Investigating the relationship between road geometry and severe bus accidents in Brazil

Investigação da relação entre a geometria rodoviária e acidentes severos com ônibus no Brasil

DOI:10.34117/bjdv9n1-065

Recebimento dos originais: 05/12/2022
Aceitação para publicação: 05/01/2023

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ABSTRACT
The objective of this paper is to investigate the relationship between road geometry and severe bus accidents in Brazil, based on an adaptation of the Umbrella Handle Model (UHM) and emphasizing the influence of unbalanced centripetal acceleration in the occurrence of these events. Three accidents of this type were selected for study, all of them recorded along or close to horizontal curves of Brazilian highways (Trindade Access, RJ 155 and SP 125 roads). The variation in centripetal acceleration of vehicles traveling under operating speed along each “smoothed tangent” was measured using the *Keuwlsoft Accelerometer Counter* app for smartphone. Transverse and longitudinal acceleration peaks were highlighted for each study section, and, in the first case, the

critical variations refer precisely to the locations of the RJ 155 and SP 125 roads where bus accidents were recorded. With regard to the Road Risk Index (*RRI*), with the exception of the RJ 155 road, the highest *RRI* values among all combinations between a tangent and a sequential horizontal curve were also observed for the places of occurrence of the investigated accidents.

Keywords: road geometry, bus, road accident, Umbrella Handle Model.

RESUMO
O objetivo deste trabalho é investigar a relação entre a geometria viária e acidentes graves de ônibus no Brasil, a partir de uma adaptação do *Umbrella Handle Model* (UHM) e enfatizando a influência da aceleração centrípeta desbalanecada na ocorrência desses eventos. Três acidentes desse tipo foram selecionados para estudo, todos eles registrados ao longo ou próximos a curvas horizontais de rodovias brasileiras (Acesso de Trindade, RJ 155 e SP 125). A variação na aceleração centrípeta dos veículos que trafegam na velocidade de operação ao longo de cada "tangente suavizada" foi medida usando-se o aplicativo *Keuwlsoft Accelerometer Counter* para smartphone. Picos de acelerações transversal e longitudinal foram destacados para cada trecho de estudo e, no primeiro caso, as variações críticas remetem precisamente aos locais das rodovias RJ 155 e SP 125 onde os acidentes com ônibus foram registrados. Já no tocante ao Índice de Risco Rodoviário (RRI), com exceção da rodovia RJ 155, os maiores valores de RRI, dentre todas as combinações entre uma tangente e uma curva horizontal sequencial, também foram observados para os locais de ocorrência dos acidentes investigados.

Palavras-chave: geometria viária, ônibus, acidentes, Umbrella Handle Model.

1 INTRODUCTION

Deaths resulting from traffic accidents, whose main causes are problems related to the road or the vehicles themselves, in addition to human errors (Barros *et al*., 2003; Almeida *et al*., 2009), can be considered avoidable, unlike those associated with health problems or natural causes. Despite this, according to the Global Report on the Status of Road Safety (WHO, 2018), in Brazil, in 2016, almost 20 traffic deaths were recorded per 100,000 inhabitants.

Despite the existence of accident prediction models for the most diverse road situations, such as those compiled in the Highway Safety Manual, or HSM (AASHTO, 2010), for the North American context, little evidence points to the design of projects based on information that refer to these accident frequency and severity rates. In the Brazilian context, similarly, although models of this nature have also been proposed (such as the Umbrella Handle Model, or UHM, proposed by Peixoto and Françoso (2021), in which a risk index is calculated as a function of traffic speed, radius and superelevation of a horizontal curve and the length and longitudinal slope of the tangent that precedes it), they are rarely used for road geometric design.

As in many other countries, the parameters that guide the geometric design of Brazilian highways regarding the limit values of radii of horizontal curves, slope, superelevation, etc., are generally based on concepts of applied physics and cost-benefit analysis (Pimenta *et al*., 2017), which, in some cases, are not aligned from the point of view of road safety. For example, as shown in Table 1 (DNER, 1999), as the design speed increases, so does the minimum radius of horizontal curves that must be used, which is correct from a scientific point of view. However, as the terrain becomes steeper, the maximum longitudinal slope of the project becomes more permissive, in order to reconcile technical problems with financial feasibility and road capacity.

Table 1: Minimum radii of horizontal curves for Brazilian highways (m).

Superelevation (%)	Design speed (km/h)									
	30	40	50	60	70	80	90	100	110	120
4	30	60	100	150	205	280	355	465	595	755
6	25	55	90	135	185	250	320	415	530	665
8	25	50	80	125	170	230	290	375	475	595
10	25	75	75	115	155	210	265	345	435	540
12	20	70	70	105	145	195	245	315	400	490

Source: DNER (1999).

Other possible inconsistencies regarding actions to mitigate traffic violence can also be discussed from the point of view of Brazilian legislation. In general, the way speed is monitored on Brazilian highways imposes a permissive scenario for disregarding the limit values presented in the Brazilian Traffic Code (CTB, 2010). According to Resolution No. 798, of September 2, 2020 (Brazil, 2020a), fixed-type speed surveillance radars cannot be displayed in a non-ostensible way, and the location of this equipment must be informed to road users before starting any inspection. Usually, this equipment is installed in places where high concentrations of accidents are observed, suggesting a “damage control” measure, not a preventive measure. Furthermore, Law No. 14,071, of October 13, 2020 (Brazil, 2020b), establishes that, compared to previous legislation, a higher number of points must be assigned for Brazilian drivers' licenses to be suspended.

Therefore, as long as this flexibility exists, it is important that compensatory measures, from a design point of view, are taken, such as the application of accident prediction models in the design of new roads.

The objective of this paper is to investigate the relationship between road geometry and severe bus accidents in Brazil, based on an adaptation of the UHM and emphasizing the influence of unbalanced centripetal acceleration in the occurrence of these events. For this, three accidents of this type that occurred in the last decade and that had great repercussion in the Brazilian press were selected for study, all of them recorded along or close to horizontal curves of Brazilian highways (Trindade Access, RJ 155 and SP 125 roads).

To achieve this goal, the following research questions must be answered:

1. What is the relevance of the UHM for accidents involving buses?
2. Regarding the geometric and operational characteristics of the road, what are the most relevant factors in this type of accident?
3. Should speed enforcement be mandatory on the winding single-lane Brazilian roads?

2 BACKGROUND

According to the Brazilian Ministry of Infrastructure (2022), in 2021, the Brazilian fleet of buses was approximately 673,000 vehicles, corresponding to 0.6% of the national total. In addition, there has been a growth over the last few years in the number of Double Decker (DD) buses in this fleet, which are taller than conventional buses (they can be manufactured with a height of up to 4.40 meters) and, therefore, must be provided with safety equipment, such as cruise control and emergency braking systems, lane departure warning, etc. (Ramos, 2020).

Although considered one of the safest modes of transport both in urban and road environments, it is not uncommon for buses to be involved in traffic accidents, even in developed countries such as those on the European continent (Evgenikos *et al.*, 2016). Furthermore, the high occupancy of passengers, combined with the non-habitual use of seat belts by them, increases the number of casualties in these events (Rhaman *et al.*, 2011). Thus, several authors have sought to identify possible factors that influence the frequency and severity of these accidents, ranging from dimensions (Chimba *et al.*, 2010) to the operating conditions of buses (Shahla *et al.*, 2009), as well as factors related to the drivers themselves (Tseng, 2012), such as age, gender, level of experience, etc., and weather conditions, in the latter case, without consensus among the different sources in the literature (Huting *et al.*, 2016).

Regarding the road geometry, the proper design of both tangents and curves, horizontal or vertical, is essential to avoid traffic accidents and early road obsolescence (Pimenta *et al*., 2017). Lamm and Choueri (1987), for example, suggest that small radii of horizontal curves have a strong correlation with accident rates involving speeding vehicles. In turn, Ferraz *et al*. (2012) argue that situations such as the existence of a long tangent section (or with smooth curves) preceding a small radius curve can also contribute to the occurrence of accidents. In the particular case of buses and trucks, the inadequate design of horizontal curves can also impair lateral stability, subjecting such vehicles to a greater risk of skidding or overturning, since the centrifugal acceleration is a function of their speed and the radius of the curve (Setti, 2011). Authors such as Li *et al*. (2017) further advocate that, for seated passengers, skidding or overturning buses result in a higher proportion of severe injuries or deaths than other types of road accidents.

Forces resulting from the vehicular movement can influence not only the occurrence of accidents, but also the comfort of bus passengers, as the acceleration of these vehicles is difficult to be “anticipated” and, therefore, can cause passengers to fall or other similar incidents (Shuber *et al*., 2017). García-Ramirez and Aguillar-Cárdenas (2021), when evaluating the effect of centripetal acceleration on occupants of vehicles traveling on a mountain road in the Andes, observed that lateral acceleration of the order of 2 m/s^2 leads to some discomfort for passengers, while that of the order of 4 m/s^2 causes great discomfort to them. In turn, Eboli *et al*., (2016) applied questionnaires to students who benefited from public transport in the region of the University of Calabria (Italy), seeking to measure the comfort perceived by these passengers during bus trips. For the latter case, the instantaneous accelerations of the buses (longitudinal, lateral and vertical) were obtained by boarding a smartphone equipped with an application program for this purpose.

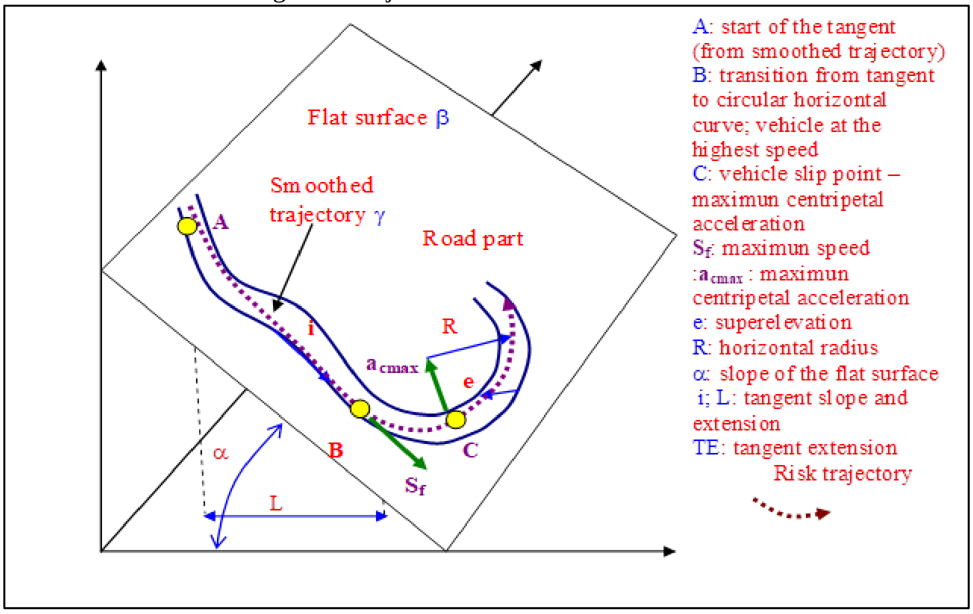
3 METHOD

This section presents the research method.

3.1 UMBRELLA HANDLE MODEL (UHM)

The UHM consists of a study model that associates the accident rate with the road geometry, in particular, for cases that involve a long and descending tangent, which induces an increase in speed, followed by a horizontal curve of reduced radius and high curvilinear extension (Peixoto and Françoso, 2021). For the full understanding of the reader, Figure 1 illustrates the adaptation of the UHM used in this research to investigate pre-selected accidents involving buses.

Figure 1: Adjusted Umbrella Handle Model.



Source: Peixoto and Françoso (2021).

Point A indicates the beginning of the tangent that precedes the horizontal circular curve and point B, in turn, corresponds to the transition point between the tangent and the curve, at which the vehicle is assumed to reach the highest traffic speed (S_f). It is important to note that the trajectory between points A and B does not correspond to a perfect straight line, with smooth curves (large horizontal radii and short lengths) being observed along it, which, in a simplistic way, can be disregarded. The reason for this lies in the fact that drivers benefit from the lateral clearance between the lane width and the vehicular width to continue gaining speed even along a sequence of curves with large horizontal radii, braking only when the visual field or the sensation of centripetal acceleration induce them to do so. In this context, as alignments with sequential reverse curves are common on single-lane roads along mountain ranges (resembling the nearest contour line), if the smoothed trajectory AB is downward, there is a high probability that the speed of vehicles entering the curve (from point B forward) may be excessive, and sudden braking does not guarantee sufficient time or space to slow down before destabilizing actions are imposed. Finally, point C in Figure 1 corresponds to the vehicle's skidding point on the main curve, where the maximum centripetal acceleration (a_{cmax}) is observed.

According to the UHM, under these conditions, the normalized Road Risk Index (RRI_F) under free math relationship can be calculated by Equation 1. The RRI_F encompasses quantities considered influential in the generation of operational risk scenarios on roads where there is a "feeling of freedom of speed" due to the low level of inspection and cultural issues. The greater its magnitude, the greater the probability of accidents occurring in the entry zones of horizontal curves. This means that accidents are more likely to occur the greater the length and longitudinal down-slope of the tangent that precedes a studied curve, and the smaller the radius and superelevation of the curve itself. Thus, despite not having statistical validation, the UHM can be used in the relative comparison between sequential curves of the same road segment.

$$RRI_F = f \times S \times \frac{TL_F}{R} \times \left(1 - \frac{i}{100}\right) \times \left(1 - \frac{e}{100}\right) \quad (1)$$

Where, f is a normalization factor; S is the traffic speed (m/s); TL_F is the length of the "smoothed tangent" (m); R is the horizontal radius of the main curve (m); i is the longitudinal slope of the tangent (%); and e is the superelevation of the main curve (%).

3.2 CASE STUDY DATA

Table 2 presents the general characteristics of the events selected for the study, all of which occurred in the southwestern region of Brazil and involved tall buses that overturned in horizontal curves under strong deflection. In turn, Figure 2 presents a geometric sketch of the road axis of each location where the bus accidents to be investigated occurred.

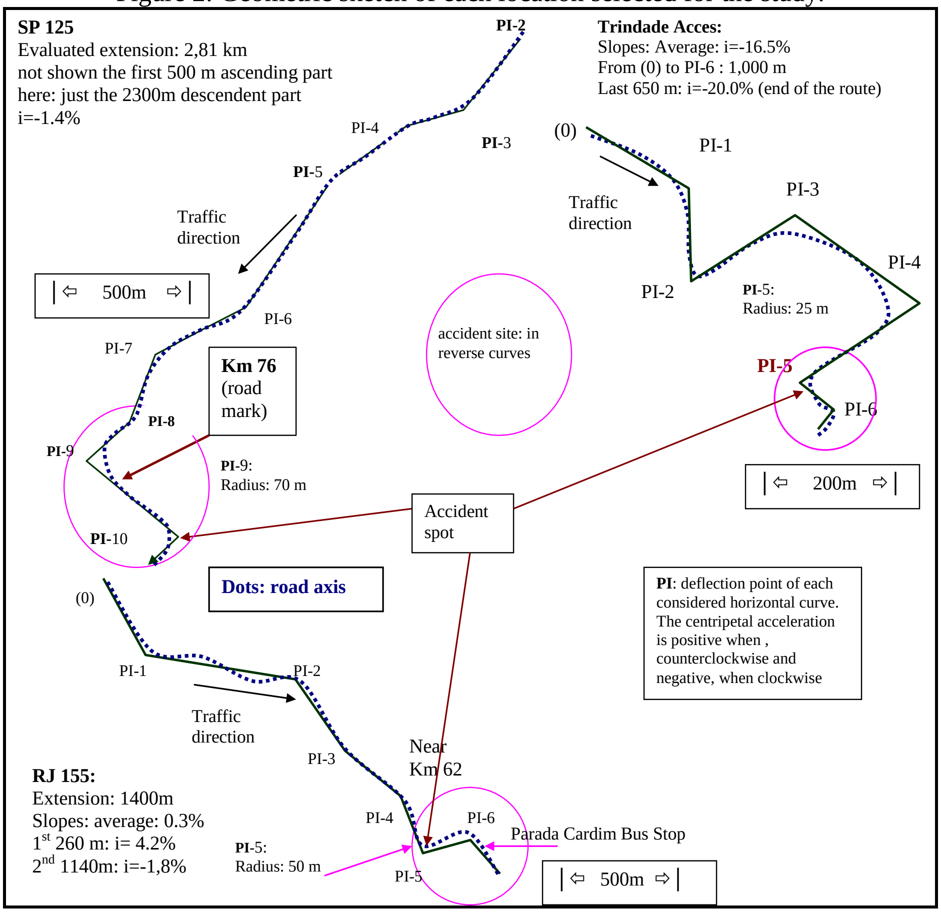
Not having *as built* design or previous field survey data available for any case, the lengths of each smoothed tangent and the horizontal radii of circular curves were estimated using the Google Earth Pro platform. The average longitudinal slopes of each alignment were also extracted from this platform, which is based on the Digital Elevation Model (DEM) derived from the Shuttle Radar Topography Mission (SRTM). The superelevation of each of the 3 curves studied was roughly estimated from the average between two transverse slope measurements taken at points on the edges of each traffic lane, one with an inclinometer app for smartphone, and the other with the Electronic Distance Meter (EDM) BOSCH GLM 80 Professional.

Traffic speeds were determined by sampling. For this, at each study site, the average time required for approximately 2% of the corresponding Average Daily Traffic (ADT) to cover a previously known length was measured, and different types of vehicles such as cars, motorcycles, buses and trucks were included in the sample. The option for speed surveillance radars was discarded because, probably, drivers would slow down once they saw such equipment, resulting in values not consistent with real traffic conditions.

Table 2: General characteristics of the events selected for the study.

Accident date	Location	County	Bus height (m)	Bus width (m)	Occupants	Injured	Deaths
Sep. 6, 2015	Trindade Access road (2.6 km ahead BR 101)	Paraty-RJ	3.20	2.50	80	60	15
Dec. 8, 2015	RJ 155 “Saturnino Braga” road (Km 62)	Getulândia-RJ	4.25	2.60	Not available	43	1
Nov. 13, 2021	SP 125 road Km 75+800 m	São Luiz do Piratininga-SP	4.10	2.60	66	48	6

Figure 2: Geometric sketch of each location selected for the study.



3.3.1 *Acceleration measurement*

According to the premise of the adapted UHM, in order to establish a "virtual straight line" preceding the horizontal curve, at each smoothed tangent, the variation in centripetal acceleration of vehicles traveling under the respective operating speeds was investigated. For this purpose, acceleration measurements were performed using the *Keuwlsoft Accelerometer Counter* app for smartphone, transported by a car along each selected road in order to measure data continuously and save them graphically. The option for the car instead of the bus (type of vehicle of interest for the study) is justified by its practicality, allowing to repeat the measurements as many times as necessary without depending on pre-stipulated schedules for the intercity public transport lines, in addition to the methodological approach of the research, which is not aimed at rigorously measuring acceleration, but at determining peak values and oscillations along winding roads.

4 RESULTS AND DISCUSSION

This section presents the results and discussion of the research.

4.1 ACCELERATION MEASUREMENT RESULTS

Figures 3 to 5 present the graphs resulting from the acceleration measurements at the places of interest of the Trindade Access, RJ 155 and SP 125 roads, respectively. All measurements were made at the corresponding average traffic speed previously estimated (in that order, 32, 85 and 72 km/h). Only for the RJ 155 road, a data transfer frequency of 20 Hz was adjusted, and for the others, the 10 Hz was used. The red lines refer to the transverse (centripetal) acceleration, whose positive values indicate clockwise curves and whose peaks are highlighted in the Figures. The green lines, in turn, refer to the longitudinal acceleration.

Figure 3: Acceleration measurements along the Trindade Access road at average traffic speed.

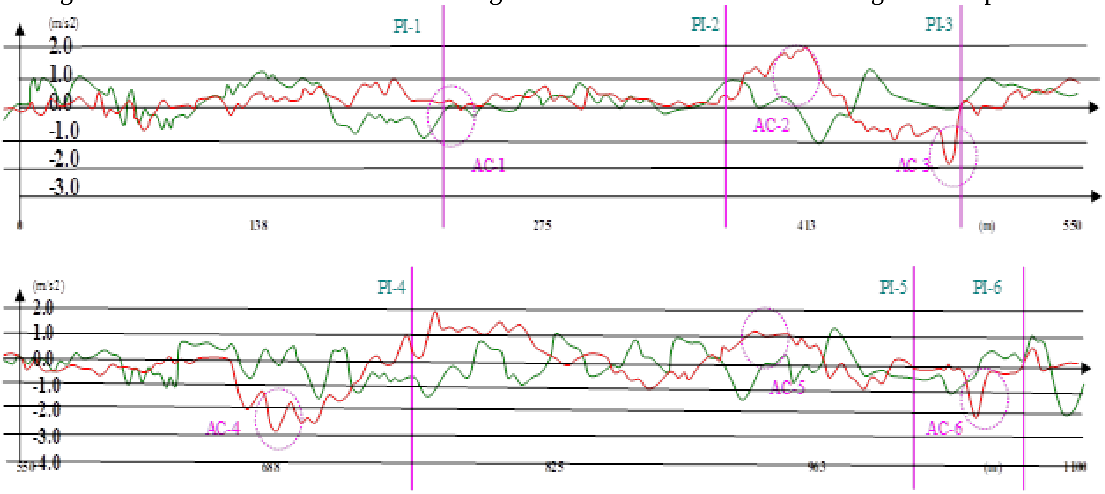


Figure 4: Acceleration measurements along the RJ 155 road at average traffic speed.

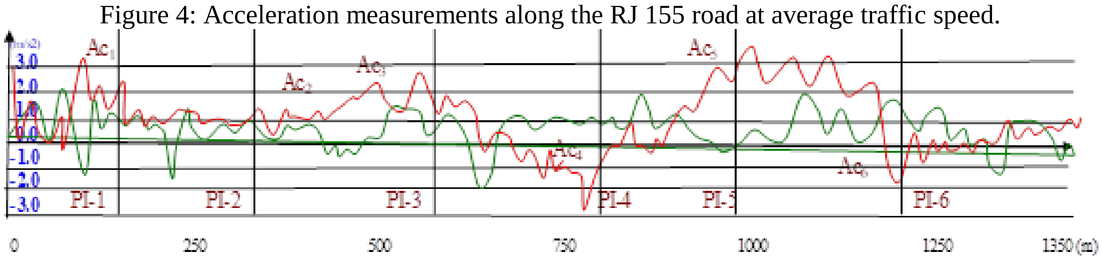
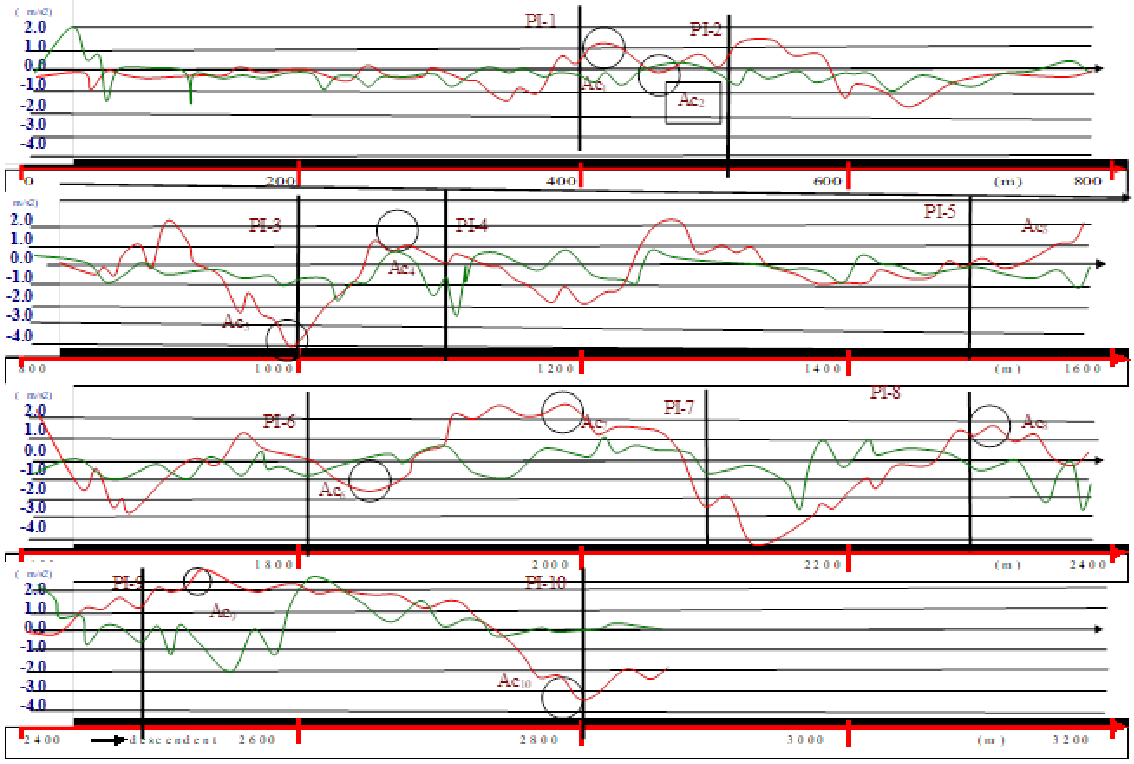


Figure 5: Acceleration measurements along the SP 125 road at average traffic speed.



The continuous variation of both centripetal and longitudinal acceleration indicates that the concept of “design movement” does not apply to the actual movements of vehicle operation. In the specific case of variation in centripetal acceleration, it is interesting to note that this acceleration does not vary exactly at points close to the PIs, indicating that the driver starts steering at some point before or even after the alignment deflection. In other words, centripetal acceleration varies, increasing or decreasing, to compensate for alignment deflections, but also under the influence of, such as driver action, use of the traffic lane width as a point of tangency, and operating speed, in the latter case, which is not necessarily limited to design speed.

Regarding the Trindade Access road, the steep longitudinal slope (which reaches values of up to 20%, two and a half times the limit that would be allowed for the project) demands continuous braking of vehicles, although the braking devices are not designed to be used in such a way. Figure 3 shows that the maximum peak of centripetal acceleration, observed near the fourth curve (PI-4), was approximately -3.0 m/s^2, and in the final stretch (accident site), between the fifth (PI-5) and sixth curves (PI-6), centripetal accelerations ranged from less than -2.0 to +0.5 m/s^2, while longitudinal accelerations ranged from +1.0 to -2.0 m/s^2 just after PI-6.

Regarding the RJ 155 road, according to Figure 4, two maximum peaks of centripetal acceleration were observed, one at 150 meters from the beginning of the smoothed tangent and another near the fifth curve (PI-5), both of the order of +3.5 m/s^2. In the latter case, a sudden change in centripetal acceleration was also observed along a length of only 250 meters, reaching a peak of -2.0 m/s^2 near the PI-6 and, thus, signaling to a road geometry that imposes fast steering, that is, two sequential and reverse curves, exactly where the bus overturned.

Regarding the SP 125 road, according to Figure 5, two maximum peaks of centripetal acceleration were also observed, one close to the third curve (PI-3) and another close to the seventh curve (PI-7), both of the order of -4.0 m/s^2. However, the greatest variation in centripetal acceleration occurred between the ninth (PI-9) and tenth (PI-10) curves, precisely the accident site, ranging from +2.5 to -3.5 m/s^2 in less than 300 meters. In other words, this means that the driver needs to steer as quickly as possible from a left to right, and thus, for tall buses, such as the DD in question, the inertial effect of the rotational acceleration around the longitudinal axis of the vehicle possibly contributes to rollovers.

4.2 ROAD RISK INDEX (RRI_F)

Table 3 summarizes the research results regarding the geometric and operational parameters of the case studies. ADTs were roughly estimated via on-site vehicle counting, for Trindade Access and RJ 155 roads; and made available by the Brazilian Department of Highways (DER), for the SP 125 road. This parameter, in turn, allowed defining the road class of each case study.

The posted speed limit is higher than the design speed only on the RJ 155 road. In all cases, however, the average operating speed exceeded the posted speed limit, as a consequence of not monitoring the traffic speed. Furthermore, regarding the comparison between average operating speed and design speed, a discrepancy was observed both on the RJ 155 road and on the SP 125 road.

With regard to the bus height/width relationship, it is noted that this parameter was lower for the vehicle involved in the Trindade Access road accident in relation to the others, indicating a greater influence of the road geometry in the occurrence of such an event, which is evidenced by its average longitudinal slope much steeper than the design limit. Furthermore, still with respect to the road geometry, the actual minimum horizontal radii of all case studies are smaller than their respective minimum design horizontal radii.

Table 3: Summary of research results.

Parameter	Accident site Trindade Access road	RJ 155 road	SP 125 road
ADT (Road class)	1,030 (II)	960 (II)	6,400 (I-A)
Design speed (km/h)	50	50	60
Posted speed limit (km/h)	30	60	40-60
Average operating speed (km/h)	32	85	72
Bus height/width ratio	1.28	1.63	1.58
Minimum design horizontal radius (m)	70-100	70-100	105-150
Actual minimum horizontal radius (m)	24	67	71
Horizontal radius at the accident site (m)	45	88	70
Maximum design longitudinal slope (%)	-7.0	-7.0	-6.0
Actual average longitudinal slope (%)	-16.5	+0.3	-1.4
Longitudinal slope at the accident site (%)	-20.0	-2.0	-4.6
|Maximum observed centripetal acceleration| (m/s²) [curve]	3.0 [4th]	3.5 [5th]	4.0 [3rd,7th]
|Critical variation in centripetal acceleration| (m/s²) [curve]	5.0 [3-4th]	5.5 [5-6th]	6.0 [9-10th]
|Maximum observed longitudinal acceleration| (m/s²) [curve]	2.0 [6th]	2.0 [3rd]	3.0 [8th]

Table 4 presents, for all case studies, the *RRI* values of each successive combination between a tangent and a horizontal curve and the RRI_F at the accident site. For calculation purposes, the normalization factor *f*=100 was adopted.

Unlike the others, in the study section of the RJ 155 road, the maximum individual *RRI* (*RRI*=1,726; PI-4) among all combinations between a tangent and a horizontal curve does not refer to the location of the investigated bus accident, which occurred near to the sixth curve (*RRI*=1,034; PI-6). The average value among these individual assessments, coincidentally, is also *RRI*=1,034. Considering the "smoothing" of the curves preceding the accident site (adapted UHM), however, the RRI_F=40,769 is determined.

The study sections of the Trindade Access and SP 125 roads, in turn, present the maximum *RRI*s precisely in the places where the investigated bus accidents were recorded, that is, *RRI*=5,040 (PI-5) and *RRI*=6,734 (PI-10), respectively. Both values are about twice as high as the average *RRI* among the corresponding individual combinations. Considering the "smoothing" of the curves preceding the accident site (adapted UHM), however, the RRI_F=5,040 is determined for the Trindade Access road; and the RRI_F=55,845 is determined for the SP 125 road. In the first case, the RRI_F value is equal to the maximum individual *RRI* of the original UHM, since the fourth curve (PI-4), which precedes the accident site (PI-5), is characterized by a long curvilinear length and steep slope, not allowing the increase in speed of vehicles when traveling there.

Table 4: Individual *RRI*s and RRI_F at the accident site.

Curve	Accident site Trindade Access road	RJ 155 road	SP 125 road
PI-1	1,861	884	4,956
PI-2	3,354	1,053	977
PI-3	918	898	4,950
PI-4	1,894	1,726	691
PI-5	5,040	610	1,847
PI-6	856	1,034	3,674
PI-7			5,692
PI-8			1,488
PI-9			1,367
PI-10			6,734
Average RRI among all tangent/horizontal curve sets	2,321	1,034	3,238
RRI_F at the accident site (adapted UHM) [curve]	5,040 [5th]	40,769 [5th]	55,845 [10th]

5 CONCLUSION

The present paper sought to use the adapted UHM to investigate the relationship between road geometry and 3 severe bus accidents that occurred in Brazil. Thus, addressing the first research question, the results of the case studies suggest the model as a potential tool for assessing the risk of accidents involving buses. In other words, when different *RRI*s were calculated for each successive combination between a tangent and a horizontal curve, it was possible to identify the places, on each specific road, with the greatest demand for corrective actions, as well as to bring up the discussion about the importance of eventual changes in the road design. Furthermore, with the exception of the RJ 155 road, the places of occurrence of the investigated accidents both on the Trindade Access and on the SP 125 roads are precisely the ones that present the highest *RRI*s among all the elements belonging to the respective alignment.

Addressing the second research question, on winding roads, drivers are often influenced by sudden changes in the route and, consequently, they seek to adapt traffic speed to the sensation of lateral stability. In this context, tall vehicles, such as DD type buses, tend to develop a movement that leads to greater risks of tipping over when traveling through sequential reverse curves and with reduced radii, since the visual field when in a previous curve restricts the detection of the next one and, therefore, may compromise safe braking distances. Vehicle rotational acceleration can also be considered a relevant risk factor from an operational point of view.

Addressing the third research question, authors such as Monari *et al*. (2021) argue that, in the context of highways, due to the fact that traffic accidents are essentially fatal (especially on single-lane roads), it is necessary that electronic speed monitoring becomes increasingly frequent on Brazilian highways. Thus, the UHM can contribute to the process of careful allocation, for example, of fixed speed cameras, helping to identify places that pose a risk by inducing drivers to increase speed.

Regarding the limitations of the research, it is worth mentioning that the entire process of measuring accelerations on the studied roads was conducted with a different type of vehicle from those involved in the investigated accidents and, therefore, it is suggested that future work be more rigorous, from a methodological point of view, in collecting this information. In addition, aiming at a more robust statistical analysis, it is suggested that a greater number of road accidents be considered, for example, those georeferenced in national databases, in order to develop accident prediction equations from the UHM, and not just indicating the "relative risk" between the various elements that make up a road section. Finally, it is essential to highlight that the values of the geometric parameters extracted from open data platforms, such as the horizontal radii and longitudinal slopes, are subject to inaccuracies and, therefore, it is also suggested that the research method be replicated whenever possible using *as built* data.

ACKNOWLEDGMENTS

The authors thank Lieutenant Colonel Márcio Ferreira Rodrigues de Freitas, commander of the 2nd CIPM - Rio de Janeiro, and Sergeants Michel and Marcel for their support during the field survey on the Trindade Access road. The authors are also grateful to Mr. Paulo Abreu, Secretary of Construction of the Municipality of Paraty-RJ, for his field support during the vehicle count.

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