International Journal of Civil Engineering

Transportation

Safety evaluation of highway geometric design criteria in horizontal curves at downgrades

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Received: February 2013, Revised: July 2013, Accepted: January 2014

Abstract

Previous studies have demonstrated that, a high percentage of traffic accidents take place in two-lane rural highways and most of them happen at horizontal curves. Meanwhile, due to economic aspects, when horizontal alignment is subjected to hard topographic conditions, designers are forced to design horizontal curves at grades and this make situation worse. Vertical angle of longitudinal slope reduces the normal force of vehicle (as a mass point) on the road, which consequently, will decrease the friction force in tire-pavement surface. This will lead to lack of sufficient driver's control over the vehicle, especially if the sharp curve is located at downgrade.

In this paper, the suitability of both operating speed and lateral friction coefficient as geometric design criteria for horizontal curves at downgrades are studied with regard to traffic safety and vehicle stability. The analysis of speed reduction of the vehicles, running on a horizontal curve at downgrades (as a response of driver's behavior), together with the use of friction ellipse theory, gives the available friction coefficient. While the dynamic analysis of forces applied on the vehicle in curve located at downgrade combined with operating speed, results in required coefficient of lateral friction. Finally, a comparison of the previous two parameters gives an estimation of actual safety level in designing horizontal curve at downgrades with regard to AASHTO's data in horizontal curve design.

Keywords: *Horizontal curve, Downgrade, Geometric design criteria, Design safety level.*

1. Introduction

Every year more than 1.2 million people are being killed by traffic accidents throughout the world, from which 70 percent happens in developing countries. Highway curves, affecting the traffic safety strongly, are one of the most important design elements in Highway alignment. The design of curves requires more attention and care since an alignment which is not in accordance with driver's expectations results in less safety for the vehicles. An inconsistent design gives more stress to the drivers and forces them to improper driving maneuver thet can lead eventually to sever traffic accidents.

To achieve a driver expectation oriented alignment design, in highway engineering, a new design speed concept has been developed that match the actual driver's behavior better, commonly known as the operating speed.

Normally, the basic equation of motion for a running vehicle on a curve is based on an assumption that the alignment is completely horizontal, whereas sections in downgrade cause the drivers not to adopt themselves on time to the complex situation before the curve entrance and to exceed the safe speed. Safety evaluation of geometric design is essential to determine the attainable safety level for the curve design under all possible conditions.

The purpose of this research is to define the accessible safety level of vehicle motion in horizontal curves at downgrades (which are designed based on AASHTO's data) prior to the construction and operation of the road, when the combination of alignment horizontal plan and its project line make the safety situation more critical. In this way, for achieving the more realistic results, some factors such as the behavior of driver and the dynamic motion of vehicle will be used in the procedure of safety evaluation.

1.1. The concept of design speed

The concept of design speed defines as a speed used to design the different geometric design elements of road including alignments [1]. But there are also some critiques as follows:

- The actual speeds to enter and to exit the curve section are not considered explicitly.
- Provided that, the tangent section before the curve

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(apart from the transition curve) is long enough and downgraded, the speed of the vehicle at the end of the tangent section and the beginning of the following curve section can possibly exceed the design speed[2].

- The current design guides include different tables for each maximum super-elevation (associated with respective weather conditions) to determine the minimum curve radii. For a certain design speed and super-elevation, each table gives a different curve radius, causing different required lateral friction coefficients for the same situation!

In contrast with the current design speed concept, there is a consensus about the definition of operating speed, i.e. the speed that 85% of drivers choose reflecting the geometrical and environmental limits of the road [2]. The most important factor influencing the operating speed is the curve radius. There is also a reverse relationship between operating speed and curvature. Hence, for many researchers, the curvature is the best parameter for prediction of the operating speed.

1.2. The Friction coefficient of pavement

The skid resistance of the pavement is one of the most important factors for road safety evaluation. 95 percent of the vehicle's rolling over in horizontal curves are because of the lack of skid resistance [3]. In curves, this factor is used to keep the vehicle in balance as a proactive measure against rollover. The problem at horizontal curves arises where the need for the lateral friction is high. Therefore, the available friction coefficient should be always higher than or equal to the required one to ensure the vehicle stability. Meanwhile, the understanding of vehicle/tire-pavement interaction at their interface has a great importance for the designers.

The friction ellipse theory is based on the fact that sum of the two combined forces, i.e. lateral and longitudinal friction, remains constant (circle) or near constant (ellipse) [4-6].

1.3. Human factors

Many human characteristics are out of control. Nevertheless, some of the drivers' behaviors interacting with road factors are predictable and can be included in design process. In this paper, three of them are considered: operating speed, deceleration distance and the driver perception of design elements.

In case that a curve section follows a tangent section, the driver work load increases in order to adopt his/her speed to enter the new section safely. Statistics show that the speed reduction begins just before the curve entrance and extends up to the middle of the horizontal curve. Studies indicate that by finishing the tangent and entering the curve, drivers tend to keep their speed. This course of action makes a part of the speed reduction process to fall into the curve section [2], [7]. It means that, in this situation, drivers have to make use of both longitudinal and lateral friction to adopt their speed to the road curvature. And subsequently, the condition becomes increasingly critical due to the limitations regarding the maximum coefficient between the tire and pavement surfaces.

In all operating speed models, there is a linear relationship between the operating speed and the horizontal curvature. This accentuates the fact that drivers have a high perception of the horizontal curves so that a small increase in curve radius causes the selected speed to increase considerably [8]. In contrast, the actual friction coefficient has a negligible effect on the drivers' behaviors. In fact, the drivers' perception of road friction can only affected by their perception of the environmental and weather conditions [9].

1.4. Safety evaluation criteria

In general, there are some criteria which can be used to evaluate the geometric design consistency. These criteria are operating speed, vehicle stability, driver work load, and alignment indices. Lamm et al. (1999) and Lamm and Wolhuter (2001) have proposed triple criteria for evaluation of safety and geometric design consistency which address the safety status and are highly adaptable to the accident situations [10], [11]. These criteria are based on the type of speed change. The amount of required lateral friction is developed especially for two-lane rural roads where 50 to 60 percent of heavy accidents in US and Europe happen. They promote the traffic safety considering 3 stability notions namely stability in design (criterion I), stability in operating speed (criterion II) and stability in driving dynamics (criterion III).

In this study, criterion III is used for safety evaluation of AASHTO's data in designing horizontal curve. Criterion III relates to the difference between the available friction coefficient (f_R) and the required one (f_{RD}). If the difference of these two parameters is bigger than 0.01 ($f_R - f_{RD} \geq 0.01$), the safety level of geometric design will be "good". Else if this difference is between -0.04 and 0.01 ($-0.04 \leq f_R - f_{RD} < 0.01$), the safety level will be "fair" and finally if the difference is less than -0.04 the safety level of geometric design will be "poor" [10], [11].

2. Past Research

Based on the data collected from two-lane rural highways in different countries, Lamm and Wolhuter have established some relationships between geometric design parameters, especially to the operating speed, and have also came up with new geometric design criteria [11].

Fitzpatrick et al. have investigated the relationship between design speed, posted speed and the operating speed [8].These specialist have proposed a geometric design approach which includes a reverse cyclic process to obtain a better adjustment between operation speed and design speed.

Hong and Oguchi have tried to include driver perception into geometric design [12].They believe that in highway geometric design, the operating speed must be taken into account. In this context, they propose an approach relying on reverse computation. By estimating the actual operating speed, the alignment elements such as horizontal curve radii and grades could be evaluated based on speed surveys.

Minimizing the difference between the operating speeds of successive sections has been emphasized by Park and Saccomannoand Arizona DOT (2005) separately [13], [14].The operating speed and its relation to design speed have also been noted here as one of the most important factors affecting the traffic safety in roads.

Charlton and Depont from Land Transport New Zealand, have investigated operating speed before and after horizontal curves. Their analysis shows that in the last part of tangent section, decrease in speed not only occurs but also extends even up to the middle part of the curve itself [7]. This issue has also been approved by Fitzpatrick et al. and based on the data they have collected, operating speed and deceleration rate models have been established [2].

Correlations made between longitudinal and lateral friction, go back to the friction ellipse theory proposed by Radt and Milliken [4]. This theory has been used since then by so many authors to present some characteristics of tire-pavement interactions [5], [6]. This concept is of great importance for curve geometric design, especially when the driver is braking and the lateral friction coefficient is under its impact.

3. Current Practice and Shortcomings

The basic equation of AASHTO in designing horizontal curves is the result of dynamic analysis of vehicles driving on curves with no longitudinal slope. Any reduction of friction coefficient or normal force in the tire-pavement interface has an effect on lateral friction force development. Therefore, the effect of longitudinal slope on normal force is very important. In addition, the operating speed, especially on curves, depends strongly on drivers' behavior. Accordingly the difference between design speed and operating speed should also be considered in safety evaluation. Another important factor related to friction is the dependability of longitudinal and lateral friction on tire-pavement interface. This is also affected by the manner of speed reduction and the art of the drivers' braking. Using friction ellipse theory combined with deceleration model, the available lateral friction coefficient is attainable.

3.1. Experimental procedure

The survey of speed reduction of the vehicles running on a horizontal curve at downgrade as a response of driver's behavior and through application of friction ellipse theory, gives the existing available friction coefficient. Furthermore, the required coefficient of lateral friction would be determined by combination of dynamic analysis of forces applied on the vehicle in curves and operating speed.

This study focuses on the stability of vehicle driving on horizontal curves at downgrades. In order to do so, criterion III is used for safety evaluation. Fig. 1 shows the proposed safety evaluation including three analyses described further below.

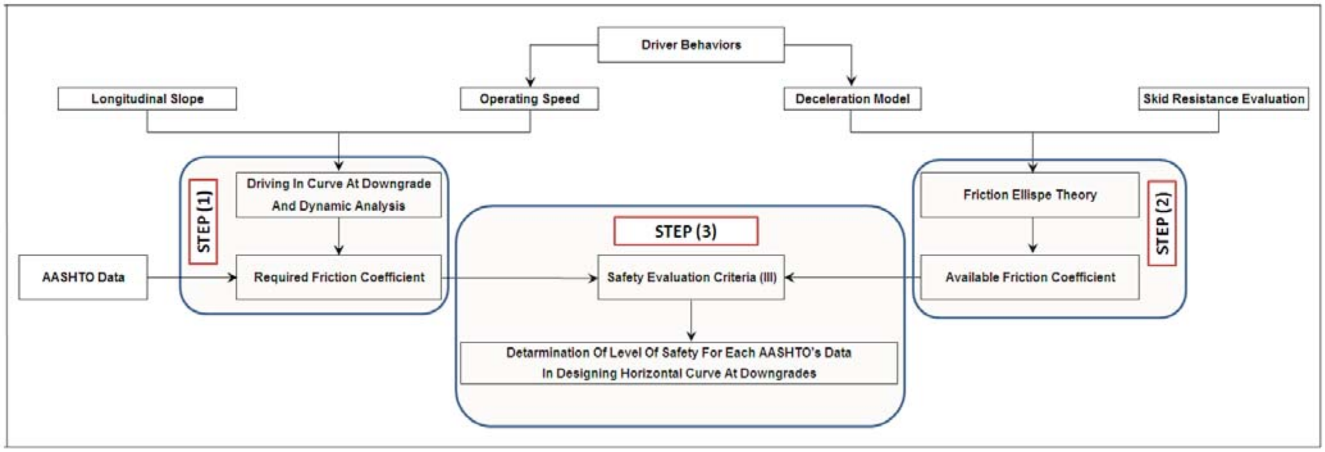


Fig. 1 The safety evaluation process

3.2. Data analysis

AASHTO has provided some information related to curve radius for designing horizontal curves for rural highways based on different maximum super-elevations in 4 tables [1]. Every table provides the horizontal curve radius using Equation (1) considering lateral slope used and selected design speed:

$$R = \frac{V^2}{127.2(e+f)} \quad (1)$$

The data analysis for safety evaluation occurs after the following three steps:

Step (1):

In order to have more realistic model of vehicle motion on horizontal curves located on longitudinal slopes, it is necessary to consider the operating speed and longitudinal slope in horizontal curve design. The lateral friction coefficient actually reflects the friction needed to ensure the driving stability of the vehicle in the situation under study.

Minimum safety radius of horizontal curve, which is located at downgrade, can be determined by using Equation (2) [15]:

$$R = \frac{V^2}{127.2\cos\theta(e+f)} \tag{2}$$

Based on Fitzpatrick's study, the operating speed model for horizontal curves at downgrades is used in the current study as follows [2]:

$$V_{85} = 105.98 - \frac{3709.9}{R}, -4\% \leq Grade < 0\% \tag{3}$$

$$V_{85} = 102.10 - \frac{3777.13}{R}, -9\% \leq Grade < -4\% \tag{4}$$

Replacing V_{85} in Equation(2) and solving it after f_{RD}, the required lateral friction coefficient attained is as follows:

$$f_{RD} = f_{required} = \frac{V_{85}^2}{127.2(\cos\theta)R} - e \tag{5}$$

Step (2):

By using model related to maximum lateral and longitudinal friction coefficients which is known as "friction ellipse theory", the available lateral friction coefficient will be determined in regard with deceleration rate at horizontal curve entrance using Equation(8).(See Fig. 2).

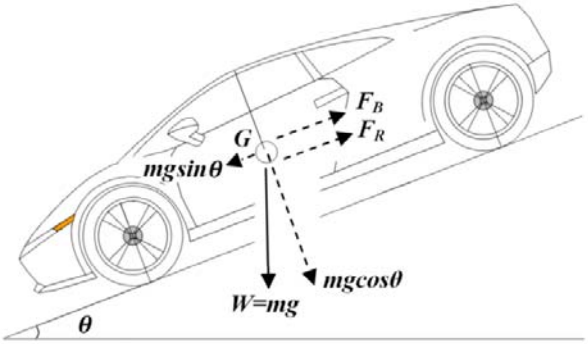


Fig. 2 Forces acting on a braking vehicle

In Equation(6) "a" is the deceleration rate as follows:

$$\begin{aligned} &\sum F_x = mg\sin\theta - (F_R + F_B) = ma \\ &\rightarrow mg\sin\theta - mg\cos\theta\mu_{Total} = ma \\ &\rightarrow \mu_{Total} = \frac{g\sin\theta - a}{g\cos\theta} \end{aligned} \tag{6}$$

Fitzpatrick et al. (2000) has presented deceleration model at horizontal curve entrance as follows [2]:

$$aeceleration(m/s2) \begin{cases} -1, R \leq 175 \\ = 0.6794 - \dfrac{295.14}{R}, 175 < R < 436 \\ 0, R \geq 436 \end{cases} \tag{7}$$

Substituting "a" from Equation (7) into Equation (6), the available longitudinal friction coefficient would be calculated:

$$f_x = \mu_{Total} = \begin{cases} \dfrac{g\sin\theta + 1}{g\cos\theta}, R \leq 175 \\ \dfrac{(g\sin\theta - 0.6794 + \dfrac{295.14}{R})}{g\cos\theta}, \quad 175 < R < 175 \\ \tan\theta, R \geq 436 \end{cases} \tag{8}$$

Finally, based on the friction ellipse theory, the available lateral friction coefficient would be calculated using Equation (9) as follows [4], [5], [6], [10]:

$$\begin{aligned} &\left(\frac{f_y}{f_{y\max}}\right)^2 + \left(\frac{f_x}{f_{x\max}}\right)^2 \leq 1 \\ &f_R = f_y \leq f_{y\max}\sqrt{1 - \left(\frac{f_x}{f_{x\max}}\right)^2} \end{aligned} \tag{9}$$

Where:

f_y: available friction factor in the radial (side) direction

f_x: available friction factor in the tangential (longitudinal) direction

f_{xmax}: maximum (permissible) friction factor in tangential (longitudinal) direction

f_{ymax}: maximum (permissible) friction factor in radial (side) direction

Maximum lateral and longitudinal friction coefficients are proposed by Lamm et al. in 1999 [10]. (Eq.10 and Eq. 11).

$$f_{xm} = 0.59 - 4.85\times10^{-3}\times V_d + 1.51\times10^{-5}\times(V_d)^2 \tag{10}$$

$$f_{ym} = 0.27 - 2.19\times10^{-3}\times V_d + 5.79\times10^{-6}\times(V_d)^2 \tag{11}$$

Step (3):

The safety evaluation can be determined by comparing required and available lateral friction coefficient based on criterion III.

The safety evaluation of the data is carried out for two different longitudinal slopes minus two and minus six percent and for AASHTO's data in designing horizontal curves. The selection of these specific slops mentioned above is only due to the high volume of data. In spite of the fact that we only used the above two longitudinal slopes, the analysis is also possible for the slopes ranging from -9 to 0 percent (Table 1). Consequently, the result of safety evaluation can be imparted for all the presented data by AASHTO in designing horizontal curve, which are based on choosing different design speed and super-elevation. As shown in Fig. 3, the computed amounts for required and available friction coefficient on the tire-pavement interface are used together with safety evaluation criteria to study the suitability of data considered for designing horizontal curves at downgrades with different radii and slopes (Table 2).

Table 1 Difference between available and required lateral friction coefficient for a -6% longitudinal slope and a maximum super-elevation of 6% (summarized)

V(km/h)	60				80				120		
		Radial Friction				Radial Friction				Radial Friction	
e(%)	R(m)	Available	Required		R(m)	Available	Required		R(m)	Available	Required
		Radial -f-	Radial -f-			Radial -f-	Radial -f-			Radial -f-	Radial -f-
1.5	1440	0.1571	0.0397		2360	0.1292	0.0189		4770	0.0873	0.0020
2	1030	0.1571	0.0551		1710	0.1292	0.0263		3510	0.0873	0.0030
2.2	919	0.1571	0.0616		1530	0.1292	0.0296		3160	0.0873	0.0035
2.4	825	0.1571	0.0684		1380	0.1292	0.0329		2870	0.0873	0.0040
				…		⋮					
2.6	746	0.1571	0.0753		1260	0.1292	0.0361		2630	0.0873	0.0045
5.4	195	0.1454	0.2469		386	0.1283	0.1268		1060	0.0873	0.0191
5.6	176	0.1417	0.2644		351	0.1275	0.1395	…	980	0.0873	0.0227
5.8	156	0.1417	0.2846		**315**	**0.1262**	**0.1551**		900	0.0873	0.0272
6	123	0.1417	0.3205		252	0.1225	0.1925		756	0.0873	0.0401

AASHTO's Data: V= 80 km/hr, R=315, e =5.8

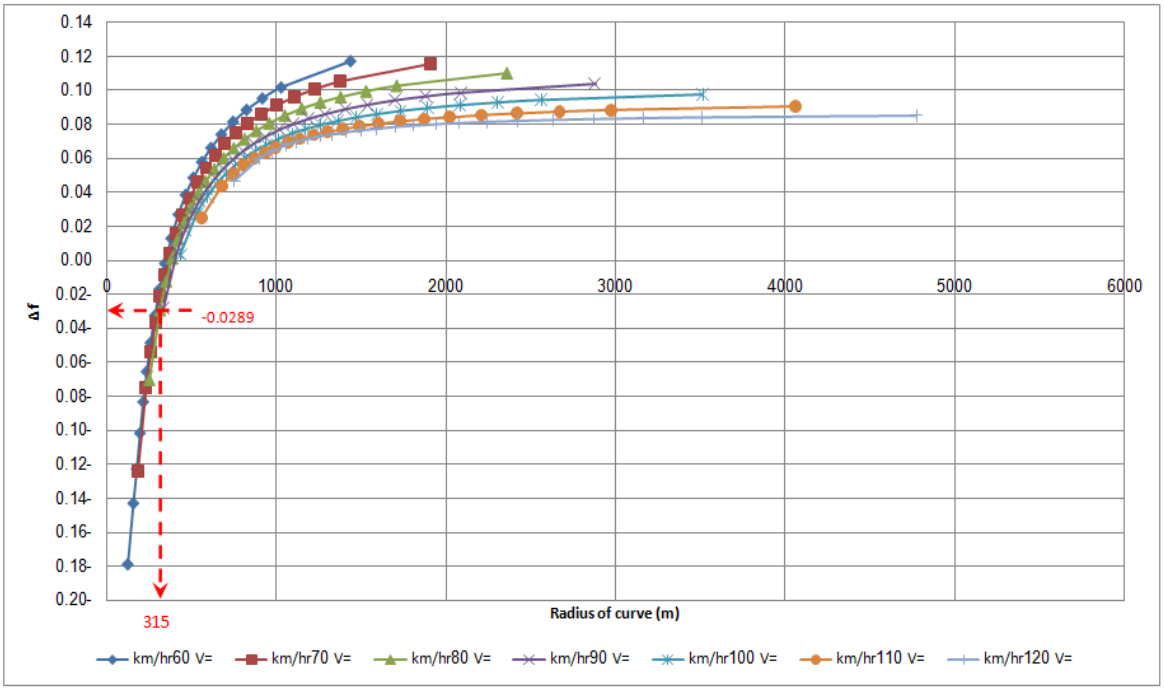
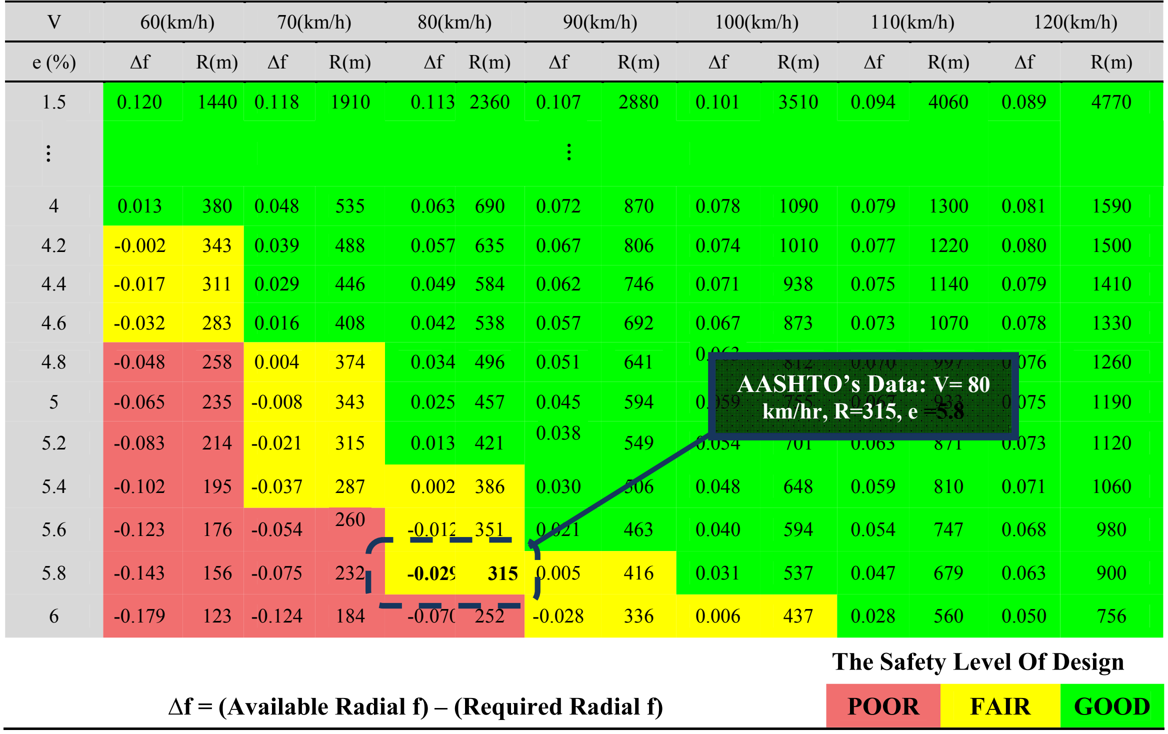


Fig. 3 Difference between available and required lateral friction coefficient for -6% longitudinal slope and maximum super-elevation of 6%

Table 2 Safety Evaluation of AASHTO Data for a -6% longitudinal slope and a maximum super-elevation of 6% (summarized)



V	60(km/h)		70(km/h)		80(km/h)		90(km/h)		100(km/h)		110(km/h)		120(km/h)	
e (%)	Δf	R(m)	Δf	R(m)	Δf	R(m)	Δf	R(m)	Δf	R(m)	Δf	R(m)	Δf	R(m)
1.5	0.120	1440	0.118	1910	0.113	2360	0.107	2880	0.101	3510	0.094	4060	0.089	4770
⋮							⋮							
4	0.013	380	0.048	535	0.063	690	0.072	870	0.078	1090	0.079	1300	0.081	1590
4.2	-0.002	343	0.039	488	0.057	635	0.067	806	0.074	1010	0.077	1220	0.080	1500
4.4	-0.017	311	0.029	446	0.049	584	0.062	746	0.071	938	0.075	1140	0.079	1410
4.6	-0.032	283	0.016	408	0.042	538	0.057	692	0.067	873	0.073	1070	0.078	1330
4.8	-0.048	258	0.004	374	0.034	496	0.051	641	0.063	812	0.070	997	0.076	1260
5	-0.065	235	-0.008	343	0.025	457	0.045	594	0.059	755	0.067	933	0.075	1190
5.2	-0.083	214	-0.021	315	0.013	421	0.038	549	0.054	701	0.063	871	0.073	1120
5.4	-0.102	195	-0.037	287	0.002	386	0.030	506	0.048	648	0.059	810	0.071	1060
5.6	-0.123	176	-0.054	260	-0.012	351	0.021	463	0.040	594	0.054	747	0.068	980
5.8	-0.143	156	-0.075	232	**-0.029**	**315**	0.005	416	0.031	537	0.047	679	0.063	900
6	-0.179	123	-0.124	184	-0.070	252	-0.028	336	0.006	437	0.028	560	0.050	756

The Safety Level Of Design

Δf = (Available Radial f) – (Required Radial f)

POOR	FAIR	GOOD

4. Conclusions

Previous studies in the field of correlation between accident rate and radius of curves, have revealed that by decreasing radii specially less than 250 m, accident rate significantly will increase. In this situation, the kind of combination of plan and project line is the cause of this problem. Moreover, considering the human behavior related factors such as operating speed and deceleration rate, give more complication.

This paper is an effort to determine the reasons of this problem. The results of the safety evaluation of AASHTO's data in designing horizontal curves at downgrade (2 & 6 percent), confirmed the previous studies and show that for radii less than 250 m, design's safety falls in poor level. In this study, required lateral friction coefficient in curve design and available lateral friction coefficient are presented for all of the AASHTO's data in curve designing in the situation under study.Results show that the super-elevation rates which are used in current practice cannot prepare adequate safety level.

By using safety evaluation criteria and the above mentioned parameters, the designer will be able to predict the safety level of alignment prior to the construction and operation of the road. Moreover, if the safety evaluation shows poor or fair level, for increasing safety level it would be possible to choose suitable super-elevation or desired radii.

This selection, become more complicated with respect to economical, technical and environmental aspects and it will be subject of future researches.

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