ANALYSIS OF THE LATERAL STABILITY OF CARGO VEHICLES COMBINATIONS - CVCS

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Abstract. *In 1998 the Resolution 68/98 of CONTRAN – National Council of Traffic, authorized the transit of Cargo Vehicles Combinations - CVCs. Because their major capacity of freight comparate with conventional combinations truck-tractor + semi-trailer, the numbers of CVCs in roads grow up rapidly, mainly the types Bi-trains and Rodotrains. Certainly representative of a cargo vehicles evolution because the increase of productivity that provide to the freight firms and by the direct and indirect goods to the country through the decrease of the product transportation's costs, these vehicles combinations must be observer about their characteristics of handling and security and the impacts that de increase of CVCs in the roads can have in the statistic of crash. Because the number of articulations, these combinations have specifics phenomenon that affect their handling. Among them the must important is the "Rearward Amplification". It is the increase of lateral displacement of the last vehicle when comparated with the lateral displacement of the tractor vehicle in curves and evasive maneuvers. In consequent of this rear amplification, the last unit is exposed to highest lateral acceleration, and can rollover, taking with it another vehicles of combination. A study for the determination of the rate of this amplification for the mainly types of CVCs is necessary to the evolution/correction of vehicles design, roads design, traffic signs and drivers courses. This was the objective of this work.*

Keywords*: lateral satability, Cargo Vehicle Combination, rollover, dynamical analysis*

1. Introduction

Handling characteristics is one of the most complex subjects in the field of vehicular dynamics and handling performance of articulated combination vehicles deteriorates with speed and variation of road and operating conditions. Investigation of road accidents point out the necessity of studies on the directional behavior and yaw stability of tractor trailer combinations (Esmailzadeh, 1996). According to Dugoff and Murphy (1971) the first research document on the directional dynamics of articulated vehicles was developed in 1937 for Huber and Dietz in Automotive Research Institute attn Stuttgart in Germany. The investigation of Huber and Dietz was experimental, consisting in a model in scale accompanied by a test program for evaluation of a trailer of 2 axles.The work of Huber and Dietz was followed by one theoretical evaluation elaborated by Ziegler in Stuttgart (Dugoff and Murphy, 1971). The simplified model neglected the sideslip effect.

With the computers advent, the solutions of complex equations that describe the motion of articulated vehicles were facilitated and many other works were developed. For example, Hales, Jindra, Ellis, Schimid and Kullberg analyzed the dynamic stability of vehicles articulated with three axles moving with constant longitudinal speed (Dugoff and Murphy, 1971); handling in articulated vehicle model was developed by Krauter and Wilson (1972); the common "jackknifing problem" in tractor-trailer vehicles was analyzed by Miculcik(1971); the vehicle stability with high gravity center was analyzed by MacAdam(1982).

Esmailzadeh (1996) developed a work about directional performance and yaw stability of articulated combination trucks. A detailed planar mathematical model for various design configurations of the tractor triaxle trailer combination, the tractor quadaxle trailer combination, and the doglogger truck were developed.

Jindra (1966) analyzed the handling characteristics of tractor-trailer combinations. Essentially, the vehicle combination under consideration was composed of four major components: a two-axle tractor; a semitrailer rotatable about the fifth wheel; a trailer dolly consisting of drawbar, axle and wheel assembly, frame for lower turntable and other rigidly mounted parts and rotatable around the tow pin; and a trailer body including the remaining parts of the full trailer such as upper turntable, full trailer chassis, rear axle, and rotatable about the turntable. Consequently, the vehicle combination is treated as a dynamic system with five degrees of freedom, corresponding to sideslip and yaw of the tractor and yaw angles of the three trailer components with respect to the tractor.

The mathematical model for dynamic analysis of Rodotrain is similar to the model used by Jindra (1966). The model was updated and adapted for the axles quantity and, the number of vehicles and articulations in the case of the Bi–train.

2. Mathematical model

All components of the systems (Fig. 1) are assumed to be rigid bodies with fixed center of gravity locations, that is, the relative motion between the axles and the vehicle bodies is neglected. It is also assumed that the fifth wheel, the drawbar hinge, and the turntable are frictionless, and they do not resist lateral motions of the single-axle trailers in relation to the tractor. Lateral forces transmitted from the road to the tires are considered to be the only important externally applied forces acting on the combined vehicle. In this analysis, rolling resistance of the wheels, aerodynamic forces, and various other dynamics effects that are present in the vehicles are ignored in the interest of simplifications.

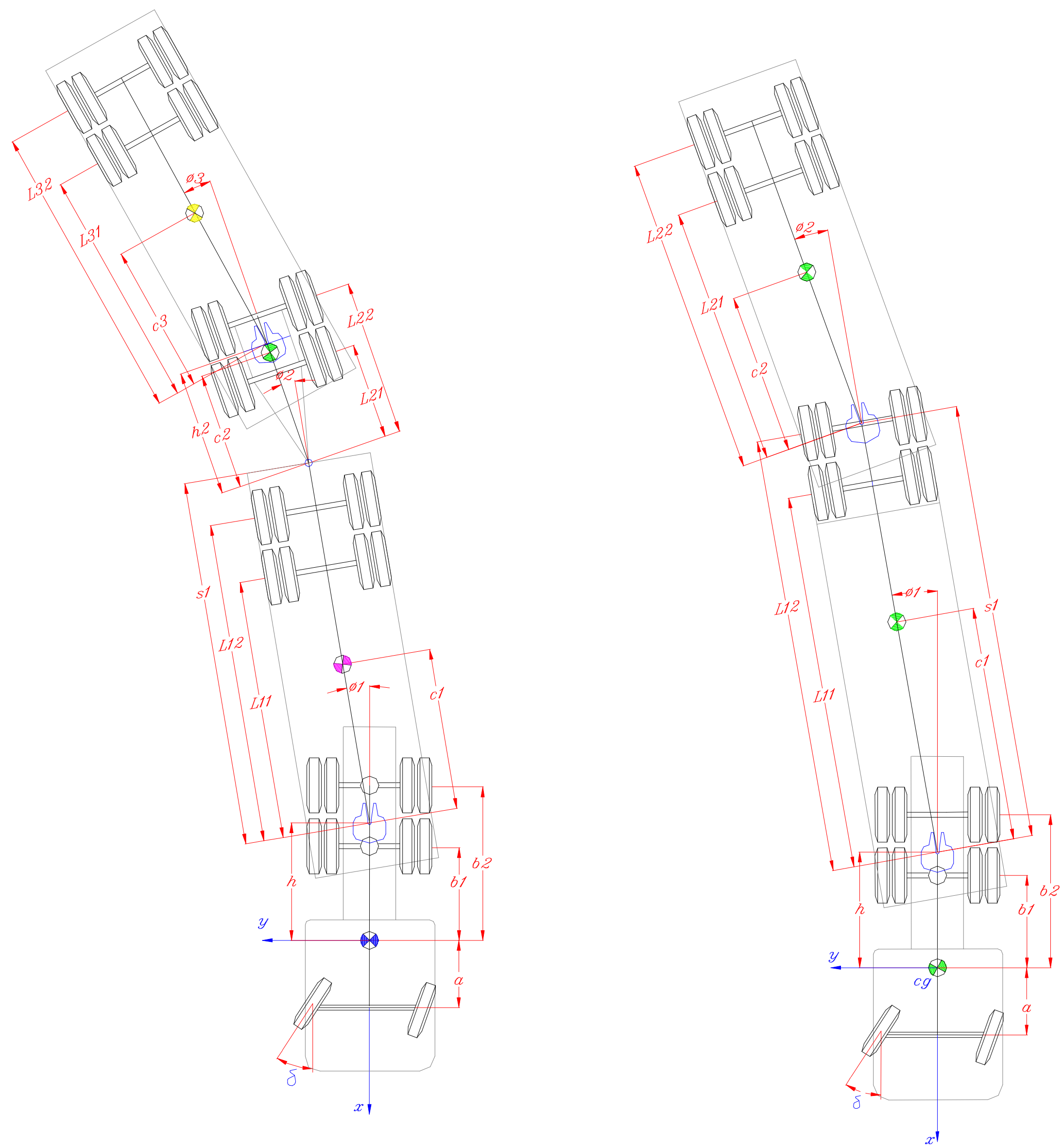


Figure 1. Rodotrain and Bi-train models

The equations of motions are developed by application of Newton’s laws for each of the vehicle’s degrees of freedom. More details about the equation can be found in Melo (2004). The motions of the each system were obtained using planar kinematics and relative motion between the bodies. The equations of motion of tractor, first semitrailer and second semitrailer of the bi-train model are:

$$
\begin{aligned}
&(m_0+m_1+m_2).\dot{v}+(\sum_{i=1}^{i=7}F_i).v/V-(m_1'+m_2').\dot{\omega}+[(m_0+m_1+m_2).V^2-(N_1'+N_2'+N_3'+N_4'+\\
&N_5'+N_6'+N_7')].\omega/V-(m_1.c_1+m_2.s_1).\ddot{\phi}_1-[N_4.L_{11}+N_5.L_{12}+(N_6+N_7).s_1].\dot{\phi}_1/V-\\
&(N_4+N_5).\phi_1-m_2.c_2.\ddot{\phi}_2-(N_6.L_{21}+N_7.L_{22}).\dot{\phi}_2/V-(N_6+N_7).\phi_2=N_1.\delta
\end{aligned}
\tag{1}
$$

$$
\begin{aligned}
&m_0.h.\dot{v}+[(N_1+N_2+N_3).h-N_1'-N_2'-N_3'].v/V+I_0.\dot{\omega}+[m_0.h.V^2+N_1.a^2+N_2.b_1^2+N_3.b_2^2-\\
&(N_1'+N_2'+N_3').h].\omega/V=N_1.(a+h).\delta
\end{aligned}
\tag{2}
$$

$$
\begin{aligned}
&-(m_1.c_1+m_2.s_1).\dot{v}-[N_4.L_{11}+N_5.L_{12}+(N_6+N_7).s_1].v/V+(I_1+m_1'c_1+m_2's_1).\dot{\omega}-\\
&[(m_1.c_1+m_2.s_1).V^2-N_4'L_{11}-N_5'L_{12}-(N_6'+N_7').s_1].\omega/V+(I_1+m_1.c_1^2+m_2.s_1^2).\ddot{\phi}_1+\\
&[N_4.L_{11}^2+N_5.L_{12}^2+(N_6+N_7).s_1^2].\dot{\phi}_1/V+(N_4.L_{11}+N_5.L_{12}).\phi_1+(m_2.c_2.s_1).\ddot{\phi}_2+(N_6.L_{21}+\\
&N_7.L_{22}).s_1.\dot{\phi}_2/V+(N_6+N_7).s_1.\phi_2=0
\end{aligned}
\tag{3}
$$

$$
\begin{aligned}
&-m_2.c_2.\dot{v}-(N_6.L_{21}+N_7.L_{22}).v/V+(I_2+m_2'c_2).\dot{\omega}-(m_2.c_2.V^2-N_6'L_{21}-N_7'L_{22}).\omega/V+\\
&m_2.c_2.s_1.\ddot{\phi}_1+(N_6.L_{21}+N_7.L_{22}).s_1.\dot{\phi}_1/V+(I_2+m_2.c_2^2).\ddot{\phi}_2+(N_6.L_{21}^2+N_7.L_{22}^2).\dot{\phi}_2/V+\\
&(N_6.L_{21}+N_7.L_{22}).\phi_2=0
\end{aligned}
\tag{4}
$$

where:

$m_1'=m_1.(h+c_1)$

$m_2'=m_2.(h+s_1+c_2)$

$N_1'=-N_1.a$

$N_2'=N_2.b_1$

$N_3'=N_3.b_2$

$N_4'=N_4.(h+L_{11})$

$N_5'=N_5.(h+L_{12})$

$N_6'=N_6.(h+s_1+L_{21})$

$N_7'=N_7.(h+s_1+L_{22})$

m_0, m_1, m_2 = tractor, first semitrailer and second semitrailer mass
I_0, I_1, I_2 = inertia moments around z-axis (tractor, first semitrailer and second semitrailer);
ω = angular velocity around z-axis;
v = lateral velocity (y-axis)
u = longitudinal velocity (x-axis)
ϕ_1 =angular displacement between first semitrailer and tractor
ϕ_2 =angular displacement between second semitrailer and first semitrailer
N_i = cornering power coefficient
α = tire slip angle

δ = steering angle
$V = ui + vj$

The motion equations of the rodotrain model are:

$$(m_0 + m_1 + m_2 + m_3).\dot{v} + (\sum_{i=1}^{i=9} F_i).v / V - (m_1' + m_2' + m_3').\dot{\omega} + [(m_0 + m_1 + m_2 + m_3).V^2 - \sum_{i=1}^{i=9} N_i'].\omega / V - [m_1.c_1 + (m_2 + m_3).s_1]\ddot{\phi}_1 - [N_4.L_{11} + N_5.L_{12} + (N_6 + N_7 + N_8 + N_9).s_1].\dot{\phi}_1 / V - (N_4 + N_5).\phi_1 - (m_2.c_2 - m_3.h_2).\ddot{\phi}_2 - [N_6.L_{21} + N_7.L_{22} + (N_8 + N_9).h_2].\dot{\phi}_2 / V - (N_6 + N_7).\phi_2 - m_3.c_3.\ddot{\phi}_3 - (N_8.L_{31} + N_9.L_{32}).\dot{\phi}_3 / V - (N_8 + N_9).\phi_3 = N_1.\delta \tag{5}$$

$$m_0.h.\dot{v} + [(N_1 + N_2 + N_3).h - N_1' - N_2' - N_3'].v / V + I_0.\dot{\omega} + [m_0.h.V^2 + N_1.a_2 + N_2.b_1^2 + N_3.b_2^2 - (N_1' + N_2' + N_3').h].\omega / V = N_1.(a + h).\delta \tag{6}$$

$$- [m_1.c_1 + (m_2 + m_3).s_1].\dot{v} - [N_4.L_{11} + N_5.L_{12} + (N_6 + N_7 + N_8 + N_9).s_1].v / V + [I_1 + m_1' c_1 + (m_2' + m_3').s_1].\dot{\omega} - \{[m_1.c_1 + (m_2 + m_3).s_1].V^2 - N_4' L_{11} - N_5' L_{12} - (N_6' + N_7' + N_8' + N_9').s_1 \}.\omega / V + [I_1 + m_1.c_1^2 + (m_2 + m_3).s_1^2].\ddot{\phi}_1 + [N_4.L_{11}^2 + N_5.L_{12}^2 + (N_6 + N_7 + N_8 + N_9).s_1^2].\dot{\phi}_1 / V + (N_4.L_{11} + N_5.L_{12}).\phi_1 + (m_2.c_2 + m_3.h_2).s_1.\ddot{\phi}_2 + [N_6.L_{21} + N_7.L_{22} + (N_8 + N_9).h_2].s_1.\dot{\phi}_2 / V + (N_6 + N_7).s_1.\phi_2 + m_3.c_3.s_1.\ddot{\phi}_3 + (N_8.L_{31} + N_9.L_{32}).s_1.\dot{\phi}_3 / V + (N_8 + N_9).s_1.\phi_3 = 0 \tag{7}$$

$$-(m_2.c_2 - m_3.h_2).\dot{v} - [N_6.L_{21} + N_6.L_{22} + (N_8 + N_9).h_2].v / V + (I_2 + m_2' c_2 + m_3' h_2).\dot{\omega} - [(m_2.c_2 + m_3.h_2).V^2 - N_6' L_{21} - N_7' L_{22} - (N_8' + N_9').h_2].\omega / V + (m_2.c_2 + m_3.h_2).s_1.\ddot{\phi}_1 + [N_6.L_{21} + N_7.L_{22} + (N_8 + N_9).h_2].s_1.\dot{\phi}_1 / V + (I_2 + m_2.c_2^2 + m_3.h_2^2).\ddot{\phi}_2 + [(N_6.L_{21}^2 + N_7.L_{22}^2 + (N_8 + N_9).h_2^2].\dot{\phi}_2 / V + (N_6.L_{21} + N_7.L_{22}).\phi_2 + m_3.c_3.h_2.\ddot{\phi}_3 + (N_8.L_{31} + N_9.L_{32}).h_2.\dot{\phi}_3 / V + (N_8 + N_9).h_2.\phi_3 = 0 \tag{8}$$

$$- m_3.c_3.\dot{v} - (N_8.L_{31} + N_9.L_{32}).v / V + (I_3 + m_3' c_3).\dot{\omega} - (m_3.c_3.V^2 - N_8' L_{31} - N_9' L_{32}).\omega / V + m_3.h_2.s_1.\ddot{\phi}_1 + (N_8.L_{31} + N_9.L_{32}).s_1.\dot{\phi}_1 / V + m_3.c_3.h_2.\ddot{\phi}_2 + (N_8.L_{31} + N_9.L_{32}).h_2.\dot{\phi}_2 / V + (I_3 + m_3.c_3^2).\ddot{\phi}_3 + (N_8.L_{31}^2 + N_9.L_{32}^2).\dot{\phi}_3 / V + (N_8.L_{31} + N_9.L_{32}).\phi_3 = 0 \tag{9}$$

where:

$m_1' = m_1.(h + c_1)$

$m_2' = m_2.(h + s_1 + c_2)$

$m_3' = m_3.(h + s_1 + h_2 + c_3)$

$N_1' = -N_1.a$

$N_2' = N_2.b_1$

$N_3' = N_3.b_2$

$N_4' = N_4.(h + L_{11})$

$N_5' = N_5.(h + L_{12})$

$N_6' = N_6.(h + s_1 + L_{21})$

$N_7{}' = N_7.(\, h + s_1 + L_{22}\,)$

$N_8{}' = N_8.(\, h + s_1 + h_2 + L_{31}\,)$

$N_9{}' = N_9.(\, h + s_1 + h_2 + L_{32}\,)$

m_0, m_1, m_2, m_3 = tractor, first semitrailer , dolly and second semitrailer mass
I_0, I_1, I_2, I_3 = inertia moments around z-axis (tractor, first semitrailer, dolly and second semitrailer);
ϕ_1 =angular displacement between first semitrailer and tractor
ϕ_2 =angular displacement between dolly and first semitrailer
ϕ_3 =angular displacement between second semitrailer and dolly

The equations (1) to (4) may be regarded as a set of four nonhomogeneous, linear algebraic equations in the five unknowns $\dot{v}$, $\dot{\omega}, \ddot{\phi}_1$ and $\ddot{\phi}_2$, and can be solved for these quantities by the usual methods for solving systems of linear equations. At the same way, equations (5) to (9) can be solved to $\dot{v}$, $\dot{\omega}, \ddot{\phi}_1, \ddot{\phi}_2$ and $\ddot{\phi}_3$. In matrix notation the equations can be represented as:

$$[A]\{y\} = [B]\{x\} \tag{10}$$

3. Results

The data used to simulate the behavior of bi-train and rodotrain are shown in Table 1.

Table 1. Physical data.

Parameter	Model type			
	bi-train		rodotrain	
	loaded	unloaded	loaded	unloaded
m_0 (kg)	8800	8800	89271	91036
m_1 (kg)	24900	5900	303619	51993
m_2 (kg)	23900	4900	29430	27468
m_3 (kg)			303619	51993
I_0 (kg.m^2)	47054	45157	52419	52419
I_1 (kg.m^2)	164003	47054	168790	23489
I_2 (kg.m^2)	106165	18280	3713	3713
I_3 (kg.m^2)			168790	23489
a (m)	1.831	1.831	1.831	1.831
b_1 (m)	1.368	1.368	1.368	1.368
b_2 (m)	2.738	2.738	2.738	2.738
h (m)	1.743	1.743	1.743	1.743
c_1 (m)	2.697	4.269	2.410	3.243
l_{11} (m)	5.955	5.955	3.799	3.799
l_{12} (m)	7.205	7.205	5.049	5.049
s_1 (m)	7.100	7.100	5.835	5.835
c_2 (m)	3.101	4.522	2.500	2.500
l_{21} (m)	3.735	3.735	2.354	2.354
l_{22} (m)	4.985	4.985	3.604	3.604
c_3 (m)			2.410	3.243
l_{31} (m)			3.799	3.799
l_{32} (m)			5.049	5.049
h_2 (m)			2.550	2.550
N_1 (N/rad)	248211*2	184503*2	248211*2	209324*2
N_2 (N/rad)	184090*4	65859*4	175816*4	59819*4
N_3 (N/rad)	167542*4	599028*4	175816*4	59819*4
N_4 (N/rad)	175816*4	44099*4	175816*4	40189*4
N_5 (N/rad)	175816*4	44099*4	175816*4	40189*4
N_6 (N/rad)	175816*4	44099*4	175816*4	40189*4
N_7 (N/rad)	175816*4	44099*4	175816*4	40189*4
N_8 (N/rad)			175816*4	40189*4
N_9 (N/rad)			175816*4	40189*4

Figure 2 shows the two steering angle (inputs) found in technical literature. These inputs were used to computational simulation.

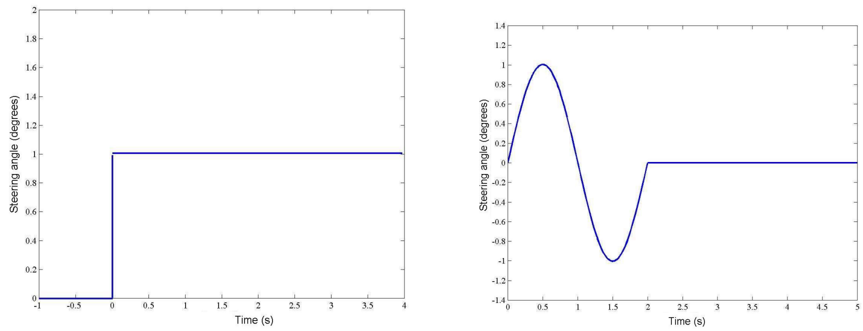
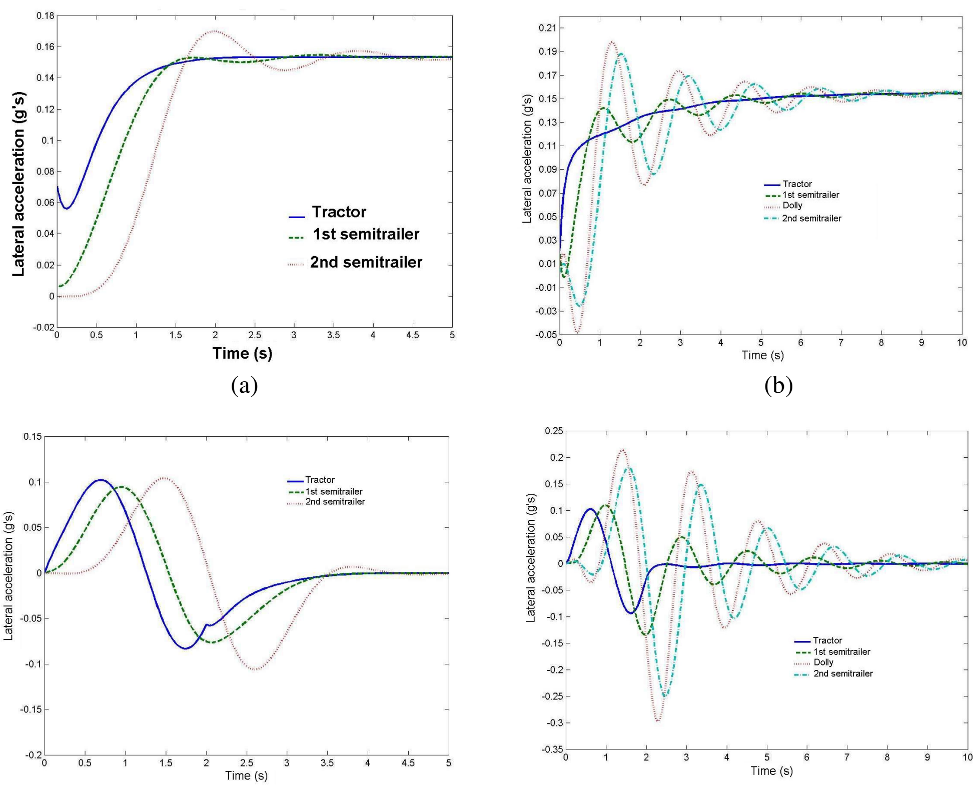


Figure 2. Step and sinusoidal inputs used to computational simulation.

Figure 3 show the lateral acceleration in time domain to the vehicle loaded for step and sinusoidal inputs. The vehicle speedy is 70 km/h. It can be noted that the stabilization time and the peak value of the acceleration for both situations it is greater for the rodotrain vehicle type (around 10 s and 0,2g). The 2[nd] semitrailer and dolly present the higher acceleration levels.

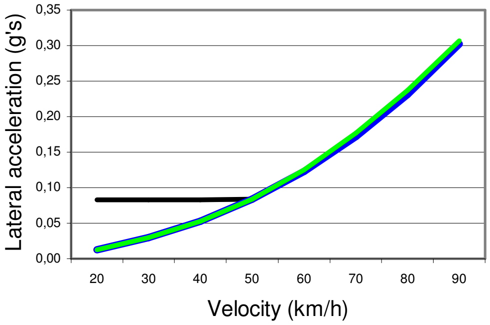


(a) (b)

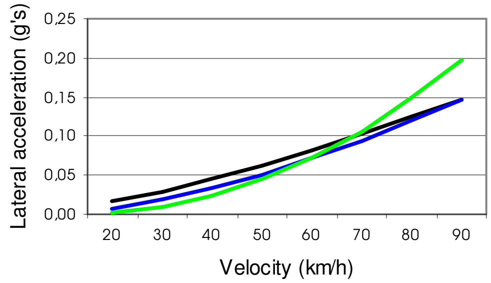
(c) (d)

Figure 3. Lateral acceleration. Step input – (a) bitrain and (b) rodotrain loaded.
Sinusoidal input - (c) bitrain and (d) rodotrain loaded.

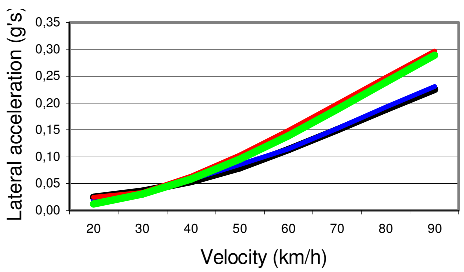
To verify the rollover limit of loaded vehicles, the velocity was varied between 20 to 90 km/h. The results were similar to the presented in Fig. 3. The peak values of lateral acceleration are shown in Fig. 4. It can verify that the greater acceleration levels are found for dolly and 2[nd] semitrailer. This fact evidences the “Rearward Amplification”. The 2[nd] semitrailer can rollover, taking with it the another vehicles of combination.



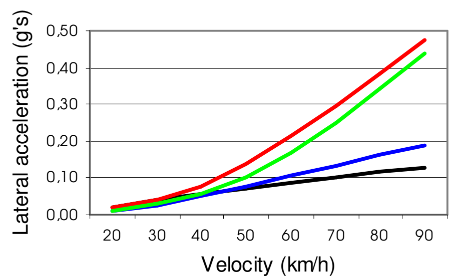
(a)



(b)



(c)



(d)

Figure 4. Lateral acceleration. Black line – tractor; blue line-1st semitrailer; green line – 2nd semitrailer and red line-dolly. Bi-train (a) step and (b) sinusoidal inputs. Rodotrain (c) step and (d) sinusoidal inputs.

Analyzing the eigenbehavior to other load situations: vehicle unloaded, first semitrailer unloaded and second semitrailer loaded, first semitrailer loaded and second semitrailer unloaded, it was possibly to verify a instable condition of rodotrain when the first semitrailer is unloaded and the second semitrailer is loaded, to vehicle velocity between 20 a 30 km/h. Figure 5 shows this situation where the amplitudes increase with time.

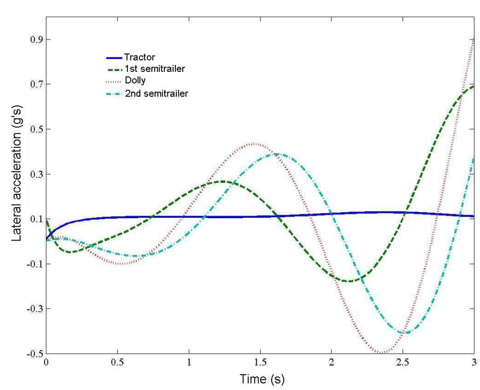


Figure 5. Lateral acceleration (v=70 km/h, step input)

4. Conclusions

In general, the Bi-train keep relatively stable in the evaluated maneuvers, with a small lateral amplification compared with presented by the Rodotrain.

In the unloaded condition, although the lateral accelerations and time of stabilization be larger, comparatively with the loaded condition, rollover risks are smaller having in mind that the inexistence of the load reduces the height of the center of gravity of the vehicles.

In the condition with the first semitrailer unloaded and second semitrailer loaded, the lateral accelerations are significantly larger in both vehicle types, and the rodotrain becomes unstable in the evaluated maneuvers, carrying to the lateral rollover.

It can be noted the "rearward amplification" of the lateral acceleration (values near or higher than 0,30 g) that can rollover the vehicle, mainly the rodotrain type.

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5. Responsibility notice

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