the first half of 2020. In China, 17% of road traffic crashes occur on curves, resulting in 23% of all fatalities (Chinese Ministry of Public Security, 2015). In the USA, more than 25% of all fatal crashes are associated with a horizontal curve. Among these crashes, one of the most significant type is vehicle rollover (Himes et al., 2019). Furthermore, crash rates on horizontal curves are significantly higher than those on straight sections, and a smaller curve radius can result in more devastating consequences. Hence, it is necessary to mitigate the occurrence of traffic accidents on curved roadway segments to reduce the injury severity of such crashes.

Road alignment and vehicle operation are two main factors of curve accidents. Previous studies have assessed the non-compliance of alignment while regarding truck rollovers as the design limitation (Richl & Sayed, 2005). In terms of truck operation, the lateral load transfer ratio (LTR) (Huang et al., 2012) and time-to-rollover (TTR) (Li et al., 2019) metrics are utilised to detect truck rollovers. Most related models are based on the estimation of the longitudinal and lateral acceleration of the vehicle wheels, and they require a precise vehicle model (Czechowicz & Mavros, 2014). Some other studies use different assessment methods or variables, such as estimating the vehicle energy condition (Li & Bei, 2019) or using real-time control inputs (Bonfitto et al., 2019).

As an easily calculated indicator, the critical rollover speed can be applied to achieve easy-to-use and real-time risk prevention. Various studies have been carried out on different aspects, including tire characteristics (Hassan et al., 2020) and aero dynamics (Bettle et al., 2003), to provide the necessary parameters to support the construction of an accurate speed model (Estébanez et al., 2017). However, parameters related to tire, wheel acceleration, or control inputs still have not been effectively simplified. Since vehicles are often out of control during rollovers that occur at excessive speeds in real scenarios, most of the relevant studies on critical states have been implemented based on simulation approaches (Nair & Sujatha, 2020). These studies are based on different degree-of-freedom vehicle models, and they analyse the effects of various types of vehicles and road factors on the critical vehicle status (Chen & Ahmadian, 2020). However, related studies are mainly focused on the continuous driving process or transient state of the vehicle while travelling at a constant speed on a sharply curved section. Comparatively, there is a lack of research on the critical state of the vehicle when engaging in braking and other risk-avoidance measures on a curve (Li et al., 2016), as well as a lack of a detailed analysis of the effects of complex road factors on rollover (Anas & Khaled, 2022).

Drawing on the ideas of previous research, in this study, critical state of vehicle is used as an entry point, and experiments are designed to investigate the effects of road design factors on the driving stability. The findings of this study can give a new perspective for road design and driving safety research into vehicle-road interactions on sharp curves. The remainder of this paper is structured as follows: Section 1 describes the process of modelling the experimental objects, including basic alignment controls, transition sections and experiment vehicles. Section 2 introduces the experiment process, in which definitions of the critical rollover speed and critical braking distance are proposed. The results of the experiment are presented in Section 3, along with an analysis of the effects of evaluation indices. Section 4 presents the main achievements, summarises the conclusions, makes a number of informative recommendations and, finally, proposes some future research areas.

1. Simulation modelling

1.1. Road design control

The study addresses sharp curves that are commonly found in rural areas; therefore, standards for rural roads are used. The basic design parameters are shown in Table 1.

For curves that have such parameters as a design speed of 60 km/h and a radius of 150 m, a transition curve must be provided in principle.

Table 1. Design parameters of experimental groups

Design speed	60 km/h
Radius of circular curve	125.00 m
Cross slope	3.0%
Maximum superelevation	6.0%~8.0%
Lanes	2-way, 4-lanes, no median, the width of each lane is 3.75 m
Curve widening	/

As the width of the lane is sufficient, widening of the curved section is not necessary.

1.2. Transition section

Considering the practical experience, transition curve and superelevation runoff should be designed simultaneously. The advantage of this design is that transition curve can be seen as a composite alignment with a 2:1 combination of tangent and curve, an appropriately advanced superelevation runoff on tangent can slow down the change rate of lateral slope, thus enhances driving safety and comfortness. Meanwhile, keeping the superelevation changing on the transition curve can avoid sudden entry into the curve after a full superelevation, so the vehicles driving along will gain smaller lateral acceleration, thus improved driving stability (Wolhuter, 2015). The way to develop superelevation is to, firstly, rotate the outside lanes from the roadway normal camber to reverse camber, and then rotate the whole roadway to the superelevation slope, as shown in Figure 1.

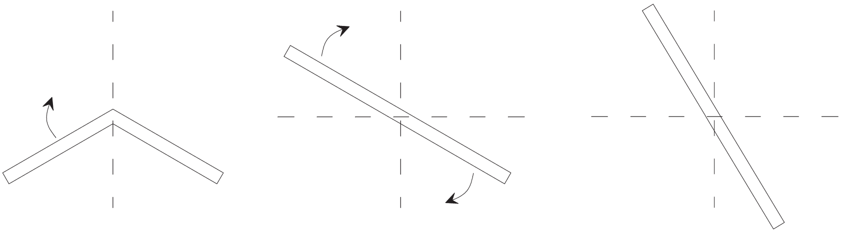

Figure 1. Superelevation development

The length of this combined transition section is calculated by Equation (1):

$$L = \frac{wne_d}{\Delta} b, \tag{1}$$

where L – length of combined transition section, m;
w – width of one traffic lane, m;
n – number of lanes rotated;
e_d – superelevation rate, %;
Δ – relative gradient, %;
b – adjustment factor for a number of lanes rotated.

For a 60 km/h, 4-lane highway, Δ = 0.64 and b = 0.70. The calculated lengths of the transition segments are shown in Table 2, with ten digit integers taken upwards for ease of calculation.

Three kinds of transition curve types were applied to investigate the effect on rollover stability: spiral curve, Bloss curve and Grabowski curve (Kobryń, 2017). A 150 m tangent entrance was provided before each transition. Considering that a blank control group was needed, a group without transition, only with superelevation runoff, was also set. The parameter of the spiral curve was set equal to the length of the circular curve section.

The shapes of the experimental alignments are shown in Figure 2. Of these, the experimental groups of Bloss and Grabowski curves are virtually indistinguishable in their basic shapes; the Grabowski

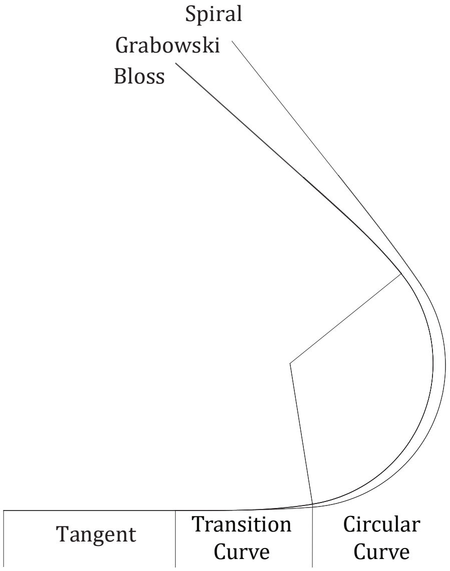

Figure 2. Experimental alignments

curve is more "opened" by an extremely slight degree. Basic alignment parameters are reported in Table 3.

Different from the spiral curve, Bloss curve provides not only the continuity of the curvature, but also the continuity of its changes. Formulas describing the Cartesian coordinates of the Bloss curve are presented in Equations (2) and (3):

$$x = L\left[t - s^2 P_2 t^3 + s^4 P_4 t^5 + \ldots\right], \tag{2}$$

$$y = L\left[sP_1 t^2 - s^3 P_3 t^4 + s^5 P_5 t^6 + \ldots\right], \tag{3}$$

where

$$t = \frac{l}{L}$$

$$s = \frac{L}{R_K}$$

$$P_1 = \frac{1}{4}t^2 - \frac{1}{10}t^3$$

$$P_2 = \frac{1}{14}t^4 - \frac{1}{16}t^5 + \frac{1}{72}t^6$$

$$P_3 = \frac{1}{60}t^6 - \frac{1}{44}t^7 + \frac{1}{96}t^8 - \frac{1}{624}t^9$$

$$P_4 = \frac{1}{312}t^8 - \frac{1}{168}t^9 + \frac{1}{240}t^{10} - \frac{1}{768}t^{11} + \frac{1}{6528}t^{12}$$

$$P_5 = \frac{1}{1920}t^{10} - \frac{1}{816}t^{11} + \frac{1}{864}t^{12} - \frac{1}{1824}t^{13} + \frac{1}{7680}t^{14} - \frac{1}{80640}t^{15},$$

where l = current length of the transition curve;
L = total length of the transition curve;
R_K = minimal radius of transition curve.

Table 2. Length of combined transition section

Maximum superelevation	Length of combined transition	Approximate value
6%	116.72 m	120 m
8%	155.63 m	160 m

Further, the Grabowski curve makes continuously the change rate of the curvature change. Formulas describing the Cartesian coordinates of the Grabowski curve are presented in Equations (4) and (5):

$$x = L\left[t - s^2 Q_2 t^3 + s^4 Q_4 t^5 + \dots\right], \tag{4}$$

$$y = L\left[s Q_1 t^2 - s^3 Q_3 t^4 + s^5 Q_5 t^6 + \dots\right], \tag{5}$$

where

$$Q_1 = \frac{1}{2}t^3 - \frac{1}{2}t^4 + \frac{1}{7}t^5$$

$$Q_2 = \frac{25}{72}t^6 - \frac{3}{4}t^7 + \frac{7}{11}t^8 - \frac{1}{4}t^9 + \frac{1}{26}t^{10}$$

$$Q_3 = \frac{125}{624}t^9 - \frac{75}{112}t^{10} + \frac{23}{24}t^{11} - \frac{3}{4}t^{12} + \frac{23}{68}t^{13} - \frac{1}{12}t^{14} + \frac{1}{114}t^{15}$$

$$Q_4 = \frac{625}{6528}t^{12} - \frac{125}{288}t^{13} + \frac{50}{57}t^{14} - \frac{33}{32}t^{15} + \frac{37}{48}t^{16} - \frac{3}{8}t^{17} + \frac{8}{69}t^{18} - \frac{1}{48}t^{19} + \frac{1}{600}t^{20}$$

$$Q_5 = \frac{625}{16128}t^{15} - \frac{625}{2816}t^{16} + \frac{5125}{8832}t^{17} - \frac{175}{192}t^{18} + \frac{457}{480}t^{19} - \frac{1437}{2080}t^{20} + \frac{457}{1296}t^{21} - \frac{1}{8}t^{22} + \frac{41}{1392}t^{23} - \frac{1}{240}t^{24} + \frac{1}{3720}t^{25}.$$

The ellipses in Equations (1)–(4) represent higher order expansion terms, but their calculations are generally omitted in view of designing accuracy.

Table 3. Alignment parameters of experimental groups

Total length	801.80 m (6% superelevation) 881.80 m (8% superelevation)
Length of tangent section	150.00 m
Length of transition section	120.00 m (6% superelevation) 160.00 m (8% superelevation)
Angle of circular curve	120.0°

1.3. Truck structure

To control the variables in the experiment, the vehicle type and driving operations remain consistent. A truck with a 3-axle cab with a 3-axle trailer is shown in Figure 3. The detailed parameters of each part are presented in Table 4.

Figure 3. A 3-axle cab with a 3-axle European trailer

Table 4. Detailed parameters of the vehicle

	Cab	Trailer	Load
Mass, kg	4455	5500	18340
Roll/ Pitch/ Yaw inertia, kg/m^2	2283.9/ 35402.8/ 34802.6	8997.1/ 150000/ 150000	12226.67/ 92082.08/ 92082.08
Position of the mass centre, mm	(–2000, 0, 1175)	(–3400, 0, 1936)	(–6000, 0, 2300)
Frontal area (Aero), m^2	10	/	4
Reference length (Aero), mm	5000	/	7500
Tires	3500 kg rating, 538 mm radius	3000 kg rating, 510 mm radius	/
Dual Tires	Axle 2 and 3, 310 mm spacing	Axle 4, 5, 6, 310 mm spacing	/

2. Simulation process

Trial and error (T&E) method (Chu et al., 2018) was used to find out the critical rollover speed (CRS) and the critical braking distance (CBD). The vehicle run with a closed-loop shifting control at all gears. During the process hard brake was applied, the operation was defined as increasing the brake control pressure to 85 psi within 0.2 s, according to the U.S. Federal Motor Vehicle Safety Standards (FMVSS) 121 (Chen et al., 2022). The experimental procedure was designed as follows.

- Step 1: Repeatedly run the simulation vehicle with different, increasing initial speed from the start of the experimental road, and maintain the initial speed throughout this process. When the CRS is reached, the simulation process by TruckSim will be suddenly terminated because of inoperable vehicles. Record this speed and identify the section where rollover accidents occur (on tangent, transition, or on curve).
- Step 2: Repeatedly run the simulation vehicle with different, pre-given initial speed. At each speed, start at different, increasing initial starting location, and apply a hard brake operation immediately. Observe the relationship between the vehicle speed and driving distance. When the vehicle speed reaches the CRS exactly at the beginning point into the rollover section identified in Step 1, record this minimum safety distance for the corresponding initial speed as CBD.
- Step 3: Repeat Steps 1 and 2 on different lanes and alignments to produce simulation results for each experimental group.

3. Result & analysis

3.1. Effect of transition curve on the critical rollover speed

Table 5 reports the effects of the transition curve types (6% superelevation) on CRS. The four lanes are named from inside to outside by numbering 1 to 4. Higher CRS represents greater safety, since driving through the curve at any constant speed below this value will not cause a rollover.

Different type of transition curves did not cause significant change to CRS under superelevation of 6% and transition length of 120 m, as all CRS values reported in Table 5 were around 80~90 km/h. However, all the groups with the transition curve still showed an increase compared to the blank group. Bloss curve obtained higher CRS compared to the spiral curve (+0.67, +0.70, +0.63 and +1.49 km/h, from lane 1 to 4). Although the Grabowski curve had extremely small change compared to the Bloss curve, it also increased CRS values by some amount (+0.07, +0.08, +0 and +0.14 km/h, from lane 1 to 4). CRS increases more significantly as the radius increases (taking the Grabowski curve as example, 83.13, 84.77, 86.26 and 87.88 km/h, from lane 1 to 4); the lanes away from the centre line (Lane 1, Lane 4) are more affected by the type of the transition curve (+0.74, +0.78, +0.63 and +1.63 km/h, from lane 1 to 4, comparing the Grabowski curve and the spiral curve).

In addition, all of the rollovers occurred on the circular curve section, indicating that it was the most dangerous section for rollover accidents. In order to investigate whether the length of the transition section was the main factor limiting the increase of transition curve types on CRS, only the transition length was extended to 160 m without changing the maximum superelevation. The results are provided in Table 6.

Extension of transition length has different effects on the different transition types: CRS increases for the spiral curve, but decreases for the Bloss curve and the Grabowski curve. Moreover, extending the length of the transition section narrowed the gap between different types of

Table 5. Effect of transition curve types on the critical rollover speed (6% superelevation, L = 120 m)

Lane	Critical rollover speed, km/h			
	No transition	Spiral	Bloss	Grabowski
1	81.77	82.39	83.06	83.13
2	83.36	83.99	84.69	84.77
3	84.96	85.63	86.26	86.26
4	85.60	86.25	87.74	87.88

Note: *All rollovers occurred on the circular curve.

Table 6. Effect of transition section length on the critical rollover speed (6% superelevation, L = 160 m)

Lane	Critical rollover speed, km/h		
	Spiral	Bloss	Grabowski
1	82.60 (+0.21)	82.69 (–0.37)	82.71 (–0.42)
2	84.24 (+0.25)	84.33 (–0.36)	84.35 (–0.42)
3	85.90 (+0.27)	85.99 (–0.27)	86.01 (–0.25)
4	87.11 (+0.86)	87.25 (–0.49)	87.29 (–0.59)

Note: *All rollovers occurred on the circular curve. Values in parentheses are differences from the corresponding data in Table 5.

curves (+0.09, +0.09, +0.09 and +0.14 km/h from lane 1 to 4, comparing the spiral curve and the Bloss curve; +0.02, +0.02, +0.02 and +0.04 km/h from lane 1 to 4, comparing the Bloss curve and the Grabowski curve). The section where rollover remained unchanged proved that continuing steering was an important operational factor leading to vehicle rollover (Xu et al., 2022).

3.2. Effect of superelevation on the critical rollover speed

In the case of lifting extra superelevation, it is necessary to extend the runoff length to ensure smooth transition of the road lateral slope. For rural roads, superelevation value from 6% to 8% is recommended, so the experiment with a superelevation of 8% was conducted. The results are shown in Table 7.

Table 7. Effect of superelevation on the critical rollover speed (8% superelevation, *L* = 160 m)

Lane	Critical rollover speed, km/h		
	Spiral	Bloss	Grabowski
1	88.45 (+6.06)	88.56 (+5.50)	88.57 (+5.44)
2	82.16 (–1.83)	82.25 (–1.74)	82.27 (–2.50)
3	87.70 (+2.07)	87.78 (+1.52)	87.79 (+1.53)
4	89.24 (+2.99)	89.38 (+1.64)	89.45 (+1.57)

Note: *All rollovers occurred on the circular curve. Values in parentheses are differences from the corresponding data in Table 5.

Superelevation of an extra 2% obtained more significant increase in CRS than changes only in transition types and length. However, the gap between the different types remained almost unchanged (+0.11, +0.09, +0.08 and +0.14 km/h from lane 1 to 4, comparing the spiral curve and the Bloss curve; +0.01, +0.02, +0.01 and +0.07 km/h from lane 1 to 4, comparing the Bloss curve and the Grabowski curve). It is important to note that increased superelevation seems to have different effects on the inner lanes, as there is a greater increase in CRS for Lane 1, while for Lane 2 there is a decrease in CRS.

3.3. Effect of transition curve on the critical braking distance

According to the results discussed in Section 3.2, all the rollover accidents occur in the circular section after the transition curve. Since most wheels of the vehicles driving at their critical speeds into circular curve are always in the hazardous state of off-ground, using the specific location where rollover actually occurs as reference is not enough informative for practice. Therefore, the starting point of the circular curve was chosen as reference, which contains a certain safety margin, and relevant conclusions can contribute as uniformed reference while setting up safety measures in practice. The vehicle should be decelerated to below CRS before reaching it. Choosing 6% as superelevation, the CBD obtained by simulation steps 2 and 3 is shown in Table 8.

Critical braking distance is the minimum distance from the circular entrance that can be safely decelerated to the critical rollover speed. Therefore, the smaller the value, the better, indicating that it is safe to perform hard brake closer. As can be seen from Table 8, the experimental group of CBD presents the following characteristics:

1. The effect of different transition curve types on the critical CBD varies with the initial vehicle speed. At an initial speed of

Table 8. Effect of transition curve types on the critical braking distance (6% superelevation, L = 120 m)

Initial speed, km/h	Lane	Critical braking distance, m		
		Spiral	Bloss	Grabowski
90 km/h	1	24.12	23.32	23.24
	2	21.47	20.43	20.30
	3	18.58	17.40	17.39
	4	17.60	14.19*	14.38*
100 km/h	1	41.52	44.70	45.17
	2	39.10	41.48	41.85
	3	36.57	38.34	38.43
	4	43.67	52.52	57.25
110 km/h	1	60.74	66.82	67.46
	2	58.01	64.48	65.26
	3	55.92	63.48	64.64
	4	66.88	77.75	78.24
120 km/h	1	79.22	86.66	86.78
	2	76.76	84.27	84.35
	3	76.57	83.83	83.99
	4	87.87	97.03	96.74

Note: *The experimental group with this mark could not be reduced to the critical safe speed through braking as this would cause rollover. The values given are the minimum values to avoid rollover.

90 km/h, the spiral curve has the worst safety performance (24.12 m for Lane 1), followed by the Bloss curve, while the Grabowski curve is the best (23.32 and 23.24 m for Lanes 2 and 3). This trend turns opposite for 100 km/h (41.52 m, 44.70 m and 45.17 m for Lane 1, comparing the spiral, Bloss and Grabowski curves), 110 km/h (60.74 m, 66.82 m and 67.46 m for Lane 1, comparing the spiral, Bloss and Grabowski curves) and 120 km/h (79.22 m, 86.66 m and 86.78 m for Lane 1, comparing the spiral, Bloss and Grabowski curves).

2. The inside lane (Lanes 2 and 3) is generally less safe than the outside lane (Lanes 1 and 4), this trend is more pronounced at higher initial speed groups. For initial speeds of 100, 110 and 120 km/h, Lane 1 has shorter CBD than Lane 4, but Lane 2 has longer CBD than Lane 3. Since these comparisons are based on different target CRS and different starting positions, due to the different kinematic properties of the vehicles at different curvatures, they do not present a stable numeral pattern.

3.4. Effect of superelevation on the critical braking distance

Let us choose superelevation of 8%, length of the transition section of 160 m, and repeat the simulation experiment. The results are shown in Table 9.

Since the target critical rollover speed varies in different superelevation, even at the same initial speed and curve alignment, direct numerical comparisons are not made under equal road and vehicle conditions. Therefore, these comparisons only reflect a general safety performance provided by the road in the critical case. The contrast reflects the following characteristics:

1. Overall, increasing the superelevation would result in Lanes 1, 3, and 4 being safer and Lane 2 being more dangerous. This effect diminishes as initial speed increases, the superelevation group of 120 km/h gains the smallest change. Superelevation of 8% extends the pattern of decreasing CBD from the spiral curve to the Grabowski curve for different gentle curve groups from 90 km/h to 100 km/h (33.23 m, 33.10 m and 33.09 m for Lane 1, comparing the spiral, Bloss and Grabowski curves). Lane 2 still always have increasing CBD, different from other lanes.
2. Increase in superelevation makes the vehicle more unstable during braking process; thus, the results did not have a stable pattern. In Lane 4, for the 100 km/h group, the CBD value of the Bloss and Grabowski curves decreased tremendously compared to superelevation of 6 % (−21.96 m, −26.76 m), a magnitude that

was significantly different from all other experimental groups; In Lane 2, for the110 km/h group, the CBD value of the Bloss and Grabowski curves decreased compared to superelevation of 6% (−0.33 m and −0.16 m), but it increased in all other groups. Lane 4 in the 120 km/h group becomes more dangerous as the superelevation increases (+8.63 m, +0.72 m and +1.52 m compared to superlevation of 6%), which is different from the pattern of the other speed groups. At a speed of 120 km/h, Lane 1, CBD for the Bloss curve is closer to the spiral line (75.87 m, 75.95 m and 87.65 m for superelevation of 8%, compared to 79.22 m, 86.66 m and 86.78 m for superelevation of 6%). Changing results proved that hard braking under changing road conditions was always a dangerous situation for vehicles (Liu et al., 2020).

Table 9. Effect of superelevation on the critical braking distance (8% superelevation, L = 160 m)

Initial speed, km/h	Lane	Critical braking distance, m		
		Spiral	Bloss	Grabowski
90 km/h	1	13.22(−10.90)	12.93(−10.39)	12.89(−10.35)
	2	24.28(+2.81)	24.16(+3.73)	24.13(+3.83)
	3	14.51(−4.07)	14.33(−3.07)	14.30(−3.09)
	4	9.71(−7.89)	9.06	8.72
100 km/h	1	33.23(−8.29)	33.10(−11.6)	33.09(−12.08)
	2	42.69(+3.59)	43.26(+1.78)	43.49(+1.64)
	3	33.49(−3.08)	33.39(−4.95)	33.38(−5.05)
	4	30.70(−12.97)	30.56(−21.96)	30.49(−26.76)
110 km/h	1	52.31(−8.13)	53.80(−13.02)	54.25(−13.21)
	2	62.97(+4.96)	64.15(−0.33)	65.10(−0.16)
	3	54.03(−1.89)	54.75(−8.73)	55.10(−9.54)
	4	63.68(−3.20)	67.48(−10.27)	69.01(−9.23)
120 km/h	1	75.87(−3.35)	75.95(−10.71)	87.65(+0.87)
	2	83.67(+6.91)	85.84(+1.43)	87.14(+2.79)
	3	75.37(−1.20)	76.86(−6.97)	78.61(−5.38)
	4	96.50(+8.63)	97.75(+0.72)	98.26(+1.52)

Note: *Values in parentheses are differences from the corresponding data in Table 8.

Conclusions

The study investigated the effects of transition curve and superelevation on the rollover behaviour of vehicles on sharp curves. With the design method of transition section being determined, variables in the experiment were limited to the type of transition curve and superelevation value. Then, via a large number of experiments of constant speed driving and hard braking, conclusions regarding the influence of these road design factors on the stability of vehicles during driving and braking along sharp curves were proposed. Based on these findings, a number of useful recommendations for drivers and road designers were put forward.

In this experiment, two observation variables were chosen as the evaluation indices: one was the maximum speed that did not lead to rollover in the sharp curve when driving at a constant speed, which was called a critical rollover speed (CRS). The other was the nearest distance that the vehicle could be decelerated to CRS at the entrance of the dangerous section in hard brake condition, called a critical braking distance (CBD).

Constant speed experiments demonstrated that setting a transition curve or choosing an optimized transition type could improve the CRS value. However, the change rate in CRS values caused by transition types was slight. With superelevation unchanged, the length of the transition section (resulting in gentle change of superelevation and curvature, also in accordance with the regulation) was extended and experiments were performed again, but it was found that for given superelevation, only lengthening the transition section could not significantly increase the value of CRS.

Next, superelevation was raised to 8% and the experiment was repeated. Results in Section 3.2 confirmed that within reasonable range, raising superelevation led to greater CRS changes than changing transition types, but the trend varied; Lane 2 decreased CRS, while other lanes increased. The CRS gap between different transition types did not change significantly, proving that a positive effect by the increase of superelevation was independent of the positive effect by optimizing transition types, the latter only related to the section length. Regardless of the alignment and slope, rollovers always happened on circular sections.

The safety pattern varied significantly in the experiments of hard braking. CBD values of the lanes near the edges (Lanes 1 and 4) were significantly greater than the lanes near the centre (Lanes 2 and 3); however, after raising the value of the superelevation, CBD characteristics of Lanes 1 and 2 completely reversed. The comparative safety relationship between different transition curve types also reverses as the initial speed increases. Another manifestation of this phenomenon is the inability to accurately generalize the pattern of CBD (for example, the case of not being able to decelerate just to the critical safe speed occurring in Table 8; or a variety of scenarios occurring after superelevation variations given in Section 3.4, Result 2, including abrupt changes in the CBD and changes in the characteristics of the CBD at a speeding situation).

The experiment provides useful suggestions for drivers and road designers. The primary recommendation is for truck drivers to avoid braking operations as much as possible, especially at high speeds, on sharp curves. Even if there is a transition curve, the most important safe driving advice is to slow down to a safe range before entering it. The uncertainties above indicate that the braking behaviour of vehicles on changing road conditions is extremely risky. When braking on the transition section, the curvature of the curve, target speed (CRS) of braking, and the changing state of the cross slope at different locations are all variables of driving safety. Even if the vehicle followed a uniform braking operation, different speed curves would be produced, leading to the change of vehicle stability in a varied and unpredictable manner.

For road designers, the study demonstrated the necessity of transition curve, and the importance of using transition types with more gentle lateral acceleration changes (the Bloss or Grabowski curves) in the alignment selection. These options increased the CRS of the vehicle, making safe the action of driving through the sharp curve over a wider range of speed. Increasing the superelevation appropriately can also increase the driving safety. However, braking on transition sections is also one of the driving strategies often implemented when travelling through a sharp curve. As part of CBD patterns is in complete conflict with CRS, the safety of the braking vehicle cannot be improved in a synchronized manner by simply increasing the superelevation or choosing different transition types. Therefore, when setting transition curves, it is important to prevent speeding vehicles from entering the transition without sufficient deceleration after tangents. The most appropriate measure is to place warning signs and deceleration facilities at a sufficient distance before entering the curve, eliminating the occurrence of the situation where drivers need to perform hard brake as much as possible. More effective safety measures should be implemented inside the curve to allow the vehicle to slow down without continuous steering, e.g., by installing an emergency evacuation lane along the tangent direction of the circular curve.

Further quantitative aspects of the variables were not explored, e.g., the position of the rotation axis during superelevation lifting or the usage of different braking modes. In the subsequent study, this idea will be extended, such as by comparing different truck types to investigate the additional effect of a trailer on truck rollover. Moreover, different friction coefficients may be set to study other safety issues of the vehicle via other observed parameters, such as sideslip.

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