Stability Models of Heavy Vehicle

Gonzalo Moreno, Simón Figueroa and Bladimir Ramon

Department of Mechanical Engineering, University of Pamplona
543050 Pamplona, Colombia

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Abstract

In many countries around the world, heavy vehicles are very important, since they are the means to move industrial production, but due to their size, these vehicles have low stability and they are propensity to rollover, which seriously affected the road safety. In this context, the static rollover threshold (SRT) is the factor used to define the stability of these vehicles, but there are several factors defined by the literature. In the present study a literature review of heavy vehicle stability factors is made, and an experimental problem of the SRT factor calculation is shown.

Keywords: Stability models, Heavy vehicle, Road safety, Rollover

1. Introduction

The stability problems of heavy vehicles (HV’s) frequently cause the rollover of these vehicles, this road accident type occur during cornering or evasive maneuvers and may be defined as a maneuver in which the vehicle rotates 90 degrees or more around its longitudinal axis such that the body, and not only the wheels, makes contact with the ground. There are three ways to identify the rollover of vehicles, the real static models (Tilt Table Rollover Test) [1, 5], the real dynamics models [3, 17, 20], and the mathematical or simulation models. However, due to the high costs associated with the first two kinds of tests, mathematical models are the most used in research.

Taking into consideration this aspect, a variety of measurements have been defined to parameterize the stability of HV’s, being the Static Rollover Threshold (SRT) the most used; this factor represents the maximum lateral acceleration in a quasi-static situation immediately before one tire loses contact with the ground [6, 7, 18]. In the classic analysis (Fig. 1) [6], when the vehicle makes a turn and taking moments about the A point, the lateral tire forces counterbalance the lateral
inertial force, resulting in a roll moment, and at the rollover threshold condition, the normal load $F_{z2}$ reaches zero, then, the $SRT$ factor can be calculated by Eq. (1):

$$SRT = \frac{a_y}{g} = \frac{t/2}{h}$$  \hspace{1cm} (1)

This factor depends on the location of the $CG$, and this location is influenced by several characteristics of the vehicle; taking into account this, the paper is organized as follows. Section 2 introduces the main two-dimensional models of $SRT$ factor. Section 3 introduces the main three-dimensional models of $SRT$ factor; the results are analyzed and discussed within a case study in Section 4. Lastly, in Section 5, we give conclusions.

2. Two-Dimensional Models

The main models consulted in the literature considered the influence of the suspension and tires on the lateral and vertical $CG$ location, and the influence of the bank angle on the load distribution of the vehicle, all this characteristic affect the vehicle behavior \[4, 6, 7, 9, 16, 19\], some models are analyzed below.

2.1 Winkler model

This model considers the influence of the suspension and tires (Fig. 2), making the same analysis of the rigid model, Eq. (2) shows the $SRT$ factor,
Equation (2) show that the lateral $CG$ movement is greater that the vertical $CG$ movement, which makes the stability factor is smaller compared to the rigid model.

### 2.2 Rill model

This model includes the roll stiffness of the suspension, and the equivalent vertical rubber stiffness of the tire (Fig. 3), Eq. (3) shows the $SRT$ factor for this model,
Equation (3) shows that the denominator is greater than that indicated in Eq. (1), which makes that the stability factor is smaller, and additionally, the second term of the equation must be subtracted.

### 2.3 Chang models

This model takes into account the influence of the suspension and the bank angle (Fig. 4), Eq. (6) show the $SRT$ factor,

\[
SRT_R = \frac{t}{h_0 + l_{12} + \frac{l_{12}}{k_\theta - 1}} - \frac{1}{k_T}
\]  

(3)

\[
k_\theta^* = \frac{k_\theta}{m g l_{12}} = \frac{k_{ls} b^2}{m g l_{12}}
\]

(4)

\[
k_r^* = \frac{t}{m g}
\]

(5)

Equation (6) shows that the bank angle increases the $SRT$ factor, but the roll angle of the suspension decreases this factor.

### 2.4 Gillespie model

This model takes into account the roll stiffness of the suspension [6], Eq. (7) show the $SRT$ factor,
Figure 5: Gillespie model 1.
Source: Adapted of Gillespie [6].

Equation (7) shows that the numerator is smaller than that indicated in Eq. 1, which makes that the stability factor is smaller.

2.5 Moreno model
This model takes into account some characteristics of the vehicle and the road [10, 12], using the Davies Method, the SRT factor is represented by the Eq. (8).

Figure 6: Moreno model 1.
Source: Adapted of Moreno [12].

Equation (8) shows that the suspension and the tires allow the CG movement, which decreases the SRT factor, and the bank angle allows the increases of this factor.
3. Three-Dimensional Models

Although there are few three-dimensional models developed, these are very important, since they allow seeing the stability as a three-dimensional phenomenon; some models are analyzed below.

3.1 Navin model
This model defines a virtual roll axis from fifth-wheel to rear outside trailer tire (Fig. 7), and considering a moment about this axis, the \( SRT \) factor is represented by the Eq. (9),

\[
SRT_N = \frac{t}{2} \left(1 - \frac{l_{ee}}{L}\right) + \frac{h}{L} (\phi - \theta) - \frac{h_s}{L} \phi + h_b \theta
\]

This model takes into account the suspension and the longitudinal \( CG \) location, but don’t have into account the stiffness of the chassis, which would allow its front and rear parts to roll almost independently, which would change the roll axis of the vehicle in the rollover threshold [8, 16, 17].

3.2 Moreno model
Using the same methodology of the two-dimensional model (Section 2.5) [11], the researchers developed a three-dimensional model that considers the main characteristics of trailer and the road (Fig. 8), the \( SRT \) factor is defined by the Eq. (10).
Figure 8: Moreno model 2. 
Source: Adapted of Moreno [11].

\[ SRT_{M2} = \frac{h_1 + h_2 e}{h_2 - (h_1 + P_1)e} \left( 1 - \frac{t_1 F_{z3} \cos \psi + P_1 (F_{z3} - W \cos \phi)}{W \cos \phi (h_1 \cos \phi + h_2 e \cos \phi)} \right) \]  \hspace{1cm} (10)

\[ P_1 = (2l_1 \sin \psi + t_2 (\cos \psi - 1))/2 \]  \hspace{1cm} (11)

Of the models analyzed, this is the most complete and specific, since that take into account the great majority of characteristics that influence on the \( SRT \) factor calculation.

4. Stability Models Comparison

Using the model and the parameters of the Moreno [11], Fig. 9 shows the \( SRT \) factor for the main models developed in this work, additionally and considering that the lateral load transfer on the front axle \( (LLR_F) \) is approximately 70% of the \( LLT_r \) coefficient on the rear axle (16); and that the recommended maximum lateral load transfer for the rear axle \( (LLT_r) \) is 60% [17, 20], the \( SRT \) factor used in USA [2], New Zealand [15], and Moreno [11] were compared.
Figure 9: SRT models.
Source: The authors.

Figure 9 shows that the SRT factor for the Moreno models [11, 12] is less than the ones currently used in the world, this fact would make that the road safety greater [13]. On the other hand, the SRT factor is dependent on lateral acceleration. Rearranging the Eq. (1) and replacing the lateral acceleration as shown in Eqs. (12) and (13).

\[
SRT = \frac{a_y}{g} = \frac{V^2}{R} \tag{12}
\]

\[
V = \sqrt{SRT \cdot g \cdot R} \tag{13}
\]

Using the Eq. (13), Table 1 shows the speed limits for a vehicle making a curve of radius \( R = 120 \) m, and taking into account the SRT factor for the three cases highlighted in Fig. 9.

<table>
<thead>
<tr>
<th>Research</th>
<th>SRT factors</th>
<th>Max. speed ((V)(km/h))</th>
</tr>
</thead>
<tbody>
<tr>
<td>USA [2]</td>
<td>0.23</td>
<td>59.2</td>
</tr>
<tr>
<td>New Zealand [15]</td>
<td>0.22</td>
<td>57.9</td>
</tr>
<tr>
<td>Moreno Model [11]</td>
<td>0.202</td>
<td>55.5</td>
</tr>
</tbody>
</table>

Source: The authors.

Table 1 shows how the SRT factor can influence the speed limits of the vehicles. The velocity of the Moreno model [11] has a decrease of around 6.3 % with respect to the velocity in USA [2] and around 2.1 % with respect to the velocity in New Zealand [15].
5. Conclusions

The results of this study demonstrate that when the vehicle length is considered, the SRT factor becomes smaller, and this is a real problem. If we use the two-dimensional SRT factor as an important feature to characterize the vehicle stability, we are neglecting the longitudinal effects.
The case study shows that when it is used the three-dimensional model [11], the SRT factor is approximately 38% lower than the reported value for a rigid vehicle.
The SRT factor decrease is important, as it allows to set new road speed limits, which contributes with road safety and decreases vehicle stability related to accidents, which are very high nowadays.

References


Stability models of heavy vehicle


**Nomenclature**

- \(a\) distance between the front axle and the trailer \(CG\)
- \(\alpha_y\) lateral acceleration
- \(e\) tangent of the bank angle
- \(F_{ci}\) tire normal load \(i\)
- \(g\) gravity acceleration
- \(h\) height of the center of gravity
- \(h_0\) height of the roll center
- \(h_1\) instantaneous lateral distance between the zero-reference frame and the \(CG\)
- \(h_2\) instantaneous \(CG\) height
- \(k_{ls}\) equivalent leaf stiffness of the suspension
- \(k_T\) equivalent vertical rubber stiffness of the tire
- \(k_\theta\) stiffness of the suspension
- \(L\) wheelbase of the trailer
- \(l_{re}\) distance from the \(CG\) to the rear axle
- \(l_{13}\) distance between the fifth-wheel and the front axle
- \(m\) mass of the vehicle
- \(R\) radius of curvature
- \(t\) vehicle track
- \(t_1\) front track width of the trailer model
- \(t_2\) front axle width
- \(\Delta t\) lateral movement of the \(CG\) relative to the center of track
- \(V\) vehicle speed
- \(W\) trailer weight
- \(\psi\) trailer/trailer angle
- \(\phi\) bank angle
- \(\theta\) roll angle of the suspension

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