ENGLISH VERSION

Estimation of heavy vehicle rollover potential using reliability principles

Estimación del potencial de rollover de vehículos pesados usando principios de confiabilidad

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Abstract

Rollover is defined as a moving vehicle's abrupt loss of the trajectory of the center of gravity. In horizontal curves, it refers to overturning by an unbalance of the lateral acceleration. The likelihood that this turnover occurs can be estimated by studying the static rollover potential, which is calculated with lateral acceleration thresholds that, when being exceeded, make the vehicle to suffer a rollover. These models consider the geometry of the vehicle, the road and operating speed, and sometimes the vehicle's suspension system. This approach is suitable for analyzing the rollover potential of individual vehicles, but it is not very practical when analyzing vehicle fleets driving at operating speeds that follow a probability distribution according to the geometrical conditions of the environment and the type of vehicle. This work analyzes the rollover phenomenon through a probabilistic approach based on the reliability theory, which allows estimating the rollover risk considering random variables. It applies the Hasofer-Lind First-Order Reliability Method to calculate the rollover probability, based on the geometry, type of vehicle, and operating speed when taking horizontal curves. Additionally, it discusses three rollover calculation methods and presents the reliability theory concepts used herein. This paper describes the construction of limit state functions, experimental design, input data, and the failure probability curves for 4 types of vehicle and 3 input speeds. It was concluded that it is not recommendable to use a horizontal curve radius of less than 170 m, especially because heavy vehicles run the risk of suffering rollover.

Keywords: *Rollover, lateral acceleration, operating speed, radius, failure probabilty, reliability*

Resumen

El rollover (volcamiento) se define como la pérdida brusca de la trayectoria del centro de gravedad de un vehículo en movimiento. En curvas horizontales, corresponde al volcamiento por descompensación de la aceleración lateral. La posibilidad de que ocurra este volcamiento se puede estimar mediante el estudio del potencial de rollover estático, el cual se estima usando umbrales de aceleración lateral que, al ser superados, llevan al vehículo a experimentar rollover. Estos modelos consideran la geometría del vehículo, del camino y la velocidad de operación y en algunos casos el sistema de amortiguación del vehículo. Este enfoque es adecuado para analizar el potencial de rollover vehículo a vehículo, pero resulta poco práctico para analizar flotas de vehículos que circulan a una velocidad de operación que sigue una distribución de probabilidades según las condiciones geométricas de entorno y tipo de vehículo. En este trabajo se analiza el fenómeno de rollover mediante un enfoque probabilístico basado en la teoría de la confiabilidad. A partir de este enfoque, es posible estimar la probabilidad de que ocurra rollover considerando variables aleatorias. Se utilizó el método de análisis de confiabilidad de primer orden de Hasofer-Lind para estimar la probabilidad de ocurrencia de rollover, en función de la geometría, tipo de vehículo y la velocidad de operación de entrada a curvas horizontales. Se discuten tres modelos de cálculo de rollover, y se presentan los conceptos de la teoría de la confiabilidad empleados. Se describe la construcción de las funciones de estado límite, el diseño experimental, los datos de entrada, y la curvas de probabilidad de falla para 4 tipos de vehículo y 3 velocidades de entrada. Se concluyó que no resulta aconsejable utilizar radios de curvas horizontales menores a 170 m toda vez que los vehículos pesados exhiben una probabilidad no nula de experimentar rollover.

Palabras clave: Rollover, aceleración lateral, velocidad de operación, radio, probabilidad de falla, confiabilidad

1. Introduction

Rollover is defined as the destabilization of a vehicle's center of gravity. It produces an overturning force that separates the vehicles' tires from the pavement, together with a sudden loss of control of the vehicle and its trajectory, which generally ends up in an accident. In horizontal curves, rollover affects mainly heavy vehicles, which enter the curves at high speeds. The phenomenon is further magnified in heavy vehicles with narrow track widths and when the center of gravity is high.

The design standards for horizontal curves usually establish design models based on skidding, a phenomenon that affects mainly light vehicles, assuming as a design condition that the design radius is sufficiently large so as not to produce rollover in heavy vehicles. Nevertheless, the occurrence of rollover accidents in national highways demonstrates that the design assumption should be examined in more detail.

There are static and dynamic models to estimate the rollover potential. The first calculates the rollover risk through a static analysis. The second uses complex models of heavy vehicle dynamics to predict rollover practically at the same time that a rollover occurs. The first has the advantage that it can be used in the geometrical design to estimate the rollover potential. Meanwhile, the second is more useful to estimate the rollover risk when driving, if the vehicle has a proper sensor system.

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This works deals with an estimate method for the rollover potential based on static models. The method follows the reliability theory and uses the First Order Reliability Method (FORM) to calculate the probability of rollover in the event of different design scenarios, operation and type of heavy vehicle.

In the first place, it describes static models of rollover estimation for heavy vehicles, which consider rigid vehicles with suspension, and subsequently, it presents the experimental design that allows applying the FORM method. Then, it explains the mathematical model used, stressing the development of the limit state function required to calculate the failure probability. Later on, simulations are carried out considering 4 types of heavy vehicles, which enable the analysis of the results and to submit the work's conclusions.

2. Static models for rollover estimation

Figure 1 shows the diagram of forces acting on a vehicle when driving on a circular banked curve. Rollover will happen if the momentum produced by the destabilizing forces exceeds the momentum generated by the stabilizing forces. When balancing the momentum in relation to the center of gravity of the vehicle and when balancing the horizontal and vertical forces, it is possible to determine the stability condition that, if not satisfied, will take the vehicle to suffer a rollover (see Equation 1).

Equation 1 expresses the above condition. On the left side of the inequality, it shows the lateral acceleration of a vehicle when driving through an horizontal curve and, on the right side, the lateral acceleration threshold that the vehicle is capable of sustaining without rolling over, based on the track width (t, in m), height of the center of gravity (h, in m), bank angle (p, in decimals) and gravitational acceleration (g = 9.81 m/s^2)

$$\frac{a_c}{g} > \left(\frac{t}{2h} + p\right) \tag{1}$$

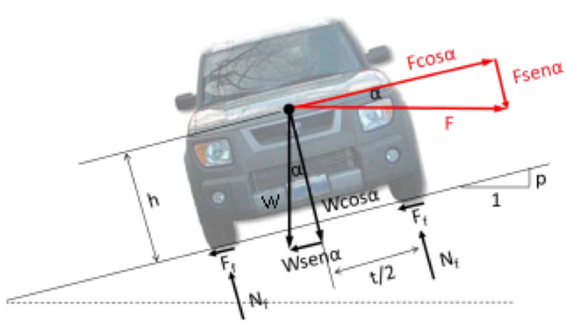
2.1 Theoretical lateral acceleration in horizontal curves

The theoretical lateral acceleration that a vehicle experiences when driving through a horizontal curve is given by the centripetal acceleration acting on the body, which enables it to describe a circular trajectory. Equation 2 shows the acceleration that depends on the vehicle's operating speed (V, in m/s) and the radius of the curve (R, in m).

$$\frac{a_c}{g} = \left(\frac{V^2}{gR} - p\right) \tag{2}$$

2.2 Lateral acceleration threshold

Rollover static models estimate the lateral acceleration threshold that a vehicle can sustain on a horizontal curve without suffering rollover. This threshold is estimated as the ratio between the limit lateral acceleration ($a_{c,lim}$) and the gravitational acceleration (g). The models consider the geometric characteristics of the vehicle (track width and height of the center of gravity), the road (radius and bank angle) and, sometimes, the suspension system of the vehicle (height of the balancing center and rotation rate). This work applied two static models of rollover: the Static Roll Threshold (SRT) of Kühn (2013) and Gillespie (1992) and the Static Stability Factor (SSF) described by Robertson and Kelley (1989) and Hac (2002).



W: vehicle weight (N)
F: centrifugal force (N)
F_f: frictional force (N)
N_f: normal reaction (N)
H: height of the center of gravity (m)
t/2: half of the vehicle's track width (m)
α: curve's transverse inclination (rad)
p= tan(α): bank angle (decimal)

Figure 1. *Forces acting on a vehicle in a horizontal curve*

The static roll threshold model

The Kühn (2013) model, calculates the rollover static threshold towards the outer side of the curve (Equation 3) and towards the inner side of the curve (Equation 4). Both equations consider the vehicles as rigid bodies, with no suspension system. In Equations 3 and 4, t is the track width of the vehicle (in m); h is the height of the center of gravity (in m) and p is the bank angle (in decimal).

$$\frac{a_{c,lim}}{g} = SRT_{Rigid\_EXT} = \frac{\frac{t}{2h}+p}{1-\frac{t}{2h}p} \quad \textbf{(3)}$$

$$\frac{a_{c,lim}}{g} = SRT_{Rigid\_INT} = \frac{\frac{t}{2h}-p}{1+\frac{t}{2h}p} \quad \textbf{(4)}$$

The Gillespie (1992) model, considers that vehicles have a suspension system. Therefore, Equations 3 and 4 add the effect of the height of the balancing center (h_o in m) and the rotation rate (r_ϕ in rad/g), as shown in Equations 5 and 6, both for rollover on the outer and inner side of the curve, respectively. The rotation rate represents the inclination speed of a vehicle, given its suspension system, due to the lateral acceleration when driving through a curve. The point at which that rotation is measured is called balancing center, which is located under the mass center of the vehicle when modelled as a rigid body (Gillespie, 1992).

$$\frac{a_{c,lim}}{g} = SRT_{Damping\_EXT} = \frac{\frac{t}{2h}+p}{\left[r_\emptyset\left(1-\frac{h_0}{h}\right)+1+\frac{t}{2h}p\right]} \quad \textbf{(5)}$$

$$\frac{a_{c,lim}}{g} = SRT_{Damping\_INT} = \frac{\frac{t}{2h}-p}{\left[r_\emptyset\left(1-\frac{h_0}{h}\right)+1-\frac{t}{2h}p\right]} \quad \textbf{(6)}$$

The static stability factor

The Static Stability Factor (SSF) allows determining the limit lateral acceleration ($a_{c,lim}$, in m/s^2) of a vehicle on a horizontal curve as the ratio between the track width of the vehicle and the height of the center of gravity (Equation 7). This factor can be interpreted as the rollover threshold when the bank angle is zero. It is valid for rigid systems.

$$\frac{a_{c,lim}}{g} = SSF = \frac{t}{2h} \quad \textbf{(7)}$$

The rollover potential

According to Equation 1, rollover is activated when the lateral acceleration of a vehicle exceeds the limit acceleration. The rollover risk decreases when the limit acceleration is higher than the lateral acceleration. This hypothesis is valid for individual vehicles. When this hypothesis is extended to the design, it is necessary to consider a fleet of vehicles with different geometric characteristics, where each vehicle drives at a different operating speed. A practical way of synthesizing this diversity of vehicles is to analyze the failure probability. That is, the probability that the operating lateral acceleration of a vehicle is higher than the rollover threshold value. This probability can be conveniently calculated by using the FORM technique (First Order Reliability Method).

3. Modelling of the rollover probability

3.1 Reliability calculation model

Lewis (1987) defines reliability as the probability that a component, mechanism, device or system operates under certain conditions for a specific period of time. In mathematical terms, it corresponds to the inverse function of the failure probability. In this case, the failure probability corresponds to: P($a_c > a_{c,lim}$).

Given the non-linear and random failure functions G1 and G2 such as: G1 = f1(X) and G2 = f2(X), where X is the vector of random variables describing the geometric characteristics. The limit state function is the function g(X) = G1 – G2 = f1(X) – f2(X). The failure probability (Pf) is defined by the probability that g(X) is less than or equal to 0, that is: P(g(X) ≤ 0). The limit state function g(X) expresses a system's failure, according to the behavior of random explanatory variables. Specifically, the limit state function corresponds to the border that demarcates the failure and non-failure zones; therefore, it corresponds to an implicit function of type g(X) = 0, where X is a vector of random variables.

The geometric place of all X points that fulfill the limit condition g(X) = 0 represents the limit state that separates the failure zone from the non-failure zone. If g(X) is a linear function, random variables follow a normal probability distribution and they are not correlated; thus, the failure probability can be described according to Equation 8 (Haldar and Mahadevan, 2000).

$$\beta = \Phi^{-1}\left(1-P_f\right);\ \beta = \frac{\mu}{\sigma} = \frac{a_0+\sum_i a_i\mu_{Xi}}{\sqrt{\sum a_i^2\sigma_{Xi}^2}} \quad \textbf{(8)}$$

Where β is the reliability index, μ and σ are the mean and standard deviation of the function g(X), a_i are deterministic constants, μ_{xi} and σ_{xi} are the mean and standard deviation of X. If a_0 = 0, i = 2 and a_i = 1, we arrive at the calculation expression of the safety margin associated to resistance and load usually employed in engineering.

In the studied case, the function g(X) is nor linear and the probability distributions of the X components are not normal. Therefore, the Hasofer and Lind (1974), method was used, which linearizes the limit state function at the design point, defines β as the minimum distance between the origin of the coordinate system and the design point located over the limit state function g(X) = 0. The method also requires the standardization of the variables, for which the Rosenblatt (1952) transformation was used. Thus, β is calculated according to Equation 9 (Hasofer and Lind, 1974).

$$\beta_{HL} = \min_{\{x \in g(X)=0\}} \sqrt{\sum_i x_i^2} \quad ; \quad u^* = -\beta_{HL}\alpha^* = \beta_{HL}\left(\frac{\frac{\partial g}{\partial x_i}}{\sqrt{\sum_{i=1}^{n}\left(\frac{\partial g}{\partial x_i}\right)}}\right) \quad (9)$$

Where u_i is the standardized variable x_i and α is the standardized vector describing the function g(u)=0 at the design point u. Equation 9 is solved numerically or with a software of reliability analysis. The failure probability is calculated with Equation 10, based on the value of β_{HL}.*

$$P_f = 1 - \Phi(\beta_{HL}) \quad (10)$$

The limit state function used in Equation 9 corresponds, in general, to Equation 11, where a_c corresponds to the operating acceleration and $a_{c,lim}$ is the limit acceleration provoking a rollover.

$$g(X) = a_{c,lim} - a_c \quad (11)$$

3.2 Limit state function

The limit condition of Equation 11 corresponds to the limit surface in which lateral acceleration thresholds and the theoretical lateral acceleration are neutralized. Considering different models for calculating the acceleration threshold (Equations 3 to 7), 5 limit state functions were defined, one for each formula, as shown in Equations 12 to 16.

$$G_1(x) = \frac{\frac{t}{2h}+p}{1-\frac{t}{2h}p} - \left(\frac{V^2}{gR} - p\right) \quad (12)$$

$$G_2(x) = \frac{\frac{t}{2h}-p}{1+\frac{t}{2h}p} - \left(\frac{V^2}{gR} - p\right) \quad (13)$$

$$G_3(x) = \frac{\frac{t}{2h}+p}{\left[r_\emptyset\left(1-\frac{h_0}{h}\right)-\frac{t}{2h}p+1\right]} - \left(\frac{V^2}{gR} - p\right) \quad (14)$$

$$G_4(x) = \frac{\frac{t}{2h}-p}{\left[r_\emptyset\left(1-\frac{h_0}{h}\right)+\frac{t}{2h}p+1\right]} - \left(\frac{V^2}{gR} - p\right) \quad (15)$$

$$G_5(x) = \frac{t}{2h} - \left(\frac{V^2}{gR} - p\right) \quad (16)$$

Functions $G_1(x)$ and $G_2(x)$ are obtained from Kühn (2013) SRT model for the inner and outer side of the curve, respectively. Functions $G_3(x)$ and $G_4(x)$ are obtained from Gillespie (1992) SRT model for the inner and outer side of the curve, respectively. Function $G_5(x)$ is obtained from the Static Stability Factor model (SSF).

4. Experimental design

4.1 Explanatory variables

Table 1 summarizes the explanatory variables of the rollover potential estimation models (Equations 3 to 7) and their respective levels and variation ranges.

4.2 Factorial design and sample size

The sample size was estimated through the Statistical Power Analysis described by Cohen (1988). This calculation considered a 95% confidence level, 95% statistical power, and an effect size of 0.25. The total number of treatment levels was 72. The total sample size includes 360 tests, which determine 5 repetitions per cell, when distributed in the factorial matrix of Table 2.

Table 1. *Levels and ranges of the model's explanatory variables*

Variable	Levels	Variation Range
Type of vehicle	4	--
Operating speed (V, in km/h)	3	40 – 100
Radius (R, in m)	3	50 – 350 (1)
Bank angle (p, in %)	2	3 – 7 (2)
Track width (t, in m)	2	1.7 – 2.1 (3)
Height of the center of gravity (h, in m)	2	1.2 – 3.4 (3)
Height of the balancing center (h_0, in m)	2	0.11 – 0.75 (3)

(1) Radius range consistent with the operating speed range used.
(2) Maximum bank angle allowed associated to the radius range used.
(3) Considers the characteristics of heavy vehicles used in the analysis.
(4) Type of vehicle.

Table 2. *Factorial matrix for simulation of scenarios*

		Curve radius, R(m)																							
		50 - 150								150 - 250								250 - 350							
		Road bank angle, p (%)																							
		3 - 5				5 - 7				3 - 5				5 - 7				3 - 5				5 - 7			
		Vehicle track width, T (m)																							
		Wide		Narrow		Wide		Narrow		Wide		Narrow		Wide		Narrow		Wide		Narrow		Wide		Narrow	
		Height of the center of gravity, h (m)																							
		Medium	High	Medium	High	Medium	High	Medium	High	Medium	High	Medium	High	Medium	High	Medium	High	Medium	High	Medium	High	Medium	High	Medium	High
V (km/h)	40-60																								
	60-80																								
	80-100																								

5. Rollover probability calculation

5.1 Input Variables

The input variables of Equations 12 to 16 were classified as deterministic and random for each type of vehicle. The following vehicle typology was used:

- *Vehicle Type 1: Wide-track light-duty truck for light transport*
- *Vehicle Type 2: Wide-track articulated truck*
- *Vehicle Type 3: Urban bus*
- *Vehicle Type 4: Double decker interurban bus*

Table 3 summarizes the geometric characteristics of the standard vehicles used in the analysis. Regarding the track width, a rectangular distribution with extreme values (R(min ; max)) was considered. In the case of the height distributions of the centers of gravity and balancing, a normal distribution was assumed, including the mean and standard deviation (N (μ; σ)) that are characteristic to each population of standard vehicles.

Table 4 summarizes the geometries considered, which were obtained from the design recommendations contained in Volume 3 of the Chilean Highway Manual (MOP, 1994), assuming the design conditions of existing roads. A rectangular distribution with extreme values (R(min ; max)) was considered both for the radius of curvature and the bank angle.

Table 5 summarizes the operating speed distributions based on the operating speed models for heavy vehicles developed by Saez (2001) and in terms of the radius of curvature in Table 4, so as to consider realistic minimum speed values that are consistent with the interference space of the speed models.

Table 3. *Geometry of the vehicles included in the analysis*

Standard Vehicle	Probability Distribution of the Track Width, in m	Probability Distribution of the Height, in m, of the:	
		Center of Gravity (CG)	Balancing Center (BC)
1	R (1.9 ; 2.1)	N (1.75 ; 0.14)	N (0.44 ; 0.0350)
2	R (1.9 ; 2.1)	N (2.85 ; 0.15)	N (0.715 ; 0.0375)
3	R (1.7 ; 1.9)	N (1.75 ; 0.13)	N (0.44 ; 0.0325)
4	R (1.7 ; 1.9)	N (2.85 ; 0.14)	N (0.715 ; 0.035)

Table 4. *Probability distribution considered for the geometry*

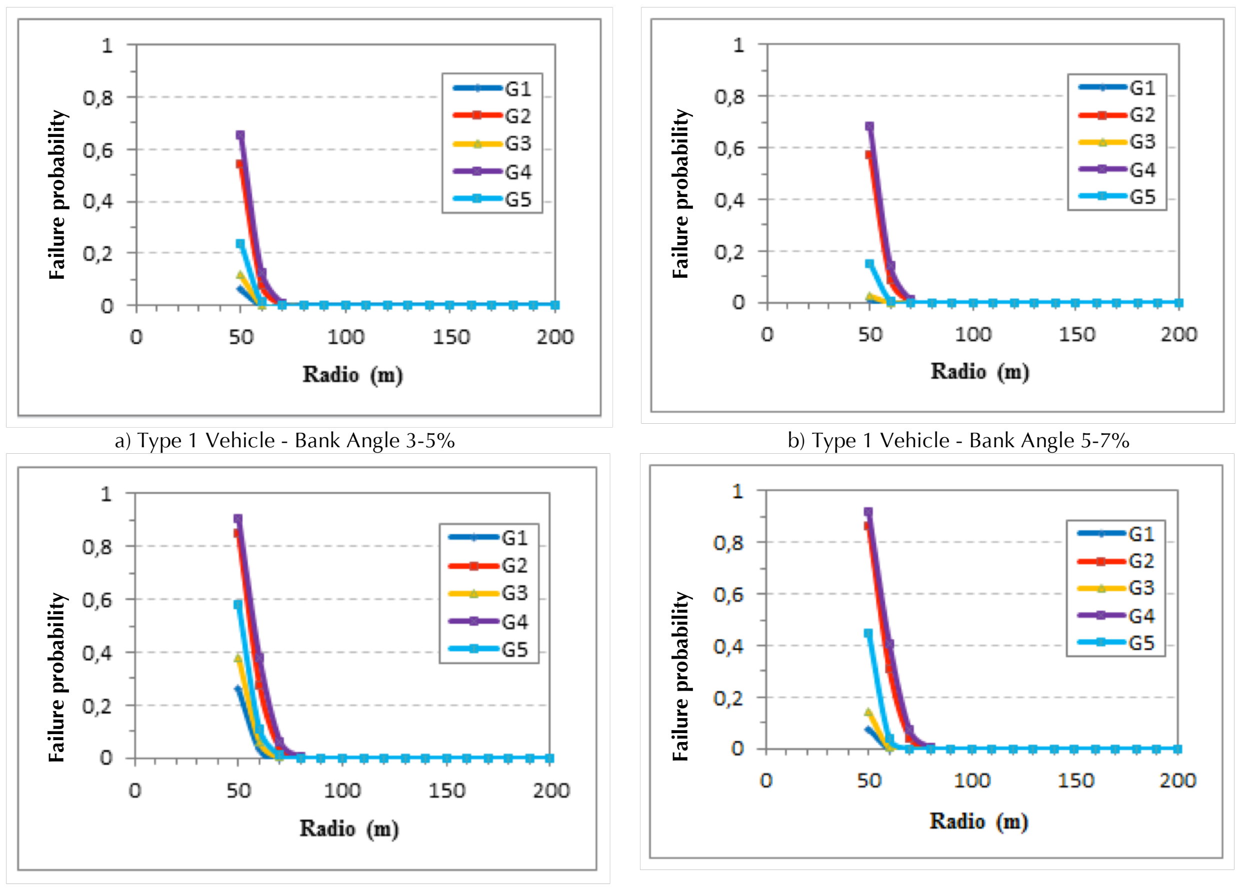
Radius (m)	Bank angle (%)
R(50 ; 79)	R(3 ; 7)
R(80 ; 109)	R(3 ; 7)
R(110 ; 139)	R(3 ; 7)
R(140; 169)	R(3 ; 7)
R(170 ; 209)	R(3 ; 7)
R(210 ; 350)	R(3 ; 7)

Table 5. *Probability distribution considered for the operating speed*

Radius (m)	Operating Speed (km/h)		
	40	60	80
R(50 ; 79)	N (40 ; 0.58)	N (60 ; 0.58)	N (80 ; 0.58)
R(80 ; 109)	N (40 ; 0.86)	N (60 ; 0.86)	N (80 ; 0.86)
R(110 ; 139)	N (40 ; 0.98)	N (60 ; 0.98)	N (80 ; 0.98)
R(140; 169)	N (40 ; 1.05)	N (60 ; 1.05)	N (80 ; 1.05)
R(170 ; 209)	N (40 ; 1.09)	N (60 ; 1.09)	N (80 ; 1.09)
R(210 ; 350)	N (40 ; 1.13)	N (60 ; 1.13)	N (80 ; 1.13)

5.2 Resulting rollover probabilities

Rollover probabilities were calculated with the VaP 1.6 Software, which allows defining non-linear limit state functions with non-normally distributed random variables, using Equations 8, 9 and 10. The software was run separately for the different speed levels. The results obtained for the mean operating speed of 60 km/h are shown in Figure 2 for vehicles 1 and 3 (simple and articulated truck) and in Figure 3 for vehicles 2 and 4 (urban bus and double decker interurban bus). Figures 4 and 5 show the results for the operating speed of 80 km/h, under the conditions already mentioned above. In all cases, limit states are illustrated for all 5 failure functions (Equations 12 to 16).



a) Type 1 Vehicle - Bank Angle 3-5%

b) Type 1 Vehicle - Bank Angle 5-7%

c) Type 3 Vehicle - Bank Angle 3-5%

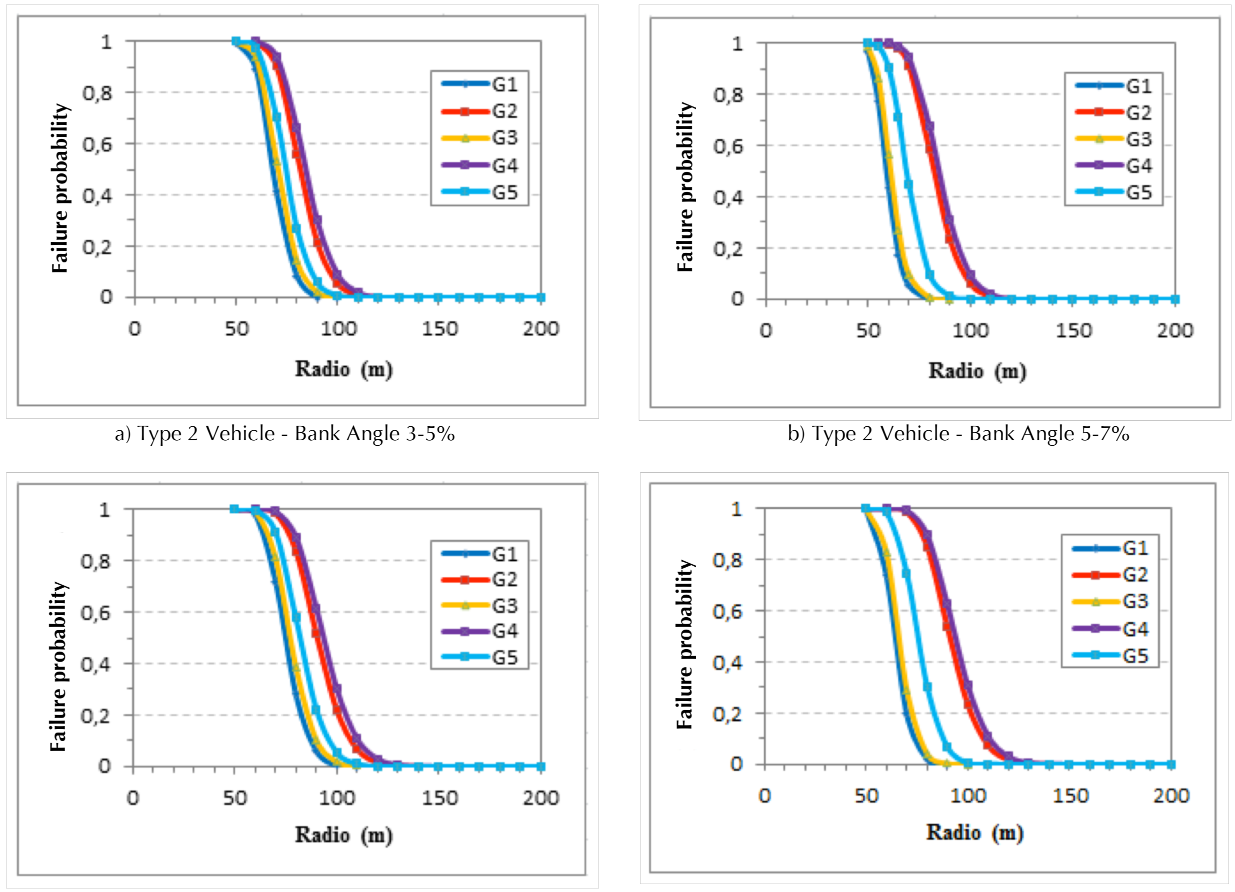
d) Type 3 Vehicle - Bank Angle 5-7%

Figure 2. *Rollover probability for vehicles 1 and 3 at an operating speed of 60 km/h*

Low operating speeds (40 km/h) evidenced that the failure probability of the different models was 0 for a radius over 50 m, where a probability higher than 0.5 was observed within a radius ranging from 30 to 35 m for rollover on the outer side of the curve, and around 40 m for rollover on the inner side of the curve. This occurred only with vehicles type 4. That is, those with narrow track width and heights of the center of gravity above 2.3 m.

For intermediate operating speeds (60 km/h), the behavior patterns of Figure 2 show that the failure probability towards the outer side of the curve (G1 and G3) is lower than 0.5, regardless of the bank angle and for all radiuses of curvature. For the inner side of the curve (G2 and G4), the failure probability of 0.5 is reached within a radius between 50 and 60 m. In this case, the geometry of the vehicle has more influence than the bank angle. If there is a failure due to static stability (G5),the failure probability is zero for wide-track vehicles. In vehicles with high center of gravity (Figure 3), the failure probability close to 0.5 towards the outer side of the curve (G1 and G3) is reached within a radius between 70 and 80 m; with greater bank angles these values drop to 60-70 m.

When visualizing the failure probability on the inner side of the curve (G2 and G4), it is possible to observe that it is high within a radius between 70 and 80 m, but this probability is reduced to 0.5 in radiuses of around 80-90 m, with the particularity that those values do not change when increasing the bank angle. Finally, concerning G5, the failure probability of 0.5 is reached within a radius between 70 and 80 m; these values remain constant when the bank angle is increased for narrow-track vehicles (vehicle 4) and they drop to 70 m for wide-track vehicles (type 2 vehicle).



a) Type 2 Vehicle - Bank Angle 3-5%

b) Type 2 Vehicle - Bank Angle 5-7%

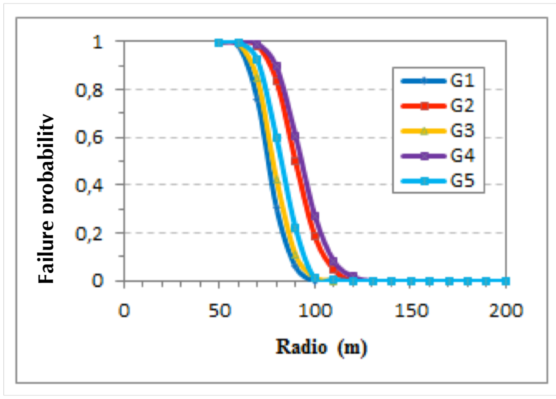
c) Type 4 Vehicle - Bank Angle 3-5%

d) Type 4 Vehicle - Bank Angle 5-7%

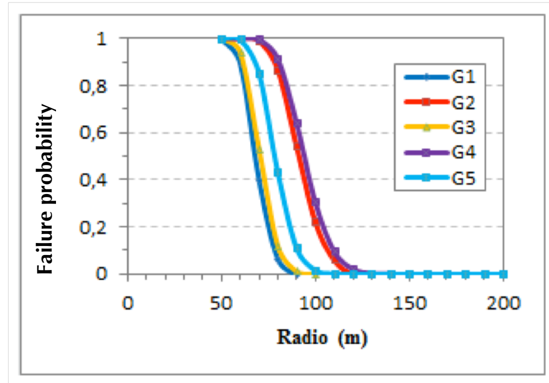
Figure 3. *Rollover probability of vehicles 2 and 4 at an operating speed of 60 km/h*

Figure 4 shows that the failure probability on the outer side of the curve is high within a radius between 50 and 60 m, dropping to a 0.5 probability within a radius between 75 and 85 m. On the inner side of the curve the situation is similar, because at speeds of 80 km/h, the failure probability of 0.5 is reached within a radiuses between 90 and 100 m; these values do not vary when the bank angle is increased and they practically double the 50 m for this probability to occur at speeds of 60 km/h. Finally, G5 shows a probability drop up to 0.5 within a radius between 80 and 90 m, slightly decreasing to 75 and 85 m when the bank angle is increased.

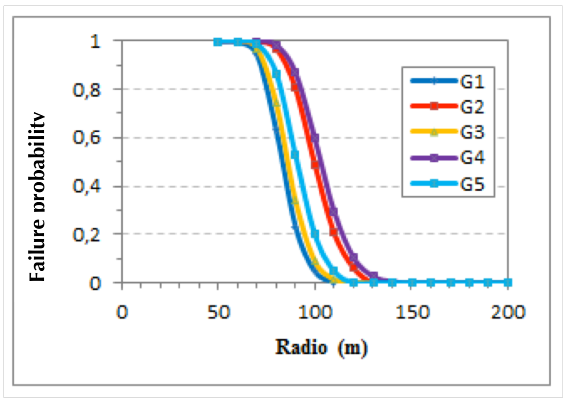
The behavior of vehicles with higher centers of gravity (vehicles 2 and 4 in Figure 5) shows that the failure probability towards the inner side of the curve is practically 1 for a radius smaller than 120 m, in the case of wide tracks, and a radius smaller than 140 m for narrow tracks. The probability decreases to 0.5 for a radius within 150 and 160 m, regardless of the bank angle being low or high. Concerning the failure probability on the outer side of the curve, we observe that it is high within a radius smaller than 100 m when the bank angle is small, and within a radius between 80 and 90 when the bank angle is high. The failure probability drops to 0.5 within a radius between 110 and 120 m. Finally, G5 shows that a failure probability higher than 0.5 occurs within a radius of approximately 140 m when the bank angle is small and around 130 m when it increases.



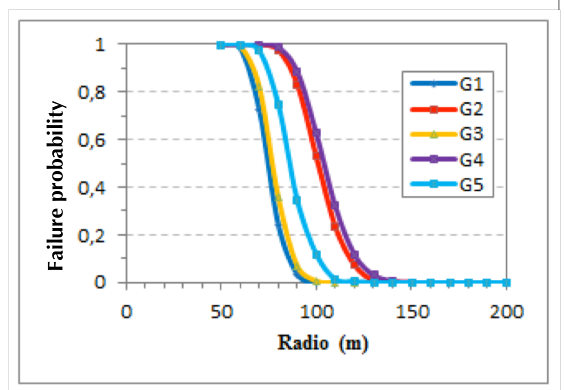
a) Type 1 Vehicle - Bank Angle 3-5%



b) Type 1 Vehicle - Bank Angle 5-7%

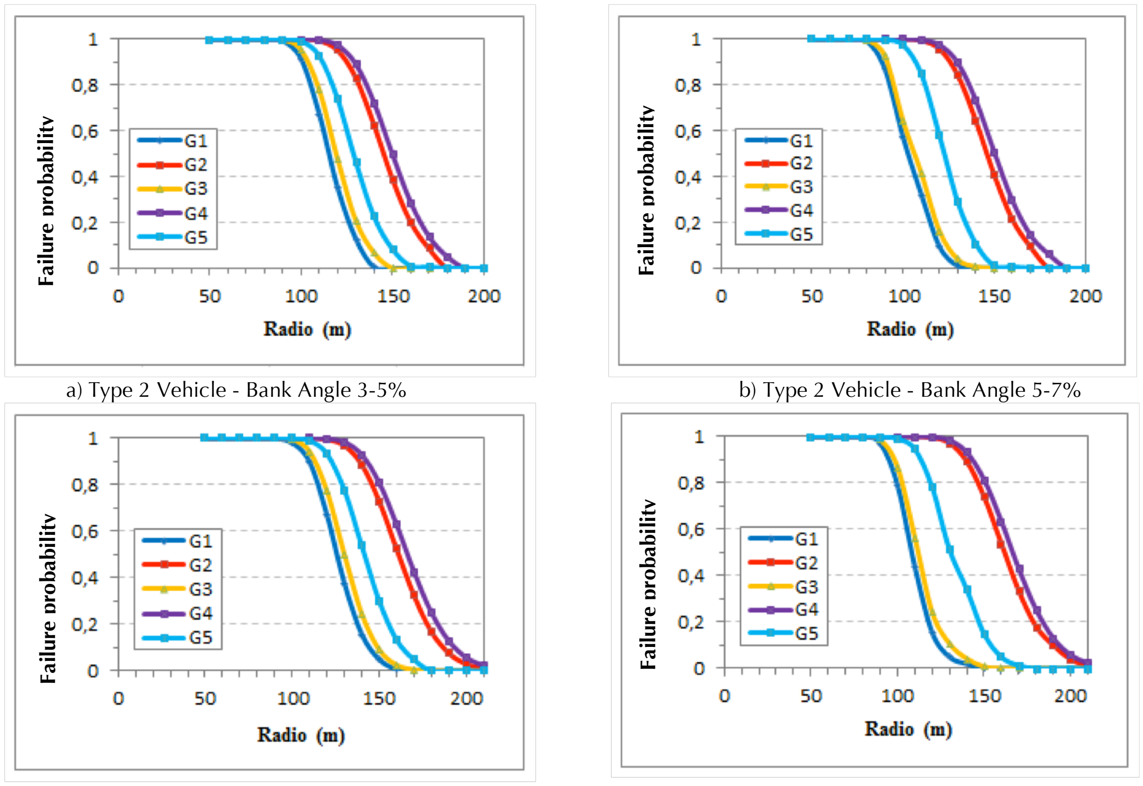


c) Type 3 Vehicle - Bank Angle 3-5%



d) Type 3 Vehicle - Bank Angle 5-7%

Figure 4. *Rollover probability of vehicles 1 and 3 at an operating speed of 80 m/h*



a) Type 2 Vehicle - Bank Angle 3-5%
b) Type 2 Vehicle - Bank Angle 5-7%
c) Type 4 Vehicle - Bank Angle 3-5%
d) Type 4 Vehicle - Bank Angle 5-7%

Figure 5. *Rollover probability of vehicles 2 and 4 at an operating speed of 80 km/h*

6. Conclusions

The purpose of this work was to propose a probabilistic approach to evaluate the rollover risk potential of heavy vehicles when driving through horizontal curves. The reliability theory was applied to obtain rollover probability curves based on the radius of curvature, with the aim of providing guidelines to consider this failure modality in the geometric design of horizontal curves in highways.

The models used to evaluate the rollover potential applied the following explanatory variables: operating speed when taking the curve, radius of curvature, and type of vehicle. These variables are generally used in the instructions of the geometric design, and the most relevant is the radius of curvature, since the standards do not only define the minimum radius but also establish criteria to specify radiuses above the minimum one. In this sense, this work offers mechanisms to determine minimum radius values that can be used in the standards related to the probability that a turnover occurs, through failure probability curves drawn up herein.

For example, and based on the above, if we assume that an acceptable failure probability is 50%, the minimum recommendable radius will depend on the input speed, so that for vehicles with high center of gravity, such as a double decker bus, the minimum radius fluctuates between 40 and 170 m for speeds between 40 and 80 km/h when taking the curve. For vehicles with a lower center of gravity and the same speed range when taking the curve, the minimum radius varies between 60 and 100 m.

Likewise, when setting a minimum radius or higher than the minimum, it is possible to estimate the limit speed value recommended for a specific horizontal curve, so as to limit the failure probability at an acceptable value.

Therefore, the results obtained in this study provide a promising approach in dealing with road design for heavy vehicles, both from the point of view of the standards and the geometric design.

Notwithstanding the above, the analysis can be improved by including other vehicles in the study, like SUV models (sport and utility cars) and vans, which would allow having a wide range of standard vehicles covering the characteristics of the local vehicle fleet.

On the other hand, the designed curves can be empirically validated based on historical data of rollover accidents, which implies an important challenge of fusing simulation and empirical data in order to produce hybrid probability curves. In other words, calibrated and validated by using theoretical and empirical data at the same time.

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