COBEM 2023
27TH INTERNATIONAL CONGRESS OF MECHANICAL ENGENEERING

ABCM
Brazilian Society of Mechanical Sciences and Engineering
27th ABCM International Congress of Mechanical Engineering
December 04-08, 2023, Florianópolis-SC, Brazil

COB-2023-0651
VALIDATION OF THE MODEL TO THE STABILITY OF HEAVY VEHICLES CALCULATION

Gonzalo G Moreno Contreras
Department of Mechanical Engineering - University of Pamplona - Colombia
gmoren@unipamplona.edu.co

Rodrigo de S. Vieira
Daniel Martins
Department of Mechanical Engineering - Federal University of Santa Catarina - Florianopolis - Brasil
rodrigo.vieira@ufsc.br, daniel@emc.ufsc.br

Abstract. *For heavy vehicle manufacturers, it is of great importance that their vehicles meet high standards of safety and comfort for their customers. In this regard, there are many aspects investigated in the literature, particularly the development of models to predict the stability of these vehicles, which consider their characteristics and the road in the calculation of the Static Rollover Threshold (SRT), a measure employed and accepted in the literature to determine the risk of rollover for this type of vehicle. However, it is essential to compare these models with other models that have already been validated and established in the literature so that the proposed methodology can be validated and accepted. With this objective in mind, the authors developed a vehicle model that incorporates a kinesthetic representation of the last unit of a heavy vehicle, and Davies' method is applied to calculate the Static Rollover Threshold. Subsequently, as the central aspect of this research, the validation of the applied technique is performed through simulation and calculation of the stability of a heavy vehicle using the TruckSim software. According to the authors, this vehicle and the one developed by the kinesthetic model share the same characteristics (tires, suspension, fifth wheel, and chassis) that have the greatest impact on stability. The tests were conducted under ISO 14792:2011 (Road vehicles — Heavy commercial vehicles and buses — Steady-state circular tests). Additionally, the stability results obtained are compared with other authors from the literature. In conclusion, it can be stated that the developed stability technique and model offer excellent results and present themselves as an efficient and innovative alternative for the analysis and calculation of heavy vehicle stability.*

Keywords: *Road safety, Static Rollover Threshold, Comfort.*

1. INTRODUCTION

The stability of heavy vehicles is a topic that has been widely investigated, for which several methodologies have been developed to detect how likely a vehicle is to rollover (Gillespie, 2021; Hac, 2002; Kamnik *et al.*, 2003; Moreno *et al.*, 2018a; Ungoren and Peng, 2004; Winkler, 1987). Likewise, several systems have been developed which it is expected to reduce the risk of accidents and increase safety on the roads (Ahmadian and Patricio, 2004; Aykent, 2010; Braghin *et al.*, 2008; Gaspar *et al.*, 2005).

One of the most important methodologies applied to determine the stability of vehicles is the Static Stability Factor (SRT), which evaluates the maximum lateral acceleration that a vehicle can withstand before overturning.

In this context, authors such as Gillespie (2021); Navin (1992); Winkler (1987); Rill (2011) have proposed models of heavy vehicles in three dimensions from which they determine the Static Rollover Threshold (SRT) considering vehicle features such as suspension, tires, and the fifth wheel.

Considering these authors and applying the Davies method, a kinestatic model was developed in which various characteristics of the vehicle and the road were simulated, and through which the SRT factor was calculated in different situations of the vehicle (Moreno *et al.*, 2018a,b).

Subsequently, to validate this model and as the basis of this article, a comparison was made between the measurements obtained from the developed model and those derived from simulating a similar vehicle using TruckSim software.

2. METHODOLOGY

In terms of stability of heavy vehicles, the trailer is the critical unit of the vehicle, since it is there where the phenomenon of vehicle overturning begins (Jindra, 1966; Rempel, 2002). This is made up in its structure by the chassis, the rear axles, the suspension, the tires, and the fifth-wheel hitch system.

As previously mentioned, studies have already been carried out to analyze the influence of several of these characteristics on vehicle stability; in this regard, Moreno *et al.* (2018a,b) developed a stability model for a heavy vehicle (Figure 1), which takes into account vehicle and road characteristics for the SRT factor calculation (Equation 1).

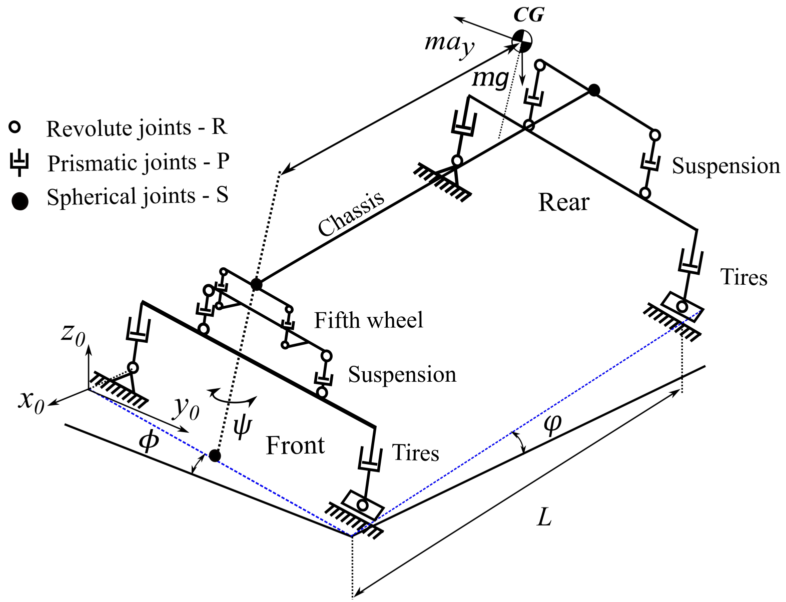

Figure 1. Trailer model of a heavy vehicle

$$SRT_{3D_{\psi\phi\varphi}} = \frac{a_y}{g} = \frac{h_1 \cos\varphi + h_2 e \cos\varphi}{h_2 - (h_1 + P_1)e} \cdot \left(1 - \frac{t_1 F_{z3} \cos\psi + P_1(F_{z17} - W \cos\phi \cos\varphi)}{W \cos\phi (h_1 \cos\varphi + h_2 e \cos\varphi)}\right) \tag{1}$$

Where $SRT_{3D_{\psi\phi\varphi}}$ is the three-dimensional stability factor of a heavy vehicle, g is the gravity acceleration, a_y is the lateral acceleration, h_1 is the lateral distance of the CG in reference to the coordinate axis, h_2 is the CG's height, e is the tangent of the lateral slope of the road, P_1 is a system variable, F_{z3} and F_{z17} are the normal supporting forces of the vehicle (F_{z3} external tire to the curve, front axle, F_{z17} inner tire to curve, rear axle), W is the vehicle weight, ϕ is the angle of lateral slope of the road, φ is the angle of longitudinal slope of the road, and ψ is the truck/trailer angle.

On the other hand, the three-dimensional model of a semi-trailer (TruckSim®) shown in Figure 2 was analyzed for the validation of the developed model. The model comprises a truck with one axle at the front, one at the rear, and a trailer with three axles. Figure 2 and Table 1 shows the vehicle parameters used in this analysis.

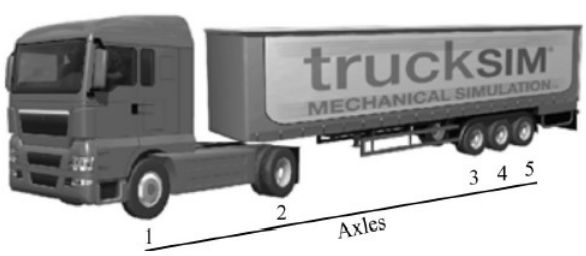

Figure 2. Semi-trailer - TruckSim®

3. CASE STUDY

3.1 TruckSim model

For the validation of the model developed by Moreno *et al.* (2018a), the steady-state circular test ISO-14792 (2011) was used to calculate the *SRT* factor; the test was made in a Circular Road with Radius $R = 60m$ (Figure 3), constant tangential speed (V), therefore a constant inertial force was applied until the lateral load transfer in the rear axles of the trailer became complete (3^{rd}, 4^{th} and 5^{th} axles as shown on Figure 2).

The test starts with a speed of 50 km/h and takes approximately 4 seconds to stabilize its responses. Figure 4 shows the normal forces on the tires of 5^{th} axle at 50 km/h, and one can notice that the lateral load transfer (*LLT*) (Rill, 2011) in the 5^{th} axle of the semi-trailer was not complete.

Table 1. Parameters of the trailer model.

Parameters	**Value**	**Units**
Vehicle weight - W	435	kN
Front and rear track widths (t)	1.815	m
Lateral separation between the spring (b)	0.95	m
Wheelbase of the trailer (L)	8.7	m
Distance from the front axle to the CG (a)	5	m
Bank angle (ϕ)	10	$\%$
Speeds of the tests (V)	50 : 1 to 60	km/h

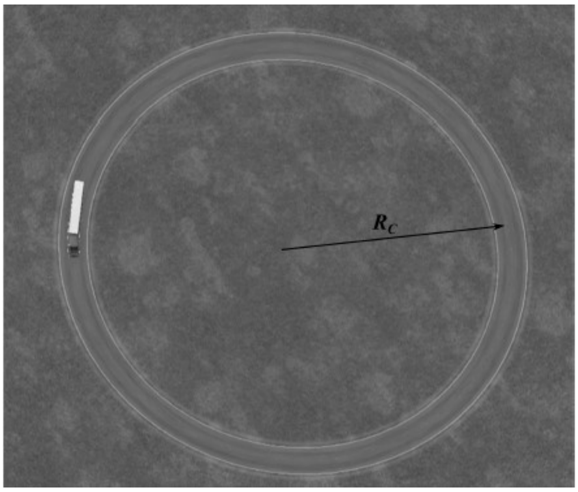

Figure 3. Circular road - TruckSim®

The lateral transfer of load in vehicles occurs during cornering because the forces acting on the vehicle (the weight and lateral inertial force) cause it to bear more weight on the outside side of the curve. This results in a shift of the load within the vehicle from the inside of the curve to the outside.

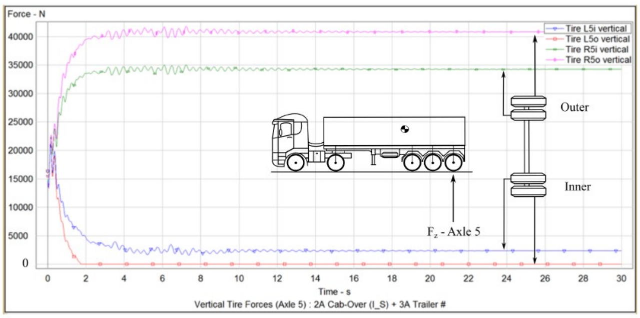

Figure 4. Normal force on tires of 5^{th} axle - $V = 50\ km/h$

Subsequently, the speed was gradually increased until reaching $58\ km/h$, where the lateral load transfer (*LLT*) in the $3^{rd}, 4^{th}$, and 5^{th} axles were complete. Figures 5 to 7 show the normal forces on tires of the $3^{rd}, 4^{th}$, and 5^{th} axles.

In this particular case, Figure 8 shows that the lateral load transfer (*LLT*) in the 2^{nd} axle of the trailer model was not complete. This fact is important since it corroborates the theory of the four-legged table developed by Blundell and Harty (2004) and applied by (Moreno *et al.*, 2018a,b) in their model.

Analyzing the normal forces on the 2^{nd} axle, the lateral load transfer is about 57 %. Rearranging the Eq. 1, and replacing the speed of the vehicle (V) and the radius of curvature (R), the $SRT_{3D_{\psi\phi\varphi}}$ factor for the TruckSim model is 0.4409.

$$SRT_{3D_{\psi\phi\varphi}} = \frac{a_y}{g} = \frac{V^2}{Rg} \tag{2}$$

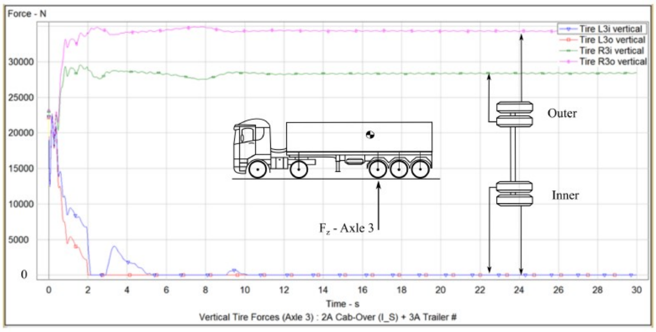

Figure 5. Normal force on tires of 3^{rd} axle - $V = 58\ km/h$

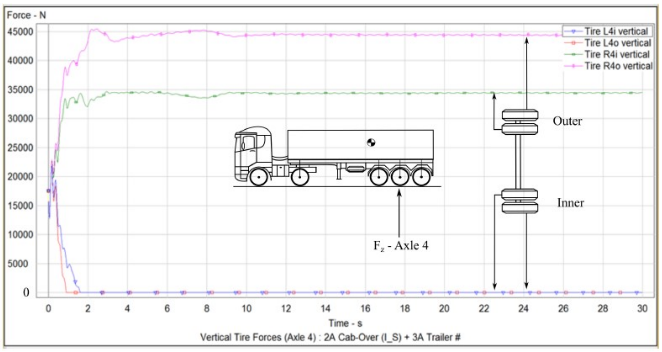

Figure 6. Normal force on tires of 4^{th} axle - $V = 58\ km/h$

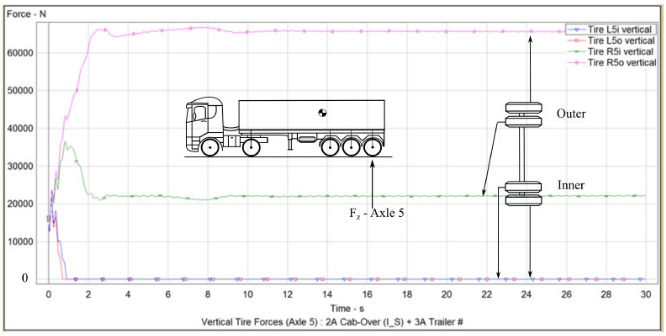

Figure 7. Normal force on tires of 5^{th} axle - $V = 58\ km/h$

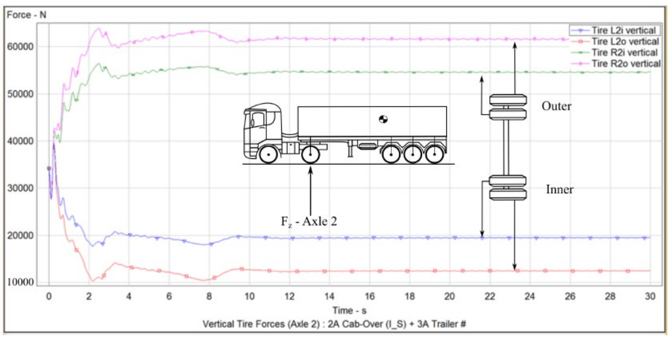

Figure 8. Normal force on tires of 2^{nd} axle - $V = 58\ km/h$

3.2 Kinematic model

The SRT factor was calculated using the model developed by Moreno *et al.* (2018a,b) (Figure 1), and the same TruckSim model parameters.

In this model, at the rollover threshold limit, the normal force in the rear inner tire reaches zero. Hence, applying this condition (Equation 1), we have that the $SRT_{3D_{\psi\phi\varphi}}$ factor is 0.4353.

4. CONCLUSIONS

Figure 9 provide a summary of some SRT factors: the rigid, the Gillespie and the Navin three-dimensional model, the proposed three-dimensional model, and the TruckSim model.

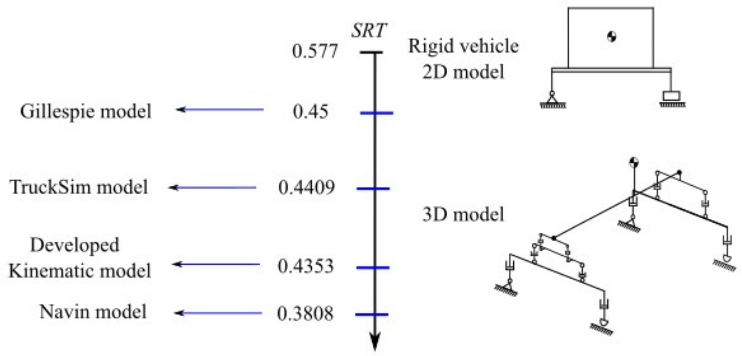

Figure 9. Case study with TruckSim

The developed kinematic model presents a difference of 1.2 % as compared to the TruckSim model and 3.2 % as compared to the Gillespie model (Gillespie, 2021).

When comparing the results obtained from the proposed model with the different models in the literature and the TruckSim model, it was possible to observe that the stability factor is very similar; this guarantees that the approach and methodology developed by Moreno *et al.* (2018a,b) is consistent and can be well accepted as a prediction model.

5. ACKOWLEDMENTS

The researchers expressed their gratitude to the TruckSim®company for providing the software for this important research at the Federal University of Santa Catarina - Brasil (2017)

6. REFERENCES

Ahmadian, M. and Patricio, P.S., 2004. “Effect of panhard rod cab suspensions on heavy truck ride measurements”. *SAE Transactions*, Vol. 113, pp. 551–559. ISSN 0096736X, 25771531. doi:https://doi.org/10.4271/2004-01-2710. URL `http://www.jstor.org/stable/44718850`.

Aykent, B., 2010. “Effects of sway acceleration control on rollover propensity and assessment of lateral specific forces”. Technical report, SAE Technical Paper. doi:https://doi.org/10.4271/2010-01-1325.

Blundell, M. and Harty, D., 2004. *Multibody systems approach to vehicle dynamics*. Elsevier.

Braghin, F., Cheli, F., Corradi, R., Tomasini, G. and Sabbioni, E., 2008. “Active anti-rollover system for heavy-duty road vehicles”. *Vehicle System Dynamics*, Vol. 46, No. sup1, pp. 653–668. doi:10.1080/00423110802033064. URL `https://doi.org/10.1080/00423110802033064`.

Gaspar, P., Szaszi, I. and Bokor, J., 2005. “Reconfigurable control structure to prevent the rollover of heavy vehicles”. *Control Engineering Practice*, Vol. 13, No. 6, pp. 699–711. ISSN 0967-0661. doi:https://doi.org/10.1016/j.conengprac.2004.06.003. URL `https://www.sciencedirect.com/science/article/pii/S0967066104001431`.

Gillespie, T., 2021. *Fundamentals of vehicle dynamics*. SAE international.

Hac, A., 2002. “Rollover stability index including effects of suspension design”. *SAE Transactions*, pp. 1403–1413. doi:https://doi.org/10.4271/2002-01-0965.

ISO-14792, 2011. “*Heavy commercial vehicles and buses - Steady state circular tests*”. Technical report.

Jindra, F., 1966. “Handling characteristics of tractor-trailer combinations”. *SAE Transactions*, pp. 378–394.

Kamnik, R., Boettiger, F. and Hunt, K., 2003. “Roll dynamics and lateral load transfer estimation in articulated heavy freight vehicles”. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, Vol. 217, No. 11, pp. 985–997. doi:https://doi.org/10.1243/095440703770383884.

Moreno, G., Nicolazzi, L.C., Vieira, R.D.S. and Martins, D., 2018a. “Stability of long combination vehicles”. *International journal of heavy vehicle systems*, Vol. 25, No. 1, pp. 113–131. doi:https://doi.org/10.1504/IJHVS.2018.089897.

Moreno, G., Vieira, R. and Martins, D., 2018b. “Highway designs: effects of heavy vehicles stability”. *Dyna*, Vol. 85, No. 205, pp. 205–210. doi:https://doi.org/10.15446/dyna.v85n205.69676.

Navin, F.P.D., 1992. “Estimating truck’s critical cornering speed and factor of safety”. *Journal of Transportation Engineering*, Vol. 118, No. 1, pp. 130–145. doi:10.1061/(ASCE)0733-947X(1992)118:1(130).

Rempel, M.R., 2002. *Improving the dynamic performance of multiply-articulated vehicles*. Ph.D. thesis, University of British Columbia.

Rill, G., 2011. *Road vehicle dynamics: fundamentals and modeling*. Crc Press.

Ungoren, A.Y. and Peng, H., 2004. "Evaluation of vehicle dynamic control for rolover prevention". *International Journal of Automotive Technology*, Vol. 5, No. 2, pp. 115–122.

Winkler, C.B., 1987. "Experimental determination of the rollover threshold of four tractor-semitrailer combination vehicles. final report". Technical Report 4.

7. RESPONSIBILITY NOTICE

The authors are solely responsible for the printed material included in this paper.