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Assessment of horizontal curves of an existing road using reliability concepts

Tomás Echaveguren, Marcelo Bustos, and Hernán de Solminihac

Abstract: Horizontal curves on road are commonly analyzed under design speed point of view, where it is assumed that the maximum speed of a vehicle in a curve is the design speed. The empirical evidence has demonstrated that when the design speed is low, the operating speed tends to be higher. This happens because of an available remaining lateral (or transverse) friction for speeds over design speed. This condition is determined by a speed limit, obtained from the demand and supply equilibrium of friction of a pavement. The difference between operating and design speeds is usually considered as the margin of safety of a horizontal curve on a road. In this study, a methodology to determine the margin of safety of an existing curve is proposed. The methodology is based on the reliability theory by which reliability of operational conditions can be analyzed by using a reliability index as a margin of safety. A case study for light vehicles is evaluated to determine high impact variables over reliability, such as, macrotexture, skid resistance, curve radius, and superelevation. The results obtained in this study demonstrated that curve radius, skid resistance, and macrotexture are variables with high impact over failure probability. In contrast, superelevation has little effect on the failure probability.

Key words: reliability, horizontal curves, operating speed, skid resistance, pavement texture.

Résumé : Les courbes de tracé en plan sont fréquemment analysées du point de vue de la vitesse de base, alors qu'il est présumé que la vitesse maximale d'un véhicule dans une courbe est la vitesse de base. L'évidence empirique a démontré que lorsque la vitesse de base est faible, la vitesse maximale réalisable tend à être plus élevée. Cela survient en raison d'un frottement latéral (ou transversal) restant pour les vitesses dépassant la vitesse de base jusqu'à une condition limite. La différence entre la vitesse maximale réalisable et la vitesse de base est normalement considérée comme la marge de sécurité d'une courbe de tracé en plan. Dans cette étude, une méthode de déterminer la marge de sécurité d'une courbe existante est proposée. La méthode est basée sur la théorie de la fiabilité par laquelle la fiabilité dans les conditions opérationnelles peut être analysée par un indice de fiabilité servant de marge de sécurité. Un cas d'étude pour des véhicules légers est évalué afin de déterminer les variables ayant un grand impact sur la fiabilité : la macrotexture, l'antidérapance, le rayon de la courbe et la surélévation. Les résultats obtenus dans cette étude ont démontré que le rayon de courbure, la résistance au glissement et la macrotexture sont des variables qui ont un grand impact sur la probabilité de défaillance. À l'opposé, la surélévation a peu d'influence sur la probabilité de défaillance.

Mots clés : fiabilité, courbe de tracé en plan, vitesse maximale réalisable, antidérapance, texture de la chaussée.

[Traduit par la Rédaction]

Introduction

Horizontal curves are commonly analyzed under design speed concept. Design speed is defined as the maximum safe speed that a vehicle can reach according to the prevailing geometrical conditions of a road or a highway (AASHTO 2001). Under this principle, a positive margin of safety will exist given by the difference between the design and operating speeds.

However, studies carried out in Australia showed that in highways with speed design lower than 90 km/h, the operating speed is higher than design speed (McLean 1983). Similar results were obtained by Lamm et al. (1990) in the United States for design speed of 100 km/h. In Chile, Echaveguren and Saez (2001) observed the same phenomena for design speeds of 100 km/h.

From the empirical evidence presented in McLean's study (McLean 1983), it can be stated that a remaining friction is available, which lets speed of vehicles in horizontal curves to be higher than the design speed with no loss of stability.

Consequently, for low design speeds, the maximum safe speed in a horizontal curve is not necessarily given by design speed. In this case, margin of safety will be given by the maximum speed that a vehicle can reach before losing stability.

Morrall and Talarico (1993) calculated the margin of safety of a horizontal curve, as the difference between the design speed and the speed limit. The latter was estimated from the equilibrium between the friction demand and the design friction.

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The speed limit obtained through this procedure is lower than the one obtained by using pavement friction instead of design friction. This is because design friction is usually lower than the one provided by the pavement, and therefore equilibrium condition tends to move to the left in a friction–speed plane.

Likewise, the method proposed by Morrall and Talarico (1993) considered design speed as the only indicator of driver's behavior, and therefore, their method does not agree with the phenomena described by McLean (1983), Lamm et al. (1990), and Echaveguren and Sáez (2001). Because of this limitation, it is necessary to include the operating vehicle speed in the analysis.

However, friction provided by a pavement is a random variable, so speed limit has to be random as well. As operating speed is also a random variable, it is not possible to consider the simple difference between the speed limit and operating speed in calculating the margins of safety. In this case, the problem has to be solved by a probabilistic approach using a reliability index to describe the operational behavior of the horizontal curve. This index is associated to the probability of an operating speed higher than a speed limit, describing the random nature of variables compounding it.

Objectives and scope

The objective of this paper is to propose a methodology for the evaluation of margin of safety in the existing horizontal curves on a road.

The proposed methodology applies McLean's conclusion (McLean 1983), as it enables the numerical estimation of speed limit and the associated margin of safety.

The methodology is applied to analyze existing horizontal curves on a road whose geometry and pavement surface conditions are known. Under these conditions, radius and superelevation are deterministic, while skid resistance and texture are probabilistic.

In this work, the new elements were included in the analysis of horizontal curves: driver's behavior by means of operating speed, pavement surface condition through available friction, and the probabilistic nature of the problem by using a reliability index to estimate the margin of safety.

Research methodology

The research methodology involves the analysis of conceptual elements to be included in the proposed methodology for the estimation of a margin of safety, formulation, and application of the methodology to a case study. This research consists of three parts. The first part discusses the theoretical background that sustains the proposed methodology by considering dynamic stability, operating speed, friction demand and supply, reliability index, and failure probability. The second part describes the calculation procedure to determine the margin of safety by taking into account the estimation of the speed limit and operating speed to finally calculate the margin of safety and failure probability. Then, the third part presents a case study applied to a road in the south of Chile. This considers a practical application of the proposed methodology and the discussion of different strategies for the improvement of margin of safety on existing horizontal curves.

Theoretical background

The conceptual topics, proposing the methodology for the estimation of a margin of safety, proposed by previous researchers need to be studied in detail. The main concepts analyzed are dynamic stability, operating speed, friction demand and supply, and reliability.

Dynamic stability in horizontal curves

The traditional model of dynamic stability in horizontal curves, known as point mass model (PMM), is based on the equilibrium of a point mass, which is displaced along a curve trajectory (Gillespie 1992). This model relates radius of curvature (R), superelevation (p), coefficient of friction (f), and vehicle speed (S) to estimate the dynamic equilibrium of a mass point. The combined effect of friction and superelevation provide the centripetal acceleration that maintains the particle on the curve trajectory and prevents it from leaving trajectory of the curve. Both effects define the condition of dynamic equilibrium, and therefore, a non-failure condition. From AASHTO (2001), the point-mass formula for a vehicle riding on a curve is as follows:

$$[1] \quad R = \frac{S^2}{g(p + f)}$$

where g is the acceleration due to gravity.

Equation [1] is the simplest expression of the PMM. There are other models for a more accurate estimation of dynamic stability, which incorporates the effect of mechanical suspension of a vehicle and the position of its centre of gravity based on the PMM. Chang (2001) developed a model that incorporates vehicle suspension to the PMM, as presented in eq. [2].

$$[2] \quad R = \frac{S^2}{k_1(k_2p + f)}$$

where radius, R , is expressed in metres and vehicle speed, S , in kilometres per hour, and k_1 and k_2 are parameters that consider the effect of mechanical suspension of light and heavy vehicles, respectively. Following Gillespie's (1992) recommendations, Chang proposed $k_1 = 121$ and $k_2 = 0.5$ (for light vehicles), and $k_1 = 122.5$ and $k_2 = 0.75$ (for heavy vehicles).

The PMM and Chang's model have some limitations, as they do not consider the interaction in the tire–pavement contact surface, the friction on each tire, and mass distribution within the real volume of a vehicle. Despite this, Chang's model is more realistic than PMM, as it considers the difference between vehicle suspension systems of light and heavy vehicles. This establishes a clear difference between the dynamic stability of light and heavy vehicles.

Friction demand and friction supply

Friction demand is defined as the friction required by a vehicle to maintain its trajectory in an existing horizontal curve (MOP 2002). Friction demand curve [$f_d(S, R, p)$] may be obtained from eq. [2]. The resulting expression is

$$[3] \quad f_d(S, R, P) = \frac{S^2}{k_1 R} - k_2 p$$

Equation [3] shows that for a given radius and superelevation, the friction demand increases as the speed rises. In existing horizontal curves, p and R are known and considered as constants.

Friction supply depends on tire–pavement interaction and vehicle speed (Kulakowski 1991). It decreases as speed increases exponentially influenced by macrotexture of the pavement surface (Corsello 1993; de Solminihac 2001).

To mathematically define friction supply f_s , the international friction index model performed by the World Road Association, PIARC, experiment was used (de Solminihac et al. 2004). The model is expressed by eq. [4] as (Wambold et al. 1995)

$$[4] \quad f_s(S) = F60e^{(60-S)/S_p}$$

where S represents speed in kilometres per hour, S_p (in kilometres per hour) is a parameter that represents the effect of macrotexture of the pavement. It is determined through eq. [5].

$$[5] \quad S_p = a + bT_x$$

where a and b are constants expressed in kilometres per hour and kilometres per hour-millimetres, respectively and T_x represents texture in millimetres. The constants a and b depend on the equipment used to measure macrotexture and are used to make the value of S_p independent from the tribometer being used (Wambold et al. 1995).

The reference friction, which is conventionally measured at a speed of 60 km/h and is independent of the tribometer being used to measure skid resistance, is represented as F_{60} (Wambold et al. 1995). It can be estimated through on-site measurements of skid resistance. The mathematical expression is

$$[6] \quad F60 = A + B(\text{FRSe}^{(S_e - 60)/S_p})$$

where A and B are calibration constants associated with the tribometer used to measure skid resistance, FRS corresponds to skid resistance measured with a specific tribometer, and S_e is the speed at which FRS has been measured. The value of S_e depends on the tribometer used and the level of wheel blockage, as it was established by the PIARC experiment (Wambold et al. 1995). Replacing the value of $F60$ and S_p in eq. [4], the expression presented in eq. [7] is obtained as

$$[7] \quad f_s(S, T_x, \text{FRS}) = \{A + B[\text{FRSe}^{(S_e - 60)/(a + bT_x)}]\} \times e^{(60 - S)/(a + bT_x)}$$

Equation [7] represents friction supply as a function of speed (S), texture (T_x) and skid resistance (FRS). Skid resistance and pavement texture are considered as random variables. Constants a , b and A , B are obtained through the calibration of macrotexture and skid resistance measuring equipment, respectively. All four of them behave as non-random variables in eq. [7].

From eq. [7] it can be said that as friction supply curve is nonlinear, its probabilistic distribution is not necessarily similar to FRS and T_x distributions. Particularly, Wambold et al. (1995) assumed that f_s adjusts to a normal probability distribution.

Recent studies do not concord to the probability distribution that should be associated with FRS variability. Cafiso (2000), on the basis of studies carried out in Italian highways, concluded that skid resistance variability follows a gamma distribution. However, other authors assume that friction adjusts to a normal probability distribution (Hirsh et al. 1987). Therefore, it is better to study the behavior of FRS and T_x in detail under different scenarios to obtain the best fit of both variables for a determined probabilistic distribution.

Design and operating speeds

According to AASHTO (2001), design speed is “the maximum safe speed that can be maintained over a specified section of highway when conditions are so favorable that the design features of the highway govern. It is a selected speed used to determine the various geometric design features of a roadway.”

Operating speed can be defined as the maximum free-flow speed that a driver can reach on a road segment according to the prevailing traffic conditions, geometry, weather, and pavement surface conditions (MOP 2002). However, drivers decide on vehicle speed depending on their risk acceptance. For this reason, operating speed varies between drivers and is not necessarily equal to design speed. Since operating speed varies from one driver to another, its value is essentially random.

Speed limit

Speed limit (S_{lim}) is the maximum speed that ensures the dynamic stability of a vehicle for a given superelevation, radius of curvature, and friction of pavement. It is the result of an equilibrium condition between friction supply and demand, as shown in Fig. 1. This equilibrium point is determined by the intersection of both curves.

When operating speeds are more than the S_{lim} , available friction is not enough to compensate demanded friction. This entails that the vehicle is at a risk of losing its dynamic stability, generating an unsafe condition that can be worse under adverse conditions (rain, snow, ice on the pavement surface).

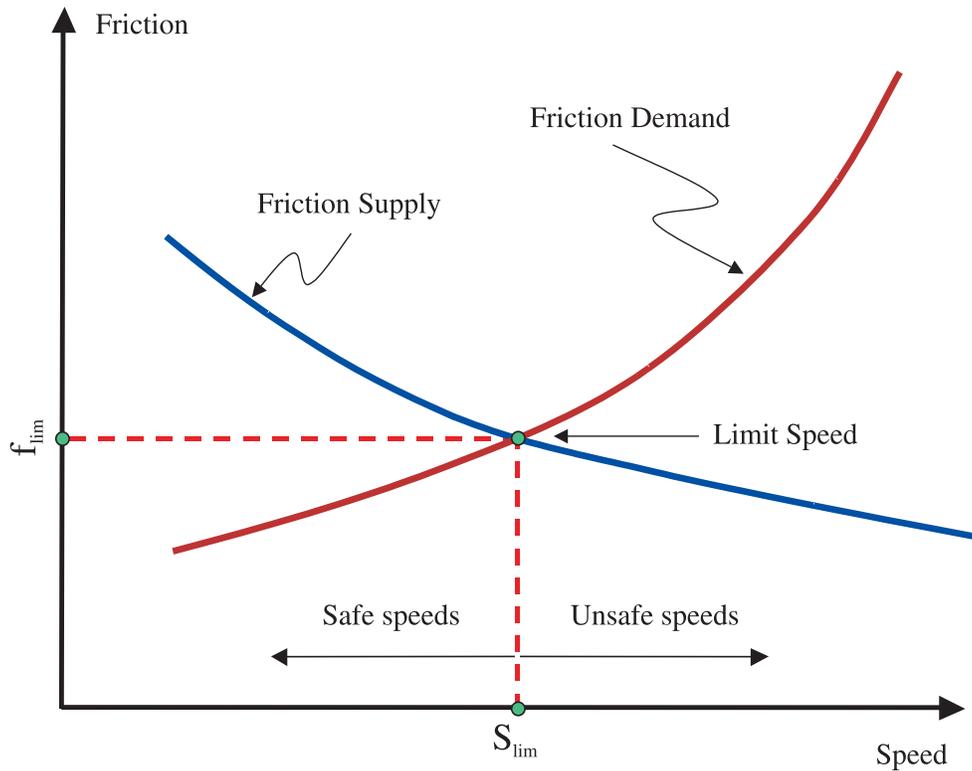
Principles of the reliability theory

Lewis (1987) defines reliability as the probability that a component, mechanism, equipment, or system, functions for a specific period of time under certain conditions. Analytically this index is the inverse function of failure probability. Graphically, it represents the minimum distance between the origin of the coordinate and the failure surface, as presented in Fig. 2.

To estimate failure probability, demand and supply curves of the studied characteristic are required. In pavement design, for instance, demand is traffic loading and supply is given by pavement structural capacity. In highway geometric design, demand can be defined as operating speed and supply by design speed.

Supply and demand are obtained as a function of the random variable vector X , as $O = f_1(X)$ and $D = f_2(X)$. The limit state function is determined as the difference between supply and demand, i.e., $g(X) = O - D = f_1(X) - f_2(X)$. Thus, failure

Fig. 1. Relation between friction supply and demand on a horizontal curve (Echaveguren et al. 2004).



probability can be defined as the probability where $g(X)$ is smaller or equal to zero, that is, $P(g(X) \leq 0)$.

If $g(X) = 0$, then the resulting surface determines the limit state between failure and nonfailure condition. The limit state can be linear or nonlinear depending on the nature of problem to be analyzed. If $g(X)$ is nonlinear regarding X , then failure probability can be determined with first or second order reliability methods (Haldar and Mahadevan 2000).

The efficiency of each method will depend on the efficiency to calculate the reliability index, β . Particularly, if random variables are not normally distributed, it is possible to consider them as gaussian random variables using Rosenbatt or Nataf transformations.

One of the most commonly used methods to determine β under nonlinear limit conditions is given by Hasofer and Lind (1974). This method linearizes the limit state function in the design point and defines β as the minimum distance between the coordinate system origin and the design point located on the limit surface $g(X) = 0$ (refer to Fig. 2). Equation [8] determines reliability index β and the design point as follows:

$$[8] \quad \beta = \{u \in g(X) = 0\} \sqrt{\sum_i u_i^2}$$

$$u^* = \beta \alpha$$

where u_i is the normalized variable, α is the normal vector of $g(u) = 0$ in the design point u^* . To apply this method, $g(u)$ function needs to be differentiable.

Actions recommended to reduce failure probability in horizontal curves

Improvement activities should be selected regarding acceptable final value for failure probability. Some of the actions that can be adopted are (Echaveguren et al. 2004):

(a) *Modifying geometry of the curve* — by changing superelevation and (or) radius of the curve, through a reconstruction. This action modifies friction demand. Friction supply would also change with the new pavement surface, a fact that must be considered in the calculation of S_{lim} .

(b) *Limiting operating speed* — attempting to reduce speeds in the curves, either by warning signals (reduce speed, dangerous curve) or regulatory signs (limitation of maximum speed). Effectiveness of both type of signs will depend on the predisposition of drivers to fulfill imposed rules and on the capacity of police to control such fulfillment. This measure affects the failure probability by changing the distribution of speeds and their variance.

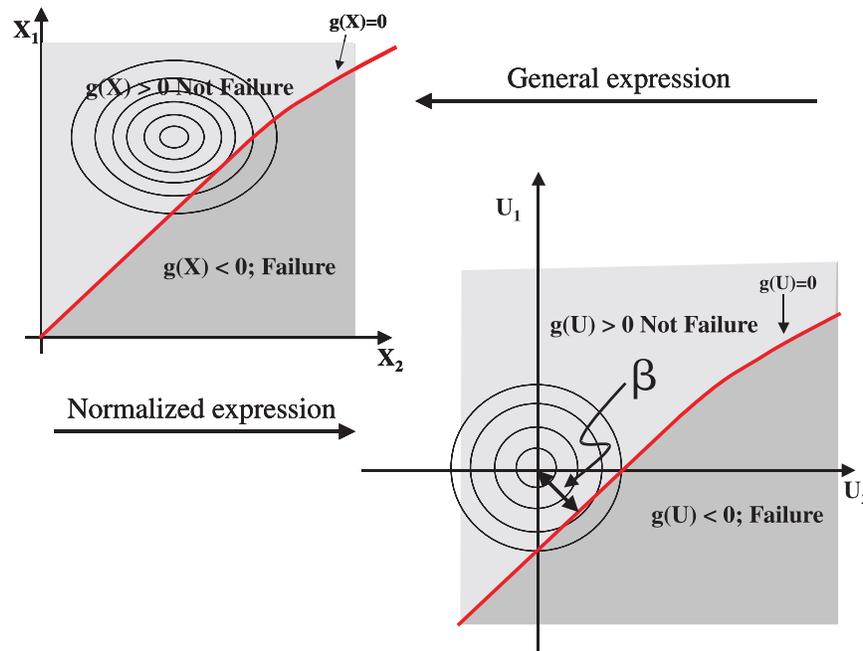
(c) *Improving surface friction conditions* — applying surface treatments, such as high friction seals or surface milling in asphalt pavements and diamond grinding in concrete pavements. Any of these actions increase pavement texture and (or) skid resistance, thereby, increasing friction supply and S_{lim} .

These actions may be applied in conjunction or individually, depending on resources available.

Proposed methodology for the estimation of margin of safety

The proposed methodology is aimed at estimating P_F based on the value of margin of safety of a curve, repre-

Fig. 2. Graphical expression of the failure probability (after Van Gelder and de Wit 2003).



sented by a reliability index. The methodology includes the following steps:

- analyze probability distributions of friction supply [$f_s(S)$]
- determine speed limit (S_{lim})
- characterize probability distributions of operating speed (S_{op})
- specify the limit state function [$G(S_{lim}, S_{op})$]
- calculate reliability index (B) and failure probability (P_F)
- propose actions to reduce P_F if a nonacceptable P_F is obtained

Analysis of friction supply probability distribution

Probability distribution of skid resistance (FRS) and texture (T_x) should be known before performing this analysis. Once they are known, values for $f_s(S)$ can be calculated for different values of speed (S). To identify the probability distribution that best fit $f_s(S)$, a variety of statistical tests can be applied, such as, chi-square, Kolmogoroff–Smirnov or Anderson–Darling.

Determination of speed limit

Different criteria can be applied to determine speed limit. Under a simple approach $f_s(S)$ can be considered deterministic and S_{lim} can be calculated using eq. [9]. This equation is the intersection of the curves presented in eqs. [3] and [7].

$$[9] \quad \frac{S^2}{k_1 R} - k_2 p = \left[A + B \left(\text{FRS} e^{\frac{S_e - 60}{a + b T_x}} \right) \right] e^{\frac{60 - S}{a + b T_x}}$$

Equation [9] can be solved for S_{lim} with the help of electronic spreadsheets. Substituting the value of S_{lim} in eqs. [3] or [7], the value of f_{lim} can be finally obtained.

If $f_s(S)$ exhibits a probabilistic behavior, the estimation of S_{lim} turns more complex. Two methods can be applied to determine S_{lim} value. One method is to study the limit function

$G(S) = f_s(S) - f_D(S)$ assuming that S has a uniform distribution. Under this approach S_{lim} is the speed value for the probability of $P[G(S)] = 0$.

The second method considers the estimation of $f_s(S)$ upper limit, lower limit, and expected value as a function of speed (S). Three expressions for $f_s(S)$ are obtained under this procedure and for each expression a S_{lim} value is obtained using eq. [9]. The three values of S_{lim} can be associated to a triangular or normal distribution.

Estimation of mean operating speed and operating speed variance

Operating speed is a random variable that can be estimated by measuring the instantaneous speed of vehicles at the mid-point of a curve (Lamm et al. 1999). For this, it is necessary to consider a sample of more than 30 speed measures per vehicle type (for instance, light and heavy vehicles). Studies carried out by Roess et al. (1998), show that speeds measured in a road section have a normal probability distribution. Despite this, normality of the sample needs to be verified by means of kurtosis and asymmetry tests. Once normality of speed probability distribution is verified, mean operating speed (S_{op}) and speed variance (S_v) can be estimated. If speed distribution is symmetrical, mean operating speed is the 50th percentile (average of the measured speeds). If the distribution has some degree of asymmetry, it is better to use the geometric mean to estimate the expected value of operating speed (Basualto 2003).

Determination of the limit state function

To determine the limit state function, the variables that describe it need to be characterized. In this case, the limit state function is defined as $G(S_{lim}, S_{op}) = S_{lim} - S_{op}$. Then, to solve the problem, the analytical expression of the function needs to be determined, or else, S_{lim} and S_{op} variables need to be characterized under their probabilistic distributions.

Equation [9] is used to determine S_{lim} . However, the analytical solution is complex, and it is recommended to calculate the upper, lower, and expected values for S_{lim} instead to design its probabilistic distribution. In both cases, it has to be assumed that S_{lim} depends on radius, superelevation, skid resistance, and texture. Radius and superelevation are considered constant for each curve, as they are fixed values in existing curves. Texture and skid resistance are random variables that describe friction supply in a nonlinear way. The speed limit also behaves as a random variable. Operating speed has a normal probability distribution, as described previously in this article.

Calculation of reliability index and failure probability

As S_{lim} is nonlinear, limit state function is nonlinear too. Therefore, for the estimation of reliability index, β , is recommended to apply first order methods, with the help of appropriate software.

To estimate the failure probability (p_f), the value of β is required. To calculate β , the following three step procedure needs to be applied:

- apply Rosenblatt or Nataf transformation to variables that do not distribute normally
- normalize random variables
- estimate β using the first order Hasofer–Lind method, and calculate P_F

The above-mentioned steps can be performed in conjunction with each other, if a software is available.

If the value of β is known, failure probability (P_F) associated with the studied horizontal curve can be determined directly by using tables of normal probability distribution. If $\beta = 0$, then S_{lim} coincides with operating speed under $P_F = 50\%$. This indicates that half of the fleet samples of the vehicle run at speeds higher than S_{lim} and are under the risk of losing their dynamic stability.

When P_F associated to a horizontal curve is known, actions to improve safety conditions can be evaluated. Failure probability can be adopted as a target value depending on the category of the road, costs associated to improvements, and social tolerance of drivers to risk.

Case of study: application of the proposed methodology for the estimation of margin of safety

The proposed methodology was applied to a case where five horizontal curves were considered, obtained from Echaveguren and Saez (2001). First, margin of safety was estimated through the proposed methodology. Then, a sensitivity study was done to identify variables with more incidences over reliability of analyzed horizontal curves.

In general, the speed of heavy vehicles shows a lower variance than the speed of light vehicles (Echaveguren and Sáez 2001). Hence, β tends to be higher for heavy vehicles than for light ones, and the failure probability tends to be lower for heavier vehicles than lighter ones. This reduces β value according to eq. [10] and increases failure probability with respect to heavy vehicles. For this reason, to consider the worse scenario, the subsequent analysis was carried out only for light vehicles.

Calculation procedure

To estimate speed limit and calculate S_p , macrotexture values between 0.5 and 1.1 mm were obtained from laser profiler measures. Skid resistance ranging from 0.4 to 1.0 were obtained from SCRIM measures.

Databases on FRS and T_x available in Chile were used. From the analysis it was obtained that the mean value for the variation coefficient of FRS and T_x was lower than 25%, consequently this value was selected for the analysis. Likewise, it was observed that FRS and T_x data were predominantly distributed normally.

A matrix was built combining three level of FRS and three of T_x . A probability distribution for FRS and T_x was associated to each tile in the matrix. These distributions were obtained from the behavior of FRS and T_x observed in the Chilean database. The matrix obtained is presented in Table 1. Table 2 shows the constants used to determine S_p and $F60$, which were then used in eq. [8] to determine friction supply. Monte Carlo simulation was used to analyze the random behavior of friction supply. Table 3 presents the probabilistic distributions obtained for friction supply.

For the estimation of friction demand, the values k_1 and k_2 , recommended by Chang (2001) for light vehicles were considered. A preliminary analysis showed that the superelevation incidence in failure probability is almost negligible for values ranging from 3% to 6%. For this reason, a constant superelevation value of 4% was considered in this analysis.

Calculation of S_{lim} and f_{lim} was made for five curves with radii ranging from 200 to 600 m, obtained from Echaveguren and Saez (2001) study. Results are presented in Table 4.

Free-flow speed data from five horizontal curves was also obtained from Echaveguren and Sáez (2001). In such study, speeds were measured with laser guns. From light vehicle speed distribution, mean speed values and variance were calculated. Results are presented in Table 5.

Reliability index and failure probability regarding each horizontal curve were determined using reliability analysis software. Random variables were transformed to a set of uncorrelated Gaussian random variables using Rosenblatt transformation. Reliability index, β , was computed using Hasofer–Lind method. Failure probabilities obtained are presented in Table 6.

To identify the factors that are more significant for reduction of failure probability, a sensitivity analysis regarding skid resistance, texture, and radius was performed. Figure 3 presents the effects of friction and texture variability over S_{lim} for two extreme conditions for texture and skid resistance. A power variation law is observed regarding radius with the functional form of $S_{lim} = aR^b$.

Figure 4 was obtained from the sensitivity analysis. From this curve it is observed that P_F decreases as road curvature decreases. The reduction rate of P_F depends on the combination of FRS and T_x . When FRS and T_x are low, failure probability is almost insensitive to the radius. However, this sensitivity increases as FRS and T_x values increase.

Analysis of case study results

From the results presented in Table 4, it is observed that as the radius of curvature increases the value of S_{lim} for a

Table 1. Skid resistance (N_{FRS}) and texture probability (N_{Tx}) distributions used in $f_s(S)$ analysis.

Skid resistance (FRS)	Texture (mm)		
	High	Medium	Low
High	$N_{Tx}(1.1, 0.275)$ $N_{FRS}(1.0, 0.25)$	$N_{Tx}(0.8, 0.20)$ $N_{FRS}(1.0, 0.25)$	Not applicable
Medium	$N_{Tx}(1.1, 0.275)$ $N_{FRS}(0.8, 0.20)$	$N_{Tx}(0.8, 0.20)$ $N_{FRS}(0.8, 0.20)$	$N_{Tx}(0.5, 0.125)$ $N_{FRS}(0.8, 0.20)$
Low	Not applicable	$N_{Tx}(0.8, 0.20)$ $N_{FRS}(0.4, 0.10)$	$N_{Tx}(0.5, 0.125)$ $N_{FRS}(0.4, 0.10)$

Table 2. Equipment constants to estimate texture and $F60$ (Wambold et al. 1995).

Variable	Equipment	PIARC code	Coefficient values	
Macrotexture	Profilometer	A2	$a = 25.8322$ (km/h)	$b = 139.68$ (Km/(h-mm))
Skid resistance	SCRIM (UK)	D5	$A = 0.03258$	$B = 0.87170$

Table 3. Friction supply probability distributions for different skid resistance (FRS) and texture levels.

Speed (km/h)	High FRS, high texture	High FRS, medium texture	Low FRS, medium texture	Low FRS, low texture
30	$N(0.85, 0.20)$	$N(0.83, 0.20)$	$N(0.36, 0.08)$	$N(0.35, 0.08)$
50	$N(0.76, 0.18)$	$N(0.72, 0.17)$	$N(0.31, 0.07)$	$N(0.28, 0.06)$
70	$N(0.67, 0.17)$	$N(0.62, 0.15)$	$N(0.27, 0.06)$	$N(0.23, 0.05)$
90	$N(0.61, 0.15)$	$N(0.54, 0.14)$	$N(0.23, 0.06)$	$N(0.19, 0.05)$
110	$N(0.53, 0.14)$	$N(0.47, 0.13)$	$N(0.20, 0.05)$	$N(0.15, 0.04)$
130	$N(0.48, 0.13)$	$N(0.40, 0.11)$	$N(0.17, 0.05)$	$N(0.12, 0.04)$

Table 4. Mean speed limit and mean limit friction for five horizontal curves for three values of mean texture (μT_x) and mean skid resistance (μFRS).

Radius (m)	μT_x (mm)	Mean speed limit (μS_{lim}) and mean limit friction (μF_{lim})					
		$\mu FRS = 0.4$		$\mu FRS = 0.8$		$\mu FRS = 1.0$	
		μS_{lim}	μF_{lim}	μS_{lim}	μF_{lim}	μS_{lim}	μF_{lim}
200	0.5	75.3	0.215	92.6	0.336		
	0.8	80.1	0.247	100.9	0.403	108.5	0.469
	1.1			105.8	0.445	113.9	0.522
300	0.5	87.1	0.19	106.1	0.292		
	0.8	93.7	0.223	116.9	0.359	125.3	0.415
	1.1			123.5	0.402	132.5	0.469
400	0.5	96.2	0.172	116.4	0.262		
	0.8	104.3	0.223	129.4	0.328	138.3	0.377
	1.1			137.3	0.371	146.9	0.431
500	0.5	103.8	0.159	124.9	0.239		
	0.8	113.1	0.193	129.6	0.304	149	0.349
	1.1			148.8	0.348	158.9	0.402
600	0.5	110.2	0.148	141	0.204		
	0.8	120.7	0.182	148.5	0.285	158.2	0.326
	1.1			158.6	0.328	169.2	0.379

given texture increases. Similarly, for the same values of radius and skid resistance, as texture increases, the value of S_{lim} also increases. For constant values of texture and radius, the value of S_{lim} increases as friction increases.

Table 5. Expected value and variance of operating speed distribution for light vehicles (Echaveguren and Sáez 2001).

Radius (m)	Operating speed (km/h)	
	Expected value (km/h)	Variance (km/h) ²
200	107.8	2.7
300	113.4	2.6
400	117.6	2.6
500	120.4	2.5
600	121	2.5

Friction supply values obtained from simulation show exactly how these variables behave with respect to speed, texture, and skid resistance. In Table 3, it is observed that variance decreases as speed increases for constant values of FRS and T_x . Likewise, skid resistance shows a higher incidence over friction supply variability as compared with texture. Eventually, this would reduce the number of random variables and simplify the analysis.

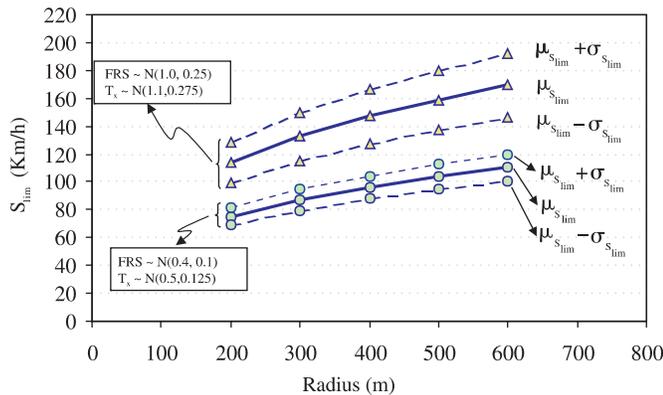
However, Fig. 4 shows that speed limit exhibits an increasing monotonic behavior toward radius for FRS and T_x values. The speed limit, S_{lim} , is clearly more sensitive to texture and skid resistance variations than to radius. If operating speed function, presented in Table 5, is overlapped to this figure, RD and T_x combinations could be preliminarily identified to have a failure probability of 100% for a given radius. This gives first approximation to the operational behavior of the analyzed curves prior to reliability index calculation.

From speed values shown in Table 5, it can be said that variance decreases as value for expected speed increases.

Table 6. Failure probability (%) obtained for horizontal curves with radius between 200 and 600 m for different mean texture (μT_x) values.

Radius (m)	Failure probability (%)					
	$\mu T_x = 0.5$ mm		$\mu T_x = 0.8$ mm		$\mu T_x = 1.1$ mm	
	FRS = 0.4	FRS = 0.8	FRS = 0.8	FRS = 1.0	FRS = 0.8	FRS = 1.0
200	100	100	76.2	57.7	47.4	34
300	100	98.8	37.4	19.2	15.8	13.6
400	99.4	91.4	15.8	5.6	5.4	6.6
500	96.7	75.7	6.3	1.7	1.8	3.6
600	88.8	53.9	2.1	0.4	0.5	1.9

Fig. 3. Variation of S_{lim} with respect to radius of curvature for low and high skid resistance and texture.



This is consistent with the findings of Garber and Gadiraju (1989), who obtained a quadratic variation of speed variance regarding average operating speed.

Table 6 shows that failure probability performs a drastic reduction as texture and skid resistance values increase for a given radius, especially for high radius. Highest failure probabilities are observed under low values of radius, textures, and skid resistance. This is true for roads having low design speed. If a maximum failure probability of 20% is considered, then an acceptable combination of texture, radius, and skid resistance can be determined. For the case under consideration, the threshold value is given by radius > 300 m, FRS > 0.8, and $T_x > 0.8$ mm.

It is observed from Fig. 4 that P_F curves present two zones with different behaviors. One zone is associated to high values of FRS and T_x , and the other to low values of FRS and T_x . From this, the following conclusions were obtained:

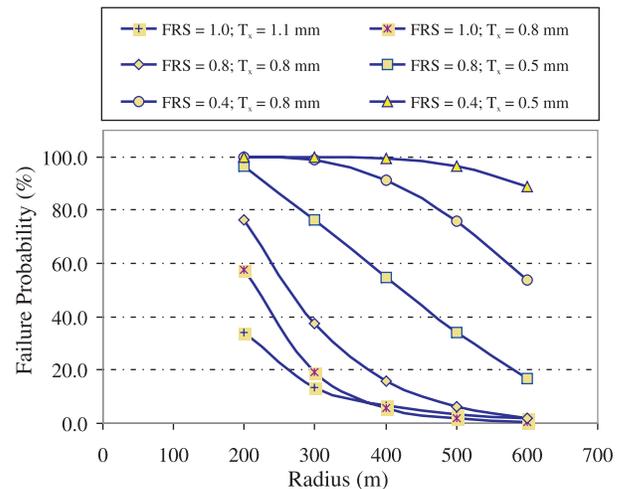
High skid resistance and texture

When the radius is higher than 400 m, failure probability is very small and variations in texture and skid resistance do not have a significant effect. The values of radius near 400 m present failure probability of certain significance (lower than 20%). For radius lower than 400 m, P_F increases significantly and reaches maximum values of 80%. When FRS is modified by 20%, P_F is reduced by 75%. Whereas, when modifying T_x to 30%, P_F is reduced by 5%.

Low skid resistance and texture

When FRS and T_x values are low, failure probability is not sensitive to the radius. In this case, failure probability is re-

Fig. 4. Variation of failure probability with respect to radius of curvature for different values of friction and texture.



duced only by modifying the surface of the pavements and locating it in the high texture and friction zone.

Conclusions

In this paper, a methodology for the analysis of existing horizontal curves was developed. This methodology includes new procedures for the analysis of existing horizontal curves, such as,

- estimation of speed limit based on equilibrium between friction provided by a pavement and friction demand,
- calculation of margin of safety based on reliability theory in terms of speed limit and vehicle operating speed, and
- analysis of the effect of geometrical and pavement conditions in existing horizontal curves over reliability.

Through the proposed methodology, it is possible to analytically solve the problem stated by McLean (1983), which is related to the behavior of drivers on horizontal curves having low design speeds.

The methodology has the advantage that texture, skid resistance, radius of curvature, and superelevation can be integrated in one index. This methodology makes it possible to evaluate different combinations of these variables and relate them to vehicle operating speeds.

Although the proposed methodology was developed for the analysis of existing horizontal curves, it can also be applied to geometrical design. For this purpose, mathematical expressions of design friction need to be considered, includ-

ing its random nature. Also speed-curve models should be considered to simulate drivers' behavior. In this case, friction demand variables are considered as the geometrical elements of the curve in addition to speed.

The methodology includes some calculation assumptions considered to simplify its application. To improve the model in terms of precision and flexibility, the following recommendations have to be taken into account:

- consider rollover effect in dynamic stability model, which is typical of heavy vehicles to widen the application field of the methodology.
- analyze the effect of speed limitation in curves over operating speed to include it as an action to reduce failure probability.
- study the failure probability admitted by a specific group of drivers to objectively compare reliability of design and existing curves.

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