SAFETY INVESTIGATION ON A RAILWAY PASSENGER VEHICLE

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Abstract: *A dynamic vehicle behaviour investigation has been developed on a railway passenger coach, of the São Paulo metropolitan commuter train system. The motivation for this project was the purpose of the Companhia Paulista de Trens Metropolitanos (CPTM) to implement and promote safety aspects on train fleet, due to an isolated accident occurred on the east side of the city. Investigation was conducted to understand the nature of the problem and to identify potential unsafe contributor causes. Vehicle dynamic behaviour, geometric track irregularities, as well as the operational conditions were investigated. Modal vehicle movements and static suspension characteristics were experimentally identified. Track layout geometry was topographically measured and analysed. A vehicle of this particular train fleet was carefully instrumented to gather information about its overall dynamic behaviour. The train travelled along the main eastern line, in operational conditions and carefully passed supposedly problematic locations. Various vehicle movements, velocities, accelerations and forces were registered, combined and analysed. Results show that a very particular confluence of unexpected factors, associated with the vehicle interaction with the track geometry, decisively contributed to produce a correctable unsafe condition.*

Keywords. *dynamic, vehicle, safety, railway*

1. Introduction

São Paulo city has approximately 18 million inhabitant (Source: *Emplasa*, 2000) and conveys 8,5 million people daily (nearly 5 million only in the city centre). Mainly three public transport systems are available to passengers: metro, commuter trains and buses. São Paulo metropolitan commuter train system is managed by Companhia Paulista de Trens Metropolitanos (*CPTM*) with 6 lines and almost 270 km of signalised double tracked lines, over 19 municipalities. The contribution of the rail transport in the city is around 32% on the whole system, as can be observed in Table 1.

Table 1 – Daily Passengers Transported

System	Pass/Day	Contribution	Length	Stations	Trains	Lines
Metro	1,000,000	20 %	57.0 km	52	350	4
CPTM	1,000,000	12 %	270.0 km	92	338	6
BUS (EMTU)	1,200,000	14 %	------	------	------	-----
BUS (SPtrans)	4,500,000	54 %	------	------	------	-----
Total	8,400,000	100 %	------	------	------	-----

Source: *EMTU*

User satisfaction if often measured by indexes such as productivity, efficiency, punctuality, comfort, safety, etc. Although user satisfaction with the commuter system (81% good and excellent for line South and 70% for east express) is not so high as that of the *Metro* (90%), it contributes significantly with long distance passenger transportation and should be improved (Source: *ANTP* 2001). The state government budget for the triennia 1999/2001 in the commuter system reached R$ 1.0 billion reais (around U$ 320 million), which allowed the implementation of line *E*, on the east side of the city. New projects are in course such as Central integration, implementation of line 5, new train acquisition, signalling and track maintenance and modernization.

As one of the most important urban transport system on this city, reliability and safety are points of great relevance. Unfortunately, in June 2000, the new train fleet 2000 operating in line *E*, with modern passenger coaches suffered a derailment. The motivation for this project was the purpose of *CPTM* to implement and promote safety aspects for this vehicle. A specialized team with company engineers and external researchers was established and received the task of investigating to identify actions for minimizing this problem. Information on accidents is usually scarce due to the natural difficult situation in the daily system operation. A wide range of possible causes and inter-relational effects (vehicle/track/operation) usually hinder the technical commission capability to produce a more general over-view of the event. It is not rare on accident reports to be missing for concluding remarks, due to the natural complexity and multidisciplinarity of the event.

Preliminary information pointed out a one-truck lateral derailment of an empty trailing car, at low speed on a sharp curve, near the station entrance. These are the figures to deal with in the challenge to identify accident causes. Investigation had been conducted to understand the nature of the problem and to identify potential unsafe contributing effects.

2. Methodology

The methodology adopted to approach the problem was to perform a vehicle track test with controlled condition, monitoring its dynamic behaviour. For this purpose a trailing car was appropriately instrumented to acquire information about its overall dynamic behaviour. The train with an instrumented car travelled along the eastern line in typical operational conditions and was also conducted with controlled speed near accident region. Before the test, an experimental measurement of the track layout and geometry was performed, particularly over the supposed problematic location. Additionally a workshop experimental investigation about the characteristics of the various systems of the vehicle was done (*Barbosa*, 2001). With all these background information, a correlation analysis was performed searching for unsafe condition according to the criteria described here after.

3. Fundamentals

Railway vehicle traffic safety condition is, still nowadays, quantified with the well-known L/V *Nadal* relationship, proposed in 1908:

$$\frac{L}{V} = \frac{\tan\alpha - \mu}{1 + \mu \tan\alpha} \tag{1}$$

This equation states a limit for the interaction of wheel/rail forces and is usually employed for safety analysis (*AAR*, 1993; *DOT*, 1973). This ratio is composed of angle of contact α defined by wheel and rail profile and contact surface property with friction coefficient μ. Note that this limit is tailored only with wheel/rail contact properties. After inspection, one can conclude that the smaller the numerator (*L* lateral contact force) and the larger the denominator (*V* vertical contact force) the smaller is the proneness of derailing for a given *L/V* limit. Based on this principle, to understand an accident, one has to search for vehicle dynamic situations or track geometric irregularities, where lateral force is high and associated with a low vertical force.

Another aspect of vital importance is the nature of the derailment. Typically, two kinds of situations are usually encountered (*Barbosa*, 1999):

- high speed derailing process (where dynamics and inertial effects have major influence),
- low speed derailing process (where quasi-static flexibility effects have major influence).

It should be pointed out that contact forces derive from the dynamic interrelation of two elastic systems, vehicle suspension and track elasticity, associated with inertial force due to vehicle mass changing direction produced by track geometry. So, with these figures pointed out, one can delimitate the investigation field with great objectivity and minimum effort. This is a goal to achieve, considering the company expectation to solve the problem and the traditional small amount of time and resource for a detailed investigation program.

4. Vehicle Characteristics

Modal vehicle description was identified with suspension characteristics and vehicle inertial properties. Static characteristics were obtained from the vehicle suspension components design, contained in the manufacturing specifications. Natural oscillating frequencies were experimentally measured from an impulsive test performed on an instrumented vehicle on the workshop. Wheel/rail contact properties where analysed base on the profiles measurements.

4.1 Suspension

Vehicle secondary suspension, which connects the vehicle structure to the truck, is equipped with pneumatic air bellows and hydraulic damper. A modern vehicle suspension system uses a torsional bar to increase rotational stiffness, to avoid large vehicle roll movement. In the longitudinal direction, a lever bushing system is employed with dampers in the lateral direction as shown in Figure 1.

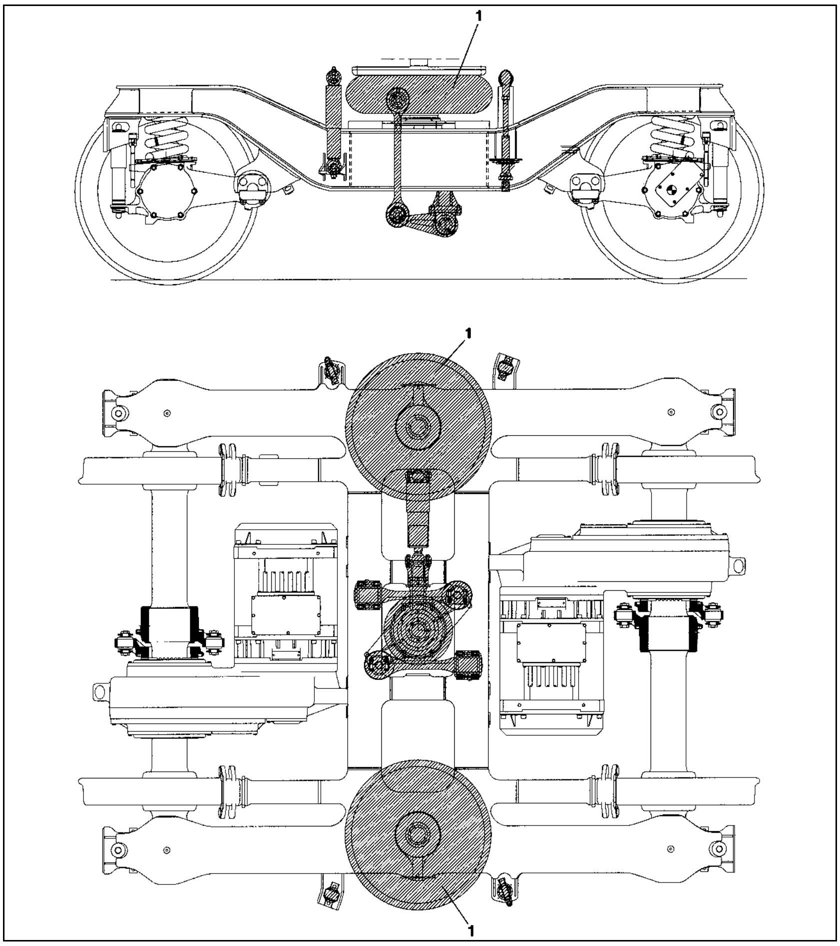

Figure 1 – Truck suspension details

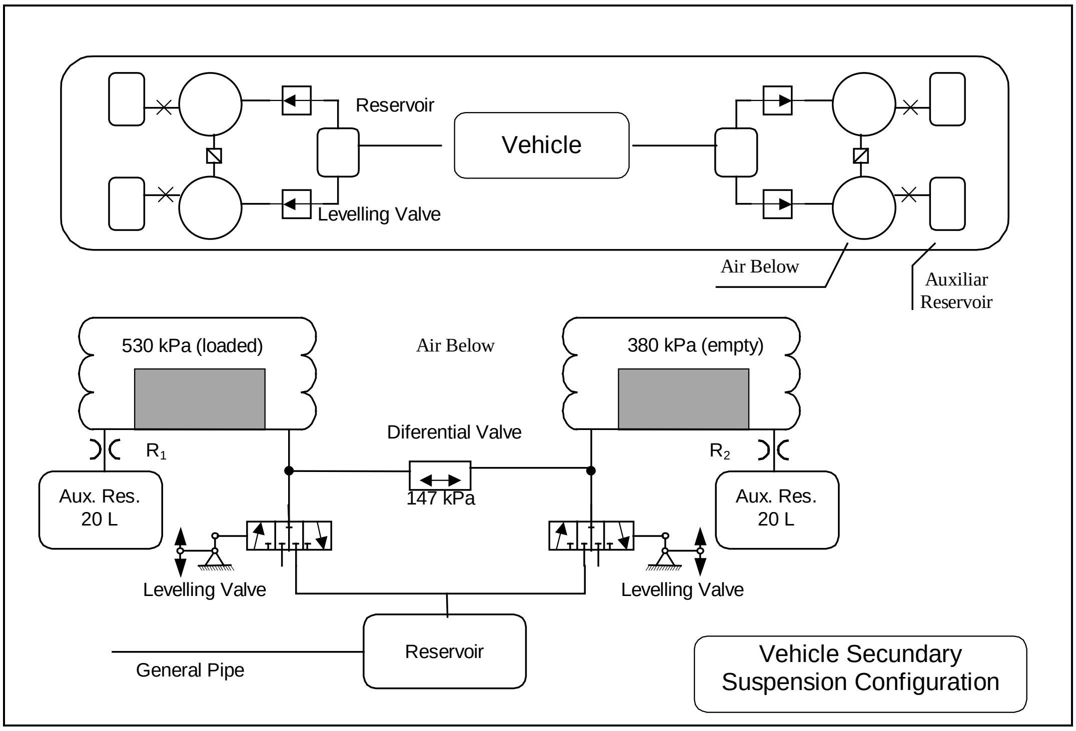

Figure 2 – Pneumatic Secondary Suspension

The vehicle pneumatic system and a truck arrangement are presented in Figure 2. Air is supplied by an external compressor and stored in an intermediary reservoir. Each bellow is connected to an auxiliary reservoir with a restrictive valve and equipped with a levelling valve, attached between truck and vehicle.

The total torsional vehicle suspension stiffness was doubled with the use of the torsional bar. Consequently the ability for absorbing static torsion from the track was reduced by the same magnitude. Additionally, the four point levelling system, produces vertical imbalance wheel load on a severe twisted track, due to its natural geometric intrinsic principle. These foreseen static problems on the vehicle vertical wheel load distribution in the negotiation of transition curves, where high twisting is expected.

Primary suspension is traditionally equipped with a spring-damper configuration. A rubber-bushing pivot at a lever extension of the bearing box provides longitudinal elasticity. Stiffness of the longitudinal degree of freedom has to promote curve negotiation and lateral stability. Usually, a compromise between both effects is searched at project level, actually producing high torque values for sharp curves.

4.2 Wheel/Rail profile analysis

Contact point between wheel/rail is determined for every wheel-set side position. Methodology to identify contact point uses wheel and rail surface profiles (normalized profiles or measured) with which is found a minimum distance. Figure 3 shows this position location on the wheel, on the rail and respective contact ellipse size. For each lateral wheel-set displacement, contact points position in each wheel, define a rolling radius, which difference, set-up a rolling cone diametric base (*UIC*, 1978). The ability of the vehicle to curve inscription with pure rolling is tailored by nominal wheel radius r_0, wheel surface conicity λ, track gage b_0 and lateral side gap between wheel flange and railhead u_Y (*Barbosa*, 1996). Equation to express this vehicle ability is obtained with next expression for a curve radius *R*:

$$R = \frac{b_o r_o}{\lambda u_y} \tag{2}$$

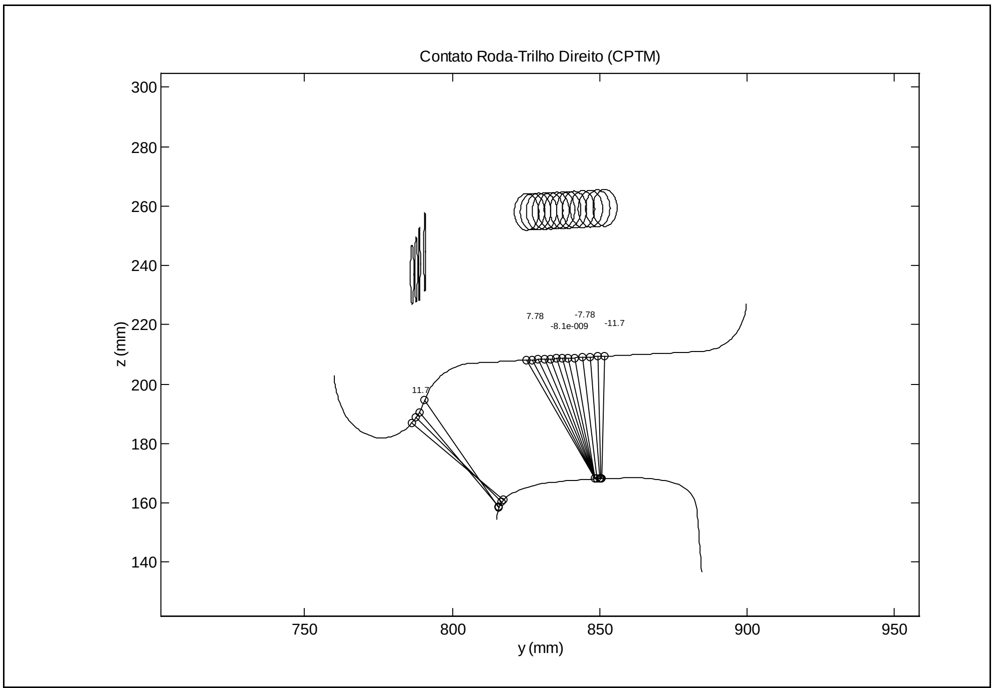

Figure 3 – Contact point and ellipse size between wheel/rail

Due to wheel surface conicity and rail profile, rolling radius for a given lateral displacement, changes non-linearly. A numeric surface program based on splines, was used to identify pure rolling curve radius. Figure 4 reports these values, where one can observe that below 900 metres radius, curve inscription occurs with sliding. When a wheel-set does not take a radial position, angle of attack produce large lateral force in the side-slip fashion, which is supported by the wheel flange contact. Additionally the internal wheel reverts its centripetal force contribution.

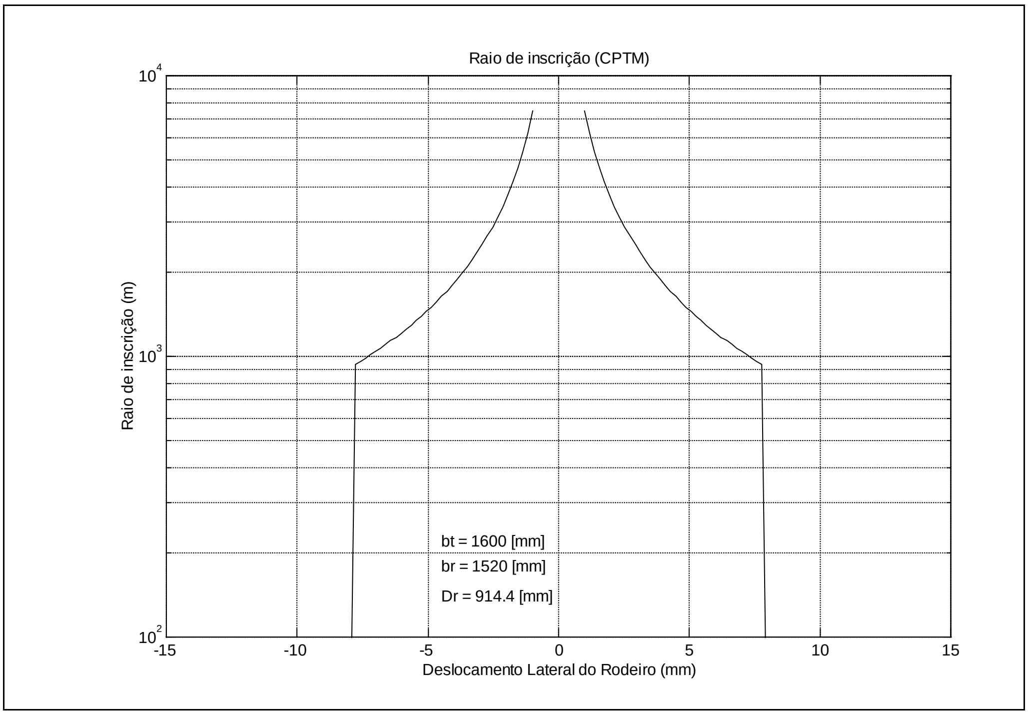

Figure 4 – Pure rolling curve radius

5. Track Geometry

To find out track geometry, an extensive measurement activity was developed. Vertical and transversal track geometry was topographically identified. Four variables were objects of measurement: in plane position (*X* and *Y* co-ordinates), external rail height (*Z* co-ordinates), track gage and elevation. At every meter, 250 points track surveillance was performed with a stationary theodolith. Figure 5a (top) shows the detrended height of each rail along the longitudinal position on the track (abscissa). On Figure 5b (bottom) is shown the traversal super-elevation where one can notice the rail staggered nature of the track (circle for each rail joint). The exact accident location is identified with a circle named "*acid*". A super-elevation around 100 mm between position 500 to 540 meters is observed, near the station entrance. This value is high for the speed traffic established in this region. Track twist is produced due to super-elevation variation on each transition curve on the extreme of the circular part (between 460 to 500 and 540 to 560 meter).

Track curvature was obtained with an intrinsic reference frame that follows the track path on the *XY* plane. For this special treatment, points measured were interpolated with splines that can be easily manipulated. To obtain track plain curvature one can use smoothed cubic spline derivatives stated as:

$$\kappa = \frac{\left(d^2Y / dX^2\right)}{\left[1 + \left(dY / dX\right)^2\right]^{3/2}} \tag{3}$$

that allows calculating numerically the curvature κ for each point measured. Figure 6 shows these results, representing curvature intensity with orthogonal arrows to the track direction (arrow size represents curvature magnitude). The transversal line on this figure represents the platform beginning at the Brás station.

From this treatment, one can plot the local curve radius and typical gage widening on the curve as a function of track length as shown in Figure 7a (top). In the lower graph is shown the typical gage widening due to rail-head wearing process on sharp curves (*UIC* Code 710R, 1978). It is noticed, in the upper graph, that the curvature is very severe (less than 250 meter radius) and circularity of track is not smooth enough. This hinders wheel-set inscription, producing large lateral forces. Note that between position 480 and 500 meter, track curve radius is around 300 meters with a severe twist from the super-elevation variation (as shown in Figure 5). This configures an unsafe condition for the vehicle traffic.

As vehicle movement is related to the track input and traffic speed, a vertical track wavelength analysis was performed to identify wavelength content of the irregularities on the track. Figure 8 shows contents of amplitude (density) for each wavelength of the vertical track irregularities.

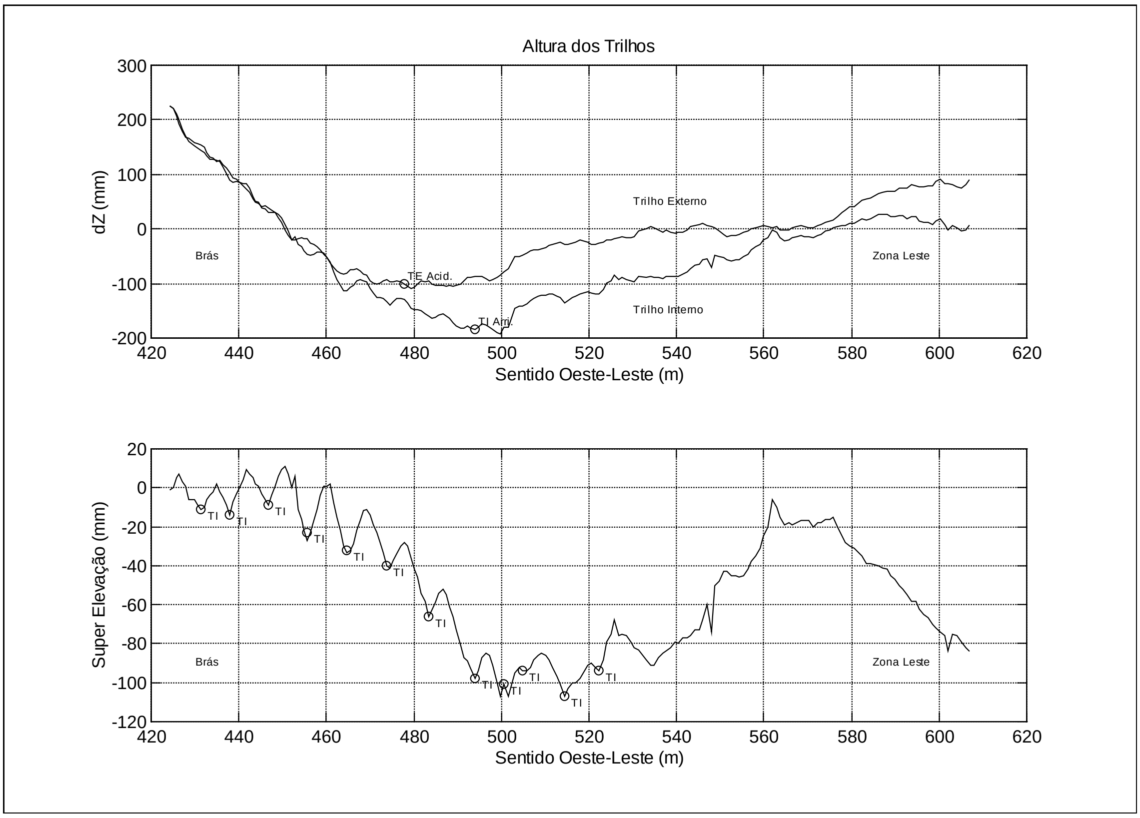

Figure 5 a)Track height and b) super-elevation

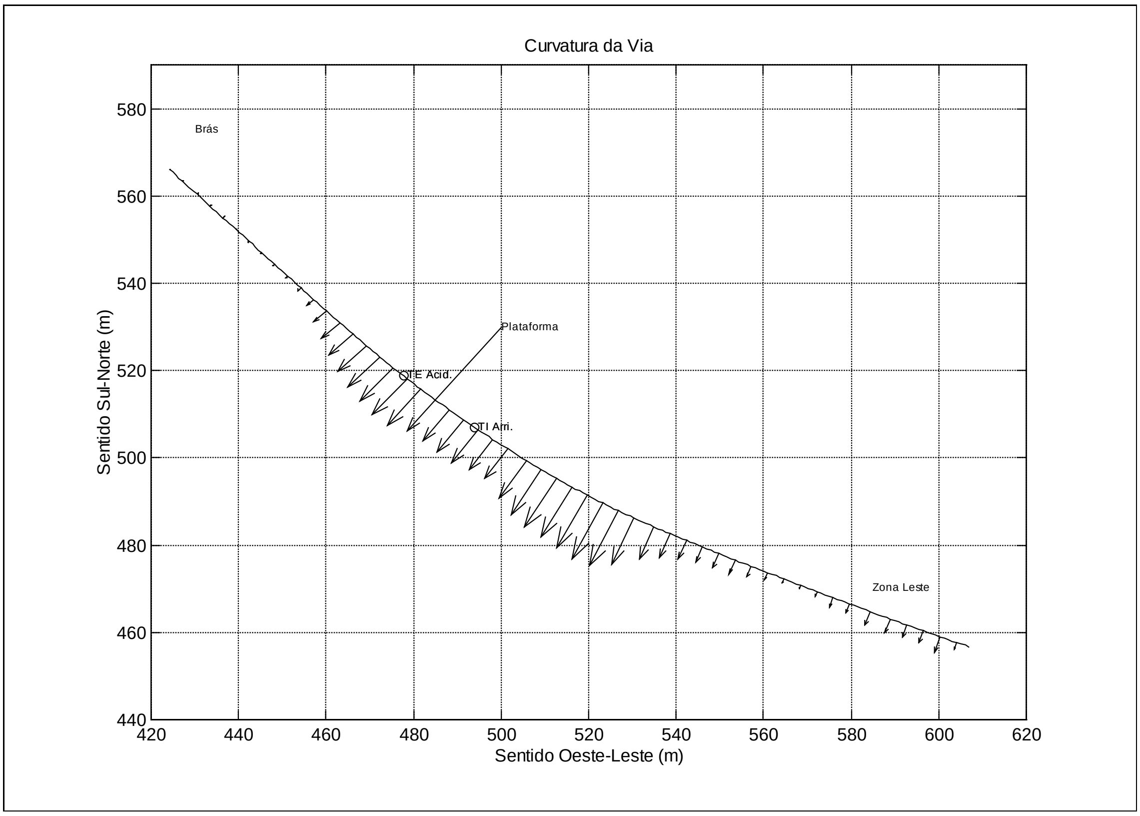

Figure 6 – Track Curvature (arrow size represents curvature magnitude)

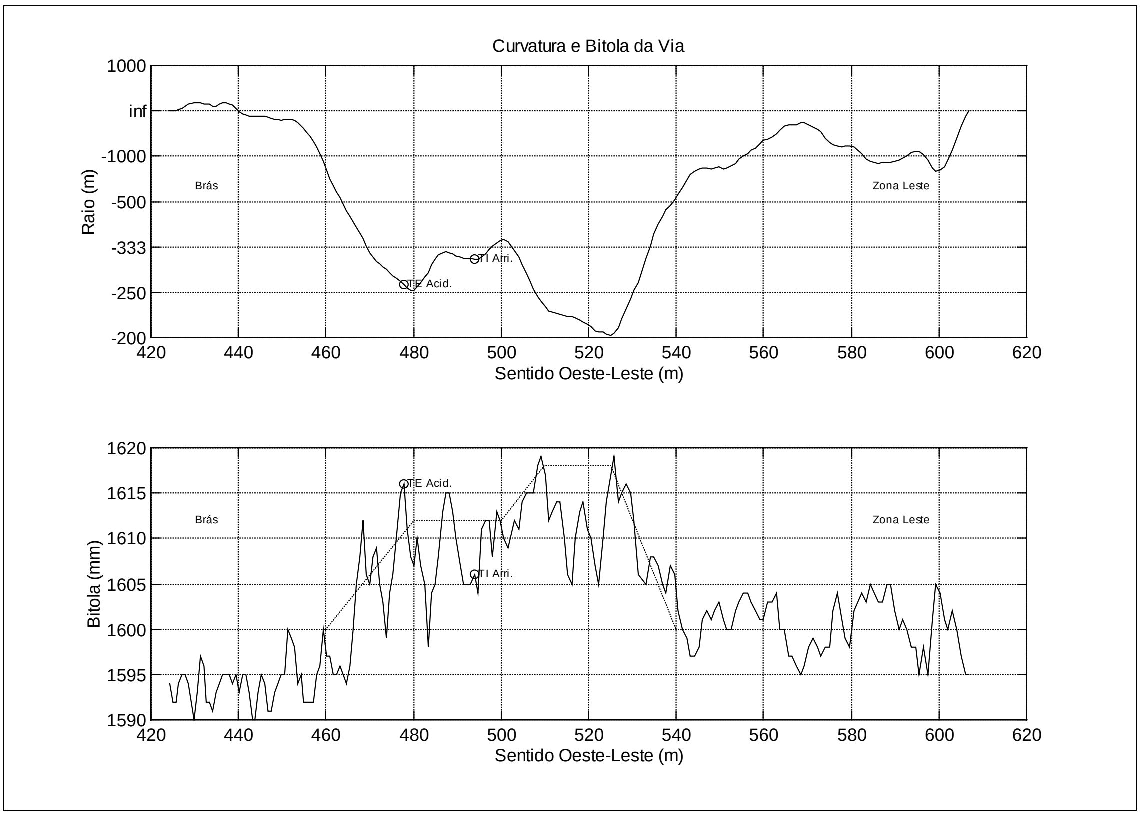

Figure 7a Track curvature b) track gage

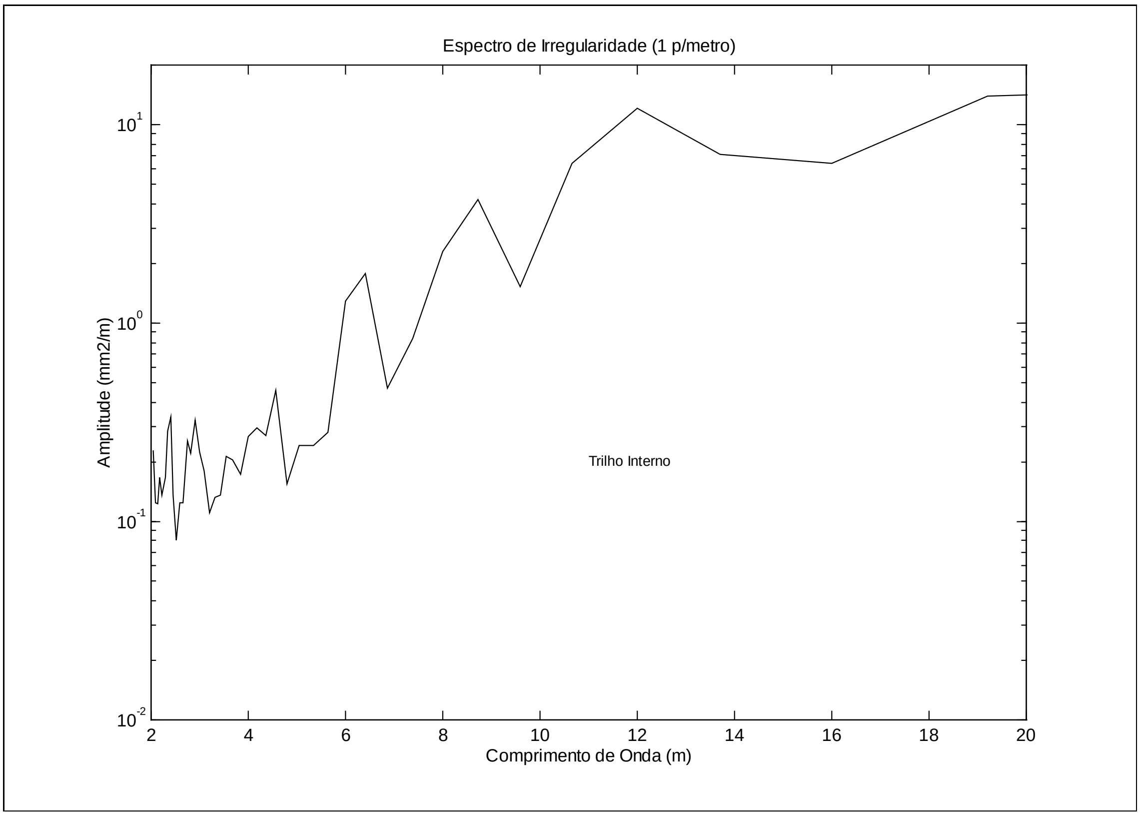

Figure 8 – Vertical Track Wavelength Analysis

6. Vehicle Instrumentation

A special vehicle instrumentation was prepared to gather information on the dynamic behaviour travelling on the track. Thirteen devices between accelerometer, pressure, torque, displacement, speed and position transducers were set-up in an empty trailing car with an on-board computer data acquisition system. They were strategically located to identify vehicle dynamic behaviour and to measure quasi-static steady state suspension configuration. Figure 9 presents a sketch with every transducer location.

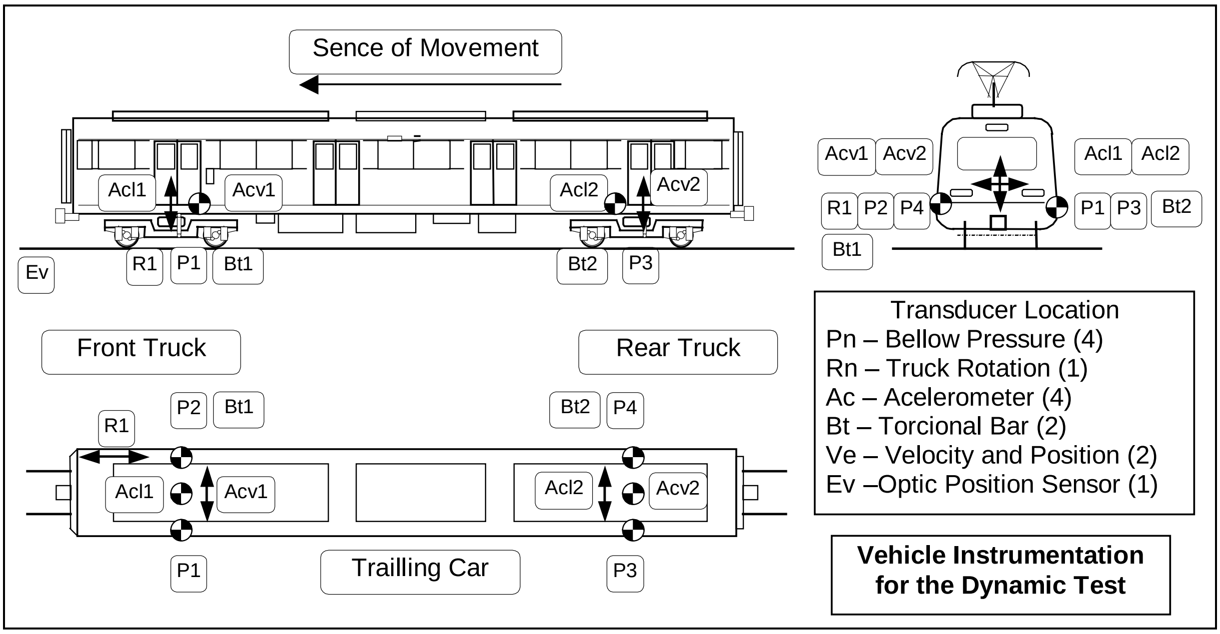

Figure 9 – Transducer locations for on track dynamic measurements

Four pressure transducers are installed on each air bellow of the vehicle. Torque is measured via shear stress gathered with stain-gages on the torsion bar. Total torque is calculated with digital signal treatment applied to the pressure difference cross-multiplied by distance between each bellow plus torsion bar torque. All transducers were previously calibrated before the on-track dynamic measurements.

7. Experimental Results Analysis

Analyses of theoretical and experimental results were spread over different aspects of the derailment nature. Wheel-set curve inscription properties and primary suspension rigidity, pointed out truck limitations. Track geometry namely super-elevation, sharpness and evenness circularity of the curve was identified.

Vehicle dynamic was monitored during a typical trip. Particular vehicle behaviour at the accident area was carefully analysed. Signal from bellow pressure and torsional bar torque were combined to compose vehicle vertical dynamic wheel load imbalance. Figure 10 shows a time story registered of the total torque between truck and car, for a constant vehicle speed passing on the accident area.

Isolating an equivalent length of track (almost 180 meters before the end of the line on the station platform) and calculating the track twist over car length basis (15 meter length) one can notice the similarity between the cause of the track twist shown in Figure 11 and the quasi-static effect on the torsion of the vehicle suspension (Figure 10).

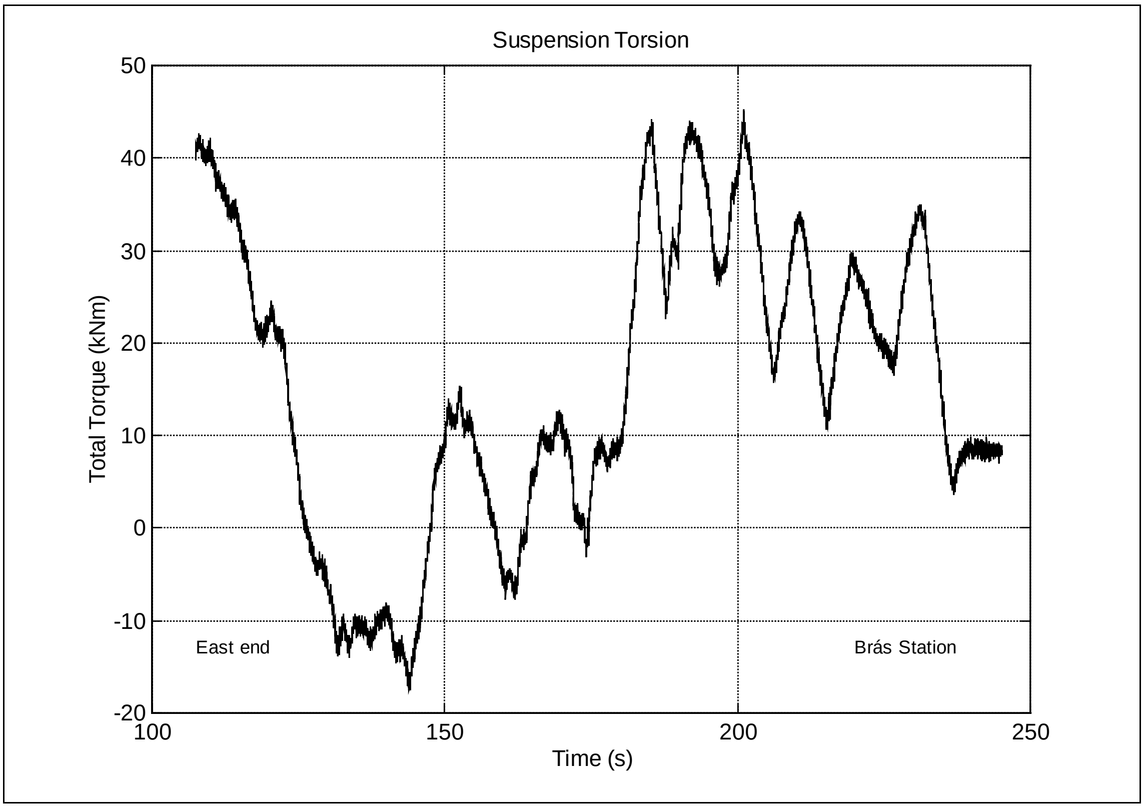

Figure 10 – Total suspension torsion (experimental)

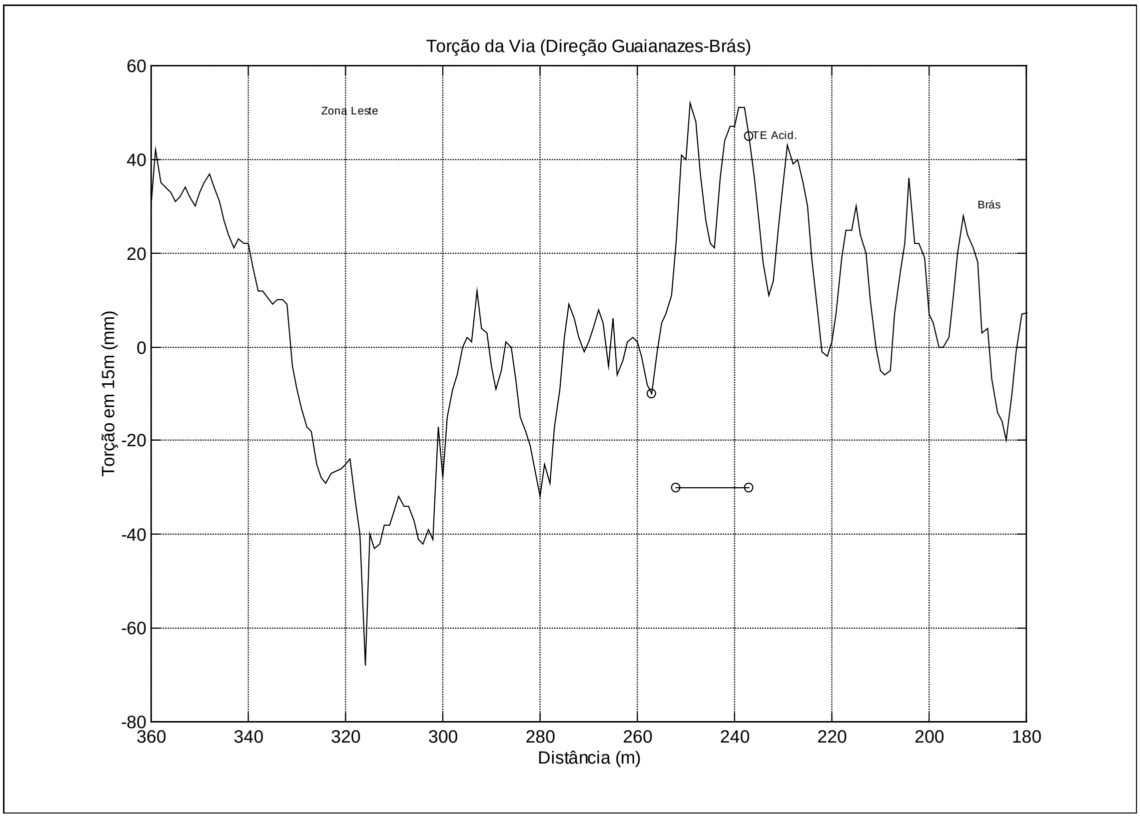

Figure 11 - Track twist (over vehicle length basis)

On this location, a torque of 40 kNm was identified that produces a vertical wheel unbalance of around 33% of the static load. This is attributed to the secondary suspension torsional rigidity, associated with severe track twist.

8. Concluding Remarks

Various aspects of the unsafe derailment nature were identified. A low speed derailment with high suspension deformation was characterized. It was proved that primary suspension restriction, curve inscription properties of the wheel-set/rail pair and unnecessary super-elevation in this particular curve, contributes to aggravate the risk of derailment. Secondary suspension four-point levelling system and torsional bar, significantly increase suspension torsional rigidity. This restricts the vehicle ability to accommodate on track irregularity, especially severe twist on transition curve with severe super-elevation.

Vertical wheel load imbalance reaches 33% with the torsional effect as mentioned in item 7, produced by track twist on this specific place. When associated with other effects, as previously related, this confluence of factors contributed to significantly reduces the safety margin. This problem may promptly be corrected with track works or/and vehicle suspension adjustments. Recommendations have been made to increase vehicle safety. Despite the modern conception of vehicle suspension, it does not seem to work properly with poor track geometry. As presented, it should be pointed out that vehicle and track components should be treated as a whole system, otherwise, own beneficial property of each component will not adjust properly to the other.

9. Acknowledgements

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