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STABILITY AND ROAD SAFETY OF LONG COMBINATION VEHICLES (LCV): ISSUES AND MODELS.

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Abstract. *Long Combination Vehicles (LCV) emerged as a solution to increase the transport of cargo volume at a lower price. Many countries worldwide had approved the road traffic of this type of vehicle in order to be more competitive. However, there are some aspects of stability that make this type of vehicles unreliable. In recent years, the incidence of the rollover accidents of LCVs has been increasing; this had allowed the development of many static and dynamic studies seeking to better understand the factors that produce this type of incident. In the present study can be seen a description of the importance of the LCVs, advantages and disadvantages, characteristics of the most common LCVs, problems, studies and finally we propose a new approach to the study of the dynamics of the rollover accidents of LCVs.*

Keywords: *Long Combination Vehicles, LCVs, vehicle dynamic, stability, road safety.*

1. INTRODUCTION

Long Combination Vehicles (LCV) emerged as a solution to increase the volume of cargo transportation, as a low price solution. Many countries worldwide, including Brazil, had approved the road traffic of this type of vehicle in order to be more competitive. Despite the advantages of this kind of transportation, there are some aspects of his stability that make them known as unreliable vehicles.

In recent years, the incidence of the rollover accidents of LCVs has been increasing dramatically. This issue has encouraged the development of many static and dynamic studies looking for a better understanding regards the factors involved in this type of incident.

Today the Long Combination Vehicles (LCV) have become the primary way of cargo transportation in Brazil. According to the National Register of Road Freight Carriers (RNTR, 2013) there are about 1.86 million registered cargo vehicles on Brazilian roads, under several classifications made by the National Transportation Agency (ANTT, 2013), the Brazilian Technical Standards Bureau (ABNT) and the National Association of Automobile Manufacturers (ANFAVEA). There are three different sectors: short, middle and long distances, where the last one is the more common, and by consequence, the most important for economic development of Brazil. Important to notice that LCV is a kind of long distance modal.

In the last years, Brazil has faced a strong increasing of Long Combination Vehicles (LCV) models. According to Petrassi (2010) and Saisse (2008), in Brazil there are about one hundred thousand LCVs, divided into 61 different types of LCVs approved by the National Traffic Council (CONTRAN, 2013) and National Traffic Department (DENATRAN, 2013) over Brazilian roads, such as LCV “Romeo and Juliet” (a local variant of 9-axles truck), B-Train, Road-Train and Triple Trailer Combination.

Besides this complex scenario, B-train and Road-train are the most common in Brazil, thanks to their advantages regarding other cargo vehicles, such as load capacity, 45% higher, and operation costs reductions, about 16% less, , according to Gonçalves (2004).

This study provides a description of the importance of the LCVs, advantages and disadvantages, characteristics of the most common LCVs, problems, studies and a new approach to the study of the dynamics of the rollover accidents of LCVs.

2. IMPORTANCE OF LONG COMBINATION VEHICLES

According to Adams et al. (2012), land freight transport plays an important role as improving the competitiveness of a country. A global world needs competitive logistics networks and the land freight transport is a key point for a

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safety and reliable delivery of goods. United States, Canada, Australia, New Zealand, Brazil and many other countries of Asia and Europa, have authorized the road traffic of the Long Combination Vehicles, since these vehicles allow higher carrying capacity and therefore a reduction in transport costs. These factors had led to an increase in the use of Long Combination Vehicles worldwide in last years.

Long Combination Vehicles, commonly called "LCVs" are tractor-trailer combinations with two or more trailers that may exceed 36 tons gross vehicle weight (GVW). The Figure 1 shows to comparison of several LCVs with some common non-LCVs.

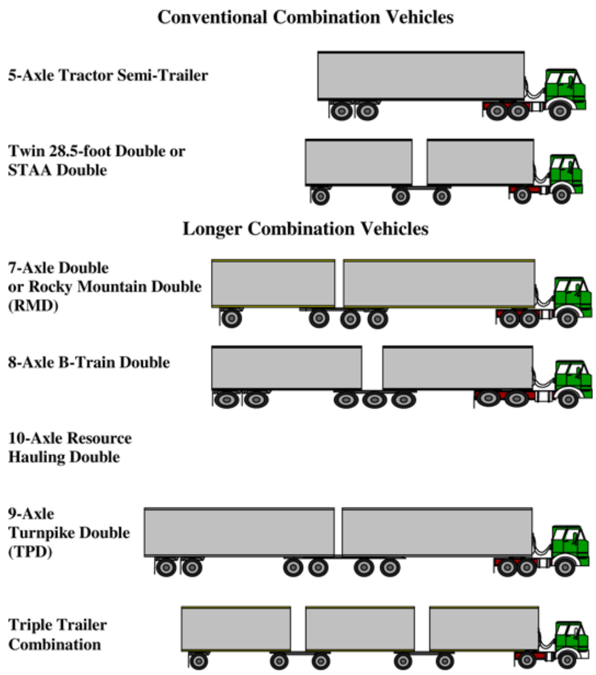

Figure 1 Comparison of Longer Combination Vehicles with Conventional Trucks
Source: U.S. Department of Transportation- Federal Highway Administration.

Robb et al. (2009) cites advantages and disadvantages for the use of LCVs as described below. There are advantages of LCVs are:

a) Productivity: LCVs improve productivity due an increase of cargo-carrying capacity of 30% to 100% per driver. This results in fewer truck trips, lower cost, and fewer miles driven.
b) Cost: transport costs may be lower due to fewer drivers needed per cargo unit, and more efficient use of fuel. The cost savings may be passed on to the consumer, or increase profits.
c) Traffic: improved productivity may result in fewer trucks on the road.
d) Air emissions: LCVs may produce lower air emissions per unit of cargo transported.

The same paper lists as disadvantages of LCVs are:

a) Safety: large trucks are involved in a disproportional percentage of fatal collisions. However, statistics on LCVs are difficult to obtain because of the low number of vehicle involved. Triples tend to sway and can leave the lane they are traveling in, although sway can be lessened by advanced connector types. Triples also require more passing length, spray more rain and snow, and have a history of being underpowered while climbing steep grades.
b) Pavement damage: heavier trucks deteriorate the pavement structure at an accelerated rate. A study at University of Texas found that one big rig pass causes the damage equivalent to 2,000 to 3,000 cars. However, the extra pavement damage from LCVs may be mitigated by the increased number of axles.
c) Infrastructure damage: LCVs, demonstrate wider off-tracking on curves than conventional truck. Off-tracking can damage shoulders, curbs and roadside signs along ramps and intersections.

2.1 Long combination vehicles (LCVs) in Brazil

As explained before, Long Combination Vehicles, commonly called "LCVs," are tractor-trailer combinations with two or more trailers that may exceed 36 tons gross vehicle weight (GVW). In Brazil the most common LCVs are B-Train and Road-Train. Both have the tractor and two semi-trailers units, connected each other by different ways.

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The B-Train is a set of three vehicles, one three axles tractor, and two double axles semi-trailer connected by a fifth wheel, as shown in Fig. 2. The main features of the bi-train are presented in Tab. 1.

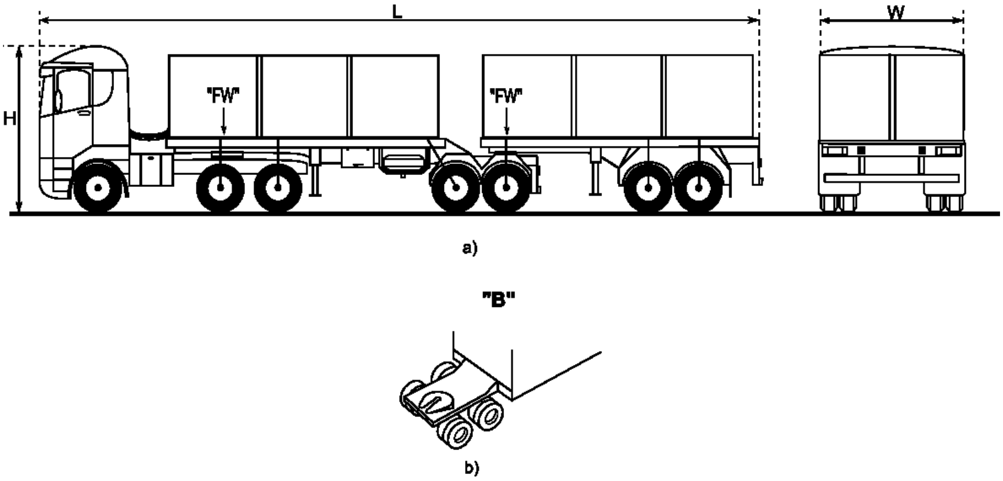

Figure 2 B-Train
a) Scheme, b) B-train connection type B.

Table 1. Characteristics the B-Train.

	Tractor 6x4			ST-1		ST-2		Total	Net Charge	Reference
Axles	1	2	3	4	5	6	7	7 or 8		Penteado (2004).
Load – TGCW[(1)] (Ton)	6	17		17		17		57	30-38	Petrassi (2010), Penteado (2005).
Length (L) (m)								17,5 - 19,8		CTB - Resolution No 210-211 of 13/11/2006.
Width (W) (m)								2,6		
Maximum Height (H) (m)								4,4		
Speed (km/h)								80		
Joints (fifth wheel)								2		
Coupling ST1-ST2								B		Winkler (2000).

[(1)] TGCW = Total Gross Combined Weight
ST – Semi-trailer

The Road-train is a set of four vehicles, a three axles tractor, two double axles semi-trailer and an intermediate structure called "dolly" with two axles. Both semi-trailers are connected by a fifth wheel, to dolly (type A or C) and to tractor, as shown in Fig. 3. The main features of the road-train are presented in Tab. 2.

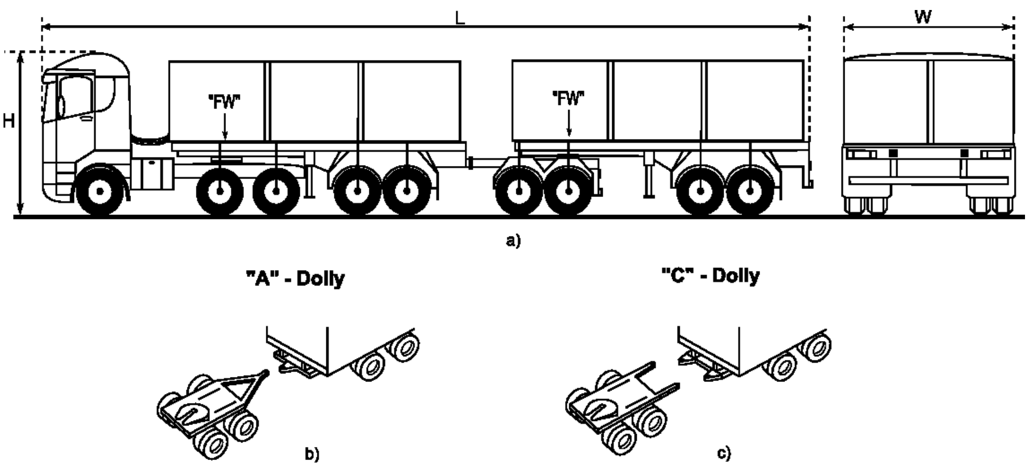

Figure 3 Road-train.
a) Scheme, b) Dolly connection type A, c) Dolly connection type C

Table 2. Road-train characteristics.

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	Tractor 6 x 4			ST-1		Dolly		ST-2		Total	Net Charge	Reference
Axles	1	2	3	4	5	6	7	8	9	9		Penteado (2004).
Load – TGCW [1] (Ton)	6	17		17		17		17		74	47-52	Petrassi (2010), Penteado (2005).
Length (L) (m)										19,8		CTB – Resolution No 210-211of 13/11/2006. Licensed until Feb. 2007
Length (L) (m)										25-30		CTB - Resolution No 210-211of 13/11/2006.
Width (W) (m)										2,6		
Maximum Height (H) (m)										4,4		
Speed (km/h)										80		
Joints (fifth wheel)										3		
Coupling ST1-Dolly										A or C		Winkler (2000).

[1] TGCW = Total Gross Combined Weight
SR – Semi-trailer

The topologies of connections between semi-trailers A, B, C have been extensively studied (Dahlberg et al. 2004), (Delisle, 1986) and (Oberoi, 2011). These studies indicate that vehicles with connection type B and C had fewer stability problems, because they had at least one more joint compared to vehicles that have connection type "A". According to Gonçalves (2006), in Brazil, the connection type used is the "A", which has a single point of engagement.

According New Zealand Transport Agency (2007), the inherent characteristics of each type of LCVs regards stability and accidents are, for B-train:

a) Due to the manner in which the trailer is coupled to the prime mover, in the event of a rollover the complete combination will roll.
b) Not susceptible to yaw except in extreme situations.
c) Very susceptible to the effects of low speed off-tracking particularly when maneuvering.

For the Road-Train, they also advise that:

a) They are susceptible to trailer yaw.
b) Rear trailer can rollover completely independent the semi-trailer.
c) Because of the large number of pivot points, this type of combination is susceptible to rearward amplification.

2.2 Studies on LCVs

According to Petrassi (2010), the main studies on the LCVs, cover the following topics:

a) Lateral stability of the LCV.
b) Geometric design of highways.
c) Influence of LCV indices accidentally on the road.
d) Impact of LCV on the highways.

The high rates of vehicle accidents and its consequences are one of the main reasons to study this problem. The National Confederation of Transport (CNT, 2013) presents very impressive numbers. There were about 189 thousand traffic accidents only on Federal Highways, with a balance of 8400 people killed and 104 thousand wounded, data from 2011. The same survey estimate that the country spends U$ 15.7 billion per year as hospital costs, loss of future incomes, traffic jams, vehicle damages, and so on.

According to Jabour (2010), in 2007 the trucks in Brazil were involved in 36% of all accidents, , 5.7% of them by overturning, and 6.5% by rollovers. According to the same study, even though accidents rates are low, the number of people killed, wounded and economic losses are quite high.

3. ROLLOVER ISSUE

Rollover 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.

According to Anderson (1997), LCVs are generally less stable than an ordinary tractor and semitrailer. The magnitude of that instability and the situations in which it occurs is still a subject of deep research. Typically, LCVs are more suitable to rollover and are subject to trailer sway and rearward amplification. In addition, the height of the center of gravity, cargo distribution, type and mechanical condition of connections, number of articulation points, trailer lengths, roadway geometry, speed, and drivers' skills, all affect the stability of an LCV. The trailer's length and the number of articulation points have a significant effect on stability. Generally, short trailers and the big number of articulation points, produce unstable vehicles. The connection between the tractor and trailers has another important

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issue. Comparing to a conventional tractor-semitrailer, a LCV is more suitable to rollover because these connections do not provide the stability as a fifth wheel does. Therefore, a tractor connected to the trailer by a fifth wheel has more resistance to rollover than the second or third trailers of an LCV have.

Trailer sway, is defined as the side-to-side movement of multiple trailers, and is not so significant as a stability factor of LCVs. The only exception is the Triple Trailer (Fig. 1), which can sway up to one foot and invade the adjacent lanes on the road. The Rocky Mountain Double (Fig. 1) does sway, but not enough to be unsafely (ANDERSON, 1997).

Another factor that affects LCV stability is rearward amplification, which occurs "when the lateral acceleration of the tractor is amplified as it travels toward the rear of the trailer." This amplification happens when a driver makes a sudden maneuver, as an unexpected steering movement, as “The Moose Test”. Triples have the highest degree of amplification, followed by shorter doubles. Rocky Mountain doubles and turnpike doubles offer more stability during sudden steering movements (ANDERSON, 1997).

According to NZ-Transport Agency (2007), rearward amplification only applies to LCVs when there is more than one articulation (pivot) point. For example, a truck and trailer combination has a pivot point in the draw bar coupling; a B-train has two pivot points, one in each turntable where the kingpin is locked into the turntable jaws. Rearward amplification, or cracking the whip, occurs during a rapid lane change where a relatively small steering input of the towing vehicle is amplified (increased), through each pivot point. As result, the end of the trailer can react very violently to the lane change. Overseas research has demonstrated that cracking the whip becomes a significant stability factor at road speeds above 60 km/h.

There are many factors that influence a vehicle’s tendency to rollover, but according to NZ-Transport Agency (2007) the following are the most crucial:

a) The vehicle’s speed.
b) The height of the center of gravity.
c) The type and condition of the suspension.
d) The type and condition of tires.
e) The rearward amplification.

Typically rollovers occur during cornering and sudden evasive steering maneuvers. According Hac (2002) and Winkler (2000) the basic measure for evaluating lateral stability of vehicles is called Static Rollover Threshold (SRT) and is expressed as the lateral acceleration in g's. The static rollover threshold is obtained by considering the balance of forces acting on a rigid vehicle in steady-state cornering. During cornering the lateral tire forces on the ground level, counterbalance the lateral inertial force acting at vehicle center of gravity, resulting in a roll moment. This moment is counterbalanced by the moments of vertical forces. The Figure 4 presents a simplified model of a heavy vehicle in a steady turn in which the vehicle, its tires, and suspensions have been “lumped” into a single roll plane. The nomenclature of the figure is as follows:

a_y is lateral acceleration
h is the height of the cg.
F_i are the vertical tire load, i = 1, 2.
Δh is the vertical motion of the cg relative to the track.
Δt_w is the lateral motion of the cg relative to the track.
M is the mass of the vehicle.
ϕ_T is the roll angle of the vehicle.

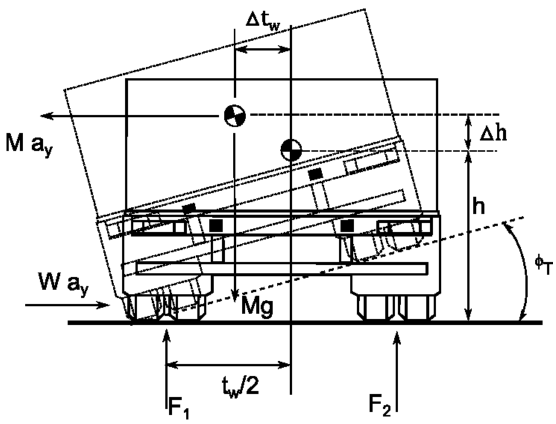

Figure 4 Model of Static Rollover Threshold (SRT).

At the limit cornering condition (rollover threshold) the normal load, F_2, reaches zero. Considering the moments to the center of contact patches for the outside tires results, as in Eq. (1), (2):

$$T = \sum Mg\left({}^{t_w}\!/_2 - \Delta t_w \right) - Ma_y\left(h + \Delta h \right) = 0 \tag{1}$$

$$SRT = \frac{a_{y_{LIM}}}{g} = \frac{\left({}^{t_w}\!/_2 - \Delta t_w \right)}{h + \Delta h} \tag{2}$$

Based on these criteria, and the use of other parameters of the vehicle, both static and dynamic mathematical models have been developed in order to obtain more reliable results regarding the limits of vehicle rollover.

3.1 Static model

The main static model used for the LCVs is the tilt-table experiment, which simulates limit vehicle rollover, as shown at Fig. 5.

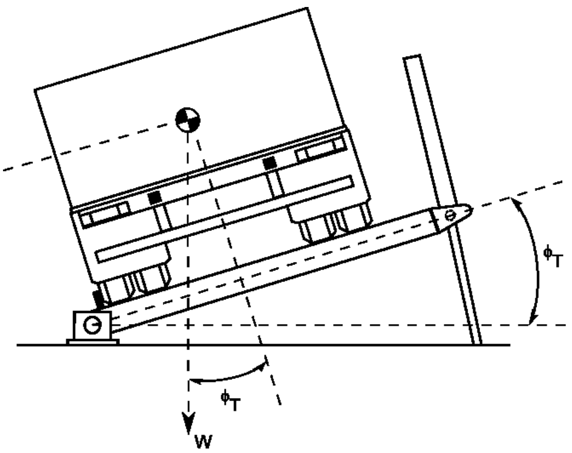

Figure 5 Tilt-table Experiment

Based on this experiment, many models were developed, considering additional parameters of the vehicles; Hac (2002) considered the displacement track gauge caused by the suspension design, and the gyroscopic forces of the vehicle. For Gertsch (2003) and Winkler (2000) the movement of the loads on tank vehicles, which influences the displacement of the center of gravity, was considered as well. Gerdes (2002) in his study on road safety, takes into account factors such as suspension, friction of the tires and the influence of the geometric configuration of tires (toe, camber, caster, and skew angles and tandem) in the steering; Arribas (2008) based on the tilt-table experiment develops a three dimensional mathematical model considering the lean angle of the vehicle.

3.2 Dynamic model

The dynamic maneuvers test (Fig. 6) and dynamic models for LCVs are much harder to achieve comparing to static models, but the results are more reliable. Most of the developed models until nowadays are concerned to the friction side and rearward amplification effects. Penteado (2005) presented a three dimensional model for validation of lateral stability. Ejzenberg (2009) developed a dynamic study that makes the design of horizontal curves of highways rapid transit in Brazil. Travis et al. (2004) used reduced radio-controlled vehicles to investigate the influence of parameters such as stiffness of the springs, dampers, roll center height and types of tires. Bogard et al. (2004) developed an embedded software on LCVs, based on Winkler's model (Winkler, 2000), to measure the effect of driving the vehicle in the model.

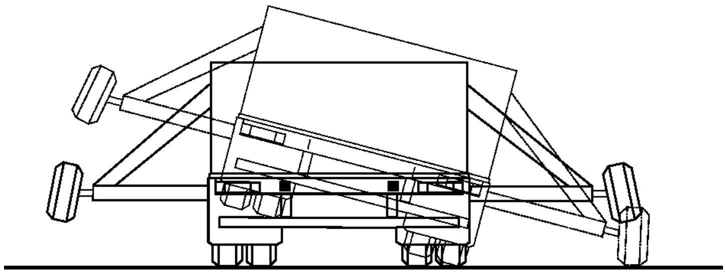

Figure 6 Dynamic Maneuvers Test.

3.3 New approach

Many studies had successfully demonstrated the applicability of the Screw Theory and Davies's Method to solve the kinematics and statics of mechanisms under a concise and compact way. On this domain, Erthal (2007), (2010), proposed a quasi-static mathematical model with two degrees of freedom to analyze the rollover of a vehicle subjected to a lateral load increasing up to the rollover threshold. The model developed considered the behavior of the suspension kinematics.

The quasi-static mathematical model developed by Erthal represents, in simplified form, a vehicle seen in the frontal plane, containing the body, two wheels, left and right, each connected to the body through two suspensions McPherson.

This model has two degrees of freedom, as is shown in Fig. 7.

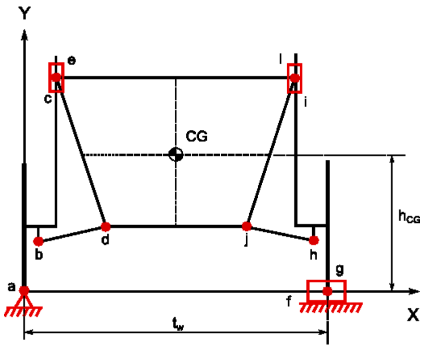

Figure 7 Erthal Model.
Source: Erthal, 2010.

Through the model, it is possible to analyze body movement, the migration of the roll center (not show in the figure) and the center of gravity, the vertical load distribution till it reaches the rollover threshold in response to a lateral acceleration, as are shown in Fig. 8 and 9.

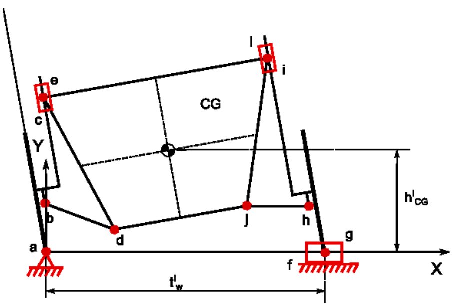

Figure 8 Erthal Model.
Source: Erthal, 2010.

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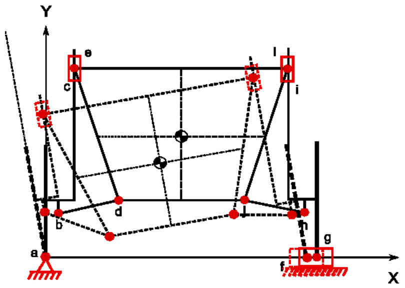

Figure 9 Erthal Model.
Source: Erthal, 2010.

The authors propose a new three-dimensional study (Figure 10) to validate the rollover tendency of the LCVs, the study will apply the technique developed by Erthal and will take into account the phenomenon of rearward amplification, typical of LCVs, cause by their joints and type of coupling.

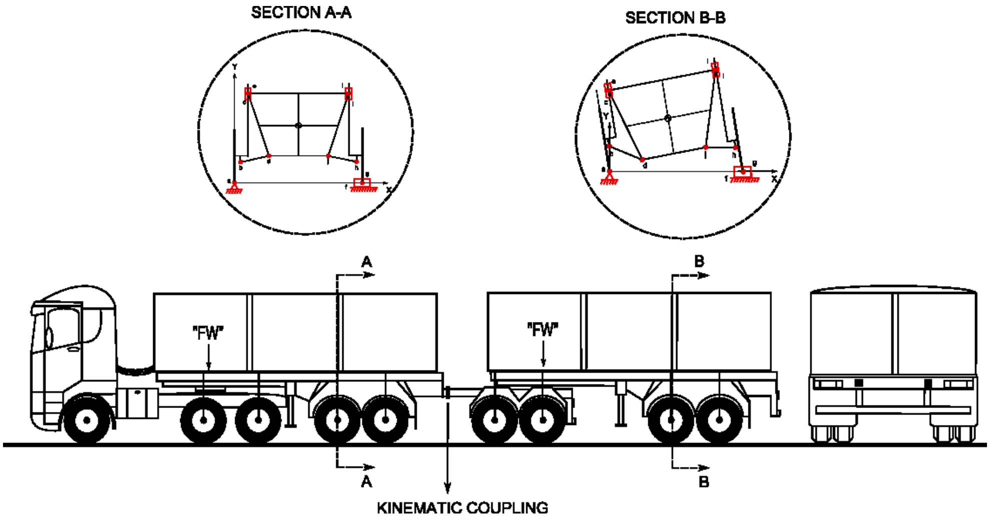

Figure 10 New Three-dimensional Study.

The application of this new approach will start adapting the Erthal Model to LCV suspension. In original work, a McPherson suspension was used. In our case, we will fit the modeling to a rigid axle suspension. To improve accuracy, we will connect the two sections (A-A) and (B-B) by a kinematic coupling and torsion bar that will represent the chassis of the trailer.

4. CONCLUSIONS

The LCV play an important role for the competitive development of many countries, including Brazil. Then, the reliability will become an important goal to ensure a service quality, besides safety issues, as previously shown in this paper.

The information that we present in this document helps us to better understand the characteristics of the LCV, their advantages and disadvantages, and the factors that influence a vehicle's tendency to rollover. Actually we are not intend to create a mechanism that can avoid the rollover issue, our contribution will be left on mathematical models that identify any kind of behavior, as vehicle body movements that will drive the LCV to a rollover situation.

We are sure that the proposed model, based on the Screw Theory and Davies's Method, as previously proved by Erthal for an independent suspension vehicles (2010) will allow a better modeling for analyzed the rollover of a Long Combination Vehicle (LCV) and the factors that influence the tendency of the vehicle to rollover.

As future works, we will construct a parameterized mathematical model for a LCV to compare with a scaled test vehicle as validation process, as proposed by Ertlmeier et al (2012).

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