Horizontal Curves with Transition. The Use of This Methodology for the Calculation of a Road Project in the City of Campinas/SP - Brazil

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Abstract. With the emergence of automobiles and other automotive means, it became necessary to create or open paths that would allow the circulation of vehicles, and it was from these requirements that highways, roads, avenues, and streets arose. Based on these concepts, the research aims to present all the parameters and principles that involve the construction of an avenue. Through consultations on current scientific articles, 2016 until 2021, all the characteristics of the theme will be presented. A specific methodology with formulas will be presented to demonstrate and specify the results and improvements in an avenue to the reader, using concepts and approaches of calculations for avenues. Finally, with the application of this new methodology, the article aims to demonstrate, in a real case, the importance of a methodology in avenue calculation, to provide a more efficient, sustainable project, which brings comfort and safety to users. This article is relevant to the topic addressed, since it brings an important and relevant approach to Civil Engineering, having a practical application, and therefore serving as a parameter for other works and future applications.

Keywords: Avenues · Case study · Road characteristics · Calculation · Urban mobility

1 Introduction

This article presents itself as an innovative item, with a bibliographic review of the covered content that is clearly presented and aims to ensure the reader's understanding of this subject [1–3]. The case study refers to the staking of an avenue. In the specific case, all parameters were carried out concerning the requirements according to the standards for presentation and illustration of the

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projects related to this avenue [4–6]. The project was based on staking a portion of a paved road, which is part of John Boyd Dunlop Avenue, one of the largest municipal roads in the city of Campinas. It has approximately 13.2 km of extension and connects the city's North West region to the downtown area [7–9]. The region of Campinas is characterized by the daily number of small and large size vehicles, which use the roads, highways, and avenues to move all around the region. In the studied avenue, there is a flow of light and heavy vehicles that will go through the adopted stretch [10] The avenue cuts about 16 trading centers and 86 districts, according to information from the Campinas City Hall. Although it is known as "avenue", in 2009, the project that transformed the avenue in the municipal road was approved. Around the area where the road is inserted, there are many businesses and residences, and this ends up causing several disorders about traffic and accidents involving that area [11,12]. The project is organized as follows (Fig. 1).

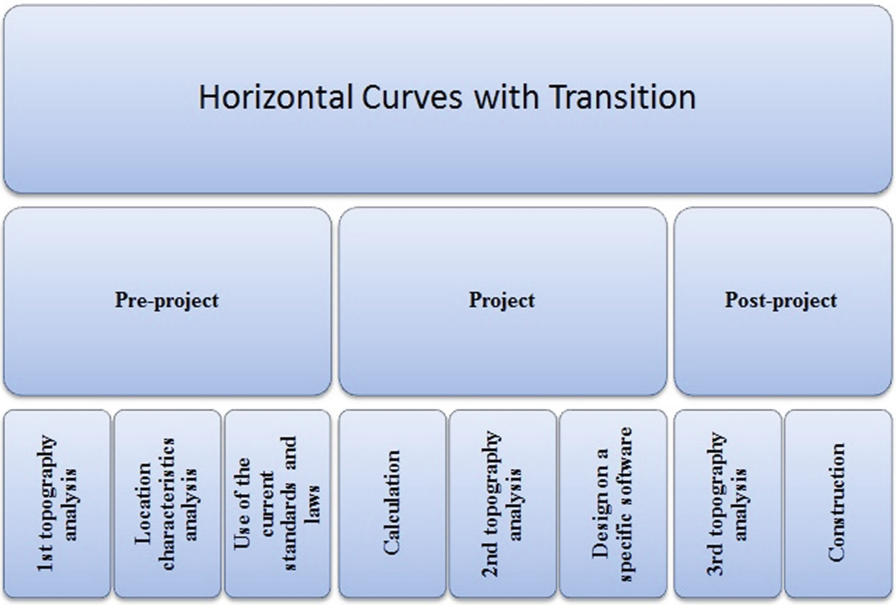

Fig. 1. Work organization

The article is structured in four sections. The first one is the introduction, where the objectives and methods are presented. The second section describes the methodology applied in this study and presents an overview of the case study. The third section brings some background knowledge about roads and presents the equations and calculations for the real case. The fourth section concludes the work highlighting the study's benefits and differential, which is the bibliographic revision and practical demonstrations on the subject of interest, which is used worldwide. After verifying the scientific literature about this theme, one can note that, nowadays, it is very relevant since there are numerous articles about it in the main database. However, when this article is compared to the previously published works, it is possible to observe that different approaches were used. Most of the works address a sustainable, efficient perspective concerning road design. This work, in contrast, focuses on the conception and basic metrics for the construction of an avenue based on a real case and shows how to apply the presented concepts, filling a gap in the academic literature [13–15]. Finally, this chapter concludes the importance of this work in the scope of scientific research, as it demonstrates in practice the importance of metrics for Civil Engineering, having a practical application, thus serving as a parameter for other works and future applications, bringing safety and saving material and human resources in road projects, since there is a lack of documents and scientific articles that specifically deal with themes, with such richness, clarity, and detail, that the present work offers to its readers, thus proposing a novelty and a differential of the studied theme.

2 Methodology

The methodology of this work was analytical, as well as the analysis of scientific articles relevant to the theme, technical standards, and Brazilian legislation, which establish safety and high-quality guidelines for roads, highways, avenues, and streets across the country [16,17].

It is important to note that the authors were concerned with collecting research and updated information (2016 to 2021). However, it is easy to identify in this article, outdated references, this is due to the fact that much of the information was collected from federal guidelines and laws that have been in force for a long time [16,17].

In the following paragraphs and sections, the procedure adopted by the team for the practical study in the John Boyd Dunlop avenue will be clearly and explicitly described. It is important to highlight that the staking technique was adopted, and the calculations were carried out according to the current technical standards in the national territory [18–21].

Figure 2 shows the whole extension of John Boyd Dunlop Avenue (blue line). The studied and analyzed stretch is emphasized by the red square. The initial positioning presented and determined by the contours showed that the road is downhill, i.e., the higher and initial contour line is 660.12 m, and the lowest is 600 m [18–21].

From the topographic map of the city of Campinas (Page SF.23-YAV-4, MI-2737-4) of the year 1974, the study case started in the chosen point. The map was printed in A1 format and the points A and B were marked: point A (≈22º56′15″ S and 47º09′47″ W) and point B (≈22º56′15″ S and 47º09′47″ W) [22].

The map is scaled at 1: 50,000 and the defined section has a length of 6.40 cm, i.e., after transforming this number into the actual length value, it was obtained a route 3,200 m or 3.2 km long [23].

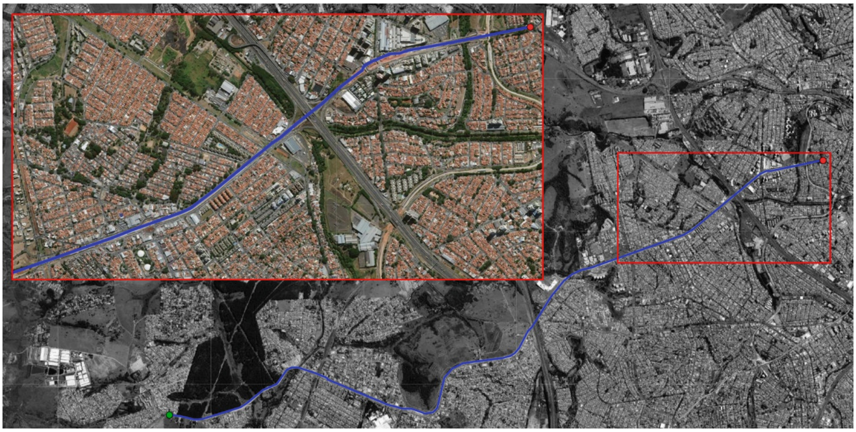

Fig. 2. Map of John Boy Dunlop Avenue (Color figure online)

For the staking, a standard 20-m distance between the stakes has been established, so the entire stretch will have about 160 stakes. It was established that each member would be responsible for 20 stakes in a 400 m section [24].

Regarding the composition, the avenue will meet all the rules and requirements established by the Brazilian agencies DNIT (National Department of Transport Infrastructure) and DER (Department of Roads and Traffic) for an avenue project. So, the avenue will be characterized as a dual carriageway road with two lanes of traffic in each direction. Each lane is about 3.6 m wide, totaling 7.20 m in each direction. All sections will contain central refuge with a drainage system and permeable material (grass). It will be 3.00 m wide, and the gutters will be 1.50 m wide [24].

The location that is inserted into the avenue is close to a residential and commercial area, so roadsides must be considered on both sides, ensuring the safety of drivers and pedestrians.

In three sections, there is the passage of a watercourse (Ribeirão Piçarrão), therefore, the construction of a bridge was necessary to allow the passage of both vehicles and pedestrians over the watercourse.

3 Background Knowledge and Results

The avenue, whose features and requirements were presented in the previous chapter, will be a two-way track with two lanes of traffic on either side. It will be on a downhill, according to the arrangement of contour lines, and is classified as a Special Class avenue. The project is based on the Level of Service (LOS) of more than 5,000 vehicles that will use the avenue daily. All adopted parameters for this study case are based on the standards and demands of DNIT for avenues projects [25–27].

Through some analysis for the assessment of needs and requirements for this road, calculations were made to scale all the factors that must be considered for the design and construction of a two-way avenue. To trace the "grade", which is a line that follows the longitudinal profile and, depending on the road class, takes up a slope (in this case, the maximum is 4%), and this line also indicates which points will need landfills or cuttings [28–30].

First, it is necessary to analyze the topography belonging to the location that is inserted into the section. In this case, there are several contours along the avenue extension marked in the map, so it will be considered as a wavy region, and the recommended speed for the avenue is estimated at 100 km/h (i.e., 27.78 m/s) with an acceleration of 0.60 m/s^2 [31–33].

One of the necessary calculations is the "Distance of Brake Visibility", which, according to Pelissari (2017), is a safe distance that enables a vehicle to stop before reaching an obstacle that may arise along the way. For this calculation, Eq. 1 is used:

$$Df = 2.52v + 0.0508v^2/(f \pm i) \tag{1}$$

The results presented in Table 1 were obtained from Eq. 1, which requires three parameters: the speed (v), whose value is 27.78 m/s (as previously mentioned), the friction factor (f), which assumes two values (0.56 for dry pavement and 0.30 for wet pavement), and the slope (i), whose value depends on the segment (segments 3 and 8 have more than one slope) and the road direction (its value is positive when the road is uphill and negative when the road is downhill).

Table 1.

Segment	Slope (i)	Dfd dry (f = 0.56)	Dfd wet (f = 0.30)	Dfu dry (f = 0.56)	Dfu wet (f = 0.30)
1	0.0003	140.0	200.8	140.0	200.5
2	0.028	143.7	214.1	136.7	189.5
3	0.029	143.8	214.6	136.5	189.1
	0.08	151.7	248.2	131.2	173.2
4	0.1	155.2	266.0	129.4	168.0
5	0.00625	140.8	203.4	139.2	198.0
6	0.00625	140.8	203.4	139.2	198.0
7	0.0085	141.1	204.5	138.9	197.1
8	0.008	141.0	204.2	139.0	197.3
	0.2	178.9	462.0	121.6	148.4
	0.022	142.9	211.0	137.3	191.7

After achieving the previous results, another calculation is related to the "Overtaking Visibility Distance" that, according to Pelissari (2017), is the necessary distance for a car to safely overtake another car on the opposing lane. For this calculus in a dual carriageway road, Eq. 2 is used:

$$Du = v(4.5 + 1.37\sqrt{v/a}) \tag{2}$$

Equation 2 has two variables: speed (v) in m/s and acceleration (a) in m/s^2. These values are equal in all segments, so that, the Overtaking Visibility Distance is the same in the whole route: 383.9 m.

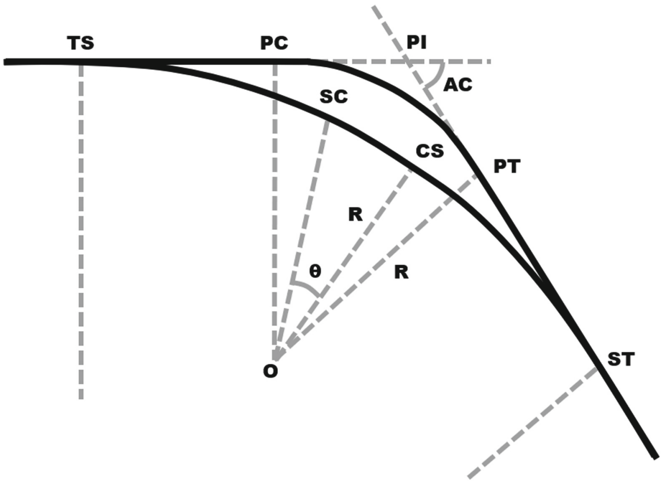

Fig. 3. Example of a transition curve and curve for describing an avenue

There are bends in all segments, but, as an example of the calculations, just passage 6 will represent the calculation of a transition curve (Fig. 3). Through the calculation, values that are required for the safety of drivers in the bends will be obtained. They ensure that the vehicle remains in the center of the lane of traffic when it is inside a bend. It is essential to understand that a vehicle can be treated like a rectangle. For that reason, when the vehicle is in a bend, it naturally takes up a greater space than its tangent. Therefore, it is imperative the need of widening the lanes in the bends so that the vehicle can keep on the right path without trespass the other lanes, avoiding accidents. It is important to emphasize that, the smaller the curve radius, the greater the need for a super width. As the radius related to the avenue class is very high, and it would be difficult to represent it in the drawing, it was allowed to adopt a radius in the drawing so that the curve stays proportional to the speed, and, in the part that has the curve, a scale 1: 3,000 was used, making it possible to perform the calculations and represent the curve [34].

Some equations make it possible to find the values for the parameters presented in Fig. 4. Equation 3 is related to the tangent (T), Eq. 4 is the bend degree (Gc), and Eq. 5 is the arc development (D).

$$T = R \cdot \tan(Ac/2) \tag{3}$$

$$Gc = 1145.9156/R \tag{4}$$

$$D = (\pi \cdot R \cdot Ac)/180^\circ \tag{5}$$

The last three equations use the same variables: the radius (R) in meters and the central angle (Ac) in degrees. These variables' values were acquired in the DER table and the data represented in the drawing transition curve [35].

After these calculations, the transition length (Lc) must be defined. To do this, two parameters are necessary: the minimum length and the maximum length. The minimum length depends on three criteria: Dynamic Criterion (Eq. 6), Safety Criterion (Eq. 7), and Esthetic Criterion (Eq. 8), and the greatest value among the three criteria is defined as the minimum transition length. The maximum transition length is given by Eq. 9.

The Dynamic Criterion is a rate established through the variation of the centripetal acceleration by a unit of time.

$$Lc \geq v^3/(0.6R) \tag{6}$$

In Eq. 6, the variables are the speed (v) in m/s and the radius (R) in meters. The Safety Criterion is related to the minimum time of 2 s relative to the wheel spin and therefore the route for the transition curve.

$$Lc \geq v \cdot t \tag{7}$$

The speed (v) is given in m/s and the time (t) is given in seconds.

The Esthetic Criterion is, according to Pelissari (2017), a parameter that ensures the "grade" difference between the edge and the shaft does not exceed a certain value, which varies according to the speed of the project. In this project, Vp will be greater than 80 km/h, so, Eq. 8 is applied:

$$Lc \geq (e \cdot w)/(0.71 - 0.00936v) \tag{8}$$

Equation 8 requires three variables: a percentual value for superelevation (e), which is determined by the regulatory agency (DER), the lane width (w) in meters, and the speed (v) in m/s.

Here, the maximum length value (Lcmax) is found through Eq. 9 and the desired length (Lc) is found through Eq. 10:

$$Lc_{max} = (\pi \cdot Ac \cdot R)/180^\circ \tag{9}$$

$$Lc = 2Lc_{min} \tag{10}$$

In Eq. 9, the central angle (Ac) and the radius (R) are the same adopted in Eqs. 3, 4, and 5. Equation 10 uses the minimum length (Lcmin) chosen among the three previous criteria, and the result must be between Lcmin and Lcmax.

The next values that must be calculated are the Sc angle (central angle of the stretch in a spiral) by Eq. 11, Yc and Xc (Cartesian coordinates of the osculating points SC and CS) by Eq. 12 and Eq. 13, respectively, “p” and “q” (rectangular coordinates of PC and PT) by Eq. 14 and Eq. 15, respectively, and finally, Ts (tangent of the curved spiral) by Eq. 16. All those parameters are present in Fig. 3.

$$Sc = Lc/(2R) \tag{11}$$

$$Yc = Lc(1 - Sc/10) \tag{12}$$

$$Xc = (Lc \cdot Sc)/3(1 - (Sc^2)/14) \tag{13}$$

$$p = Xc - R[1 - \cos(Sc)] \tag{14}$$

$$q = Yc - R \cdot \sin(Sc) \tag{15}$$

$$Ts = q + (p + R)\tan(Ac/2) \tag{16}$$

The variables used in the last six equations are the adopted transition length (Lc), calculated with Eq. 10, the radius (R), whose value is the same used in the previous calculations, and the central angle (Ac) that is the same as well.

Finally, the curve super width is calculated with the following data: physical width of the vehicle (L) in meters, axle distance (E) in meters, the distance between the front of the vehicle and the front axle (F) in meters, the radius of the curve (R) in meters, speed (v) in m/s, and the width of the lanes in meters, which is the criterium for achieving the value of Gl, in Eq. 20, from a regulatory agency table, and calculating LB value in Eq. 21 (lane width times the number of lanes).

The first equation is the Gc (static bodywork of the vehicle on the curve), represented by Eq. 17.

$$Gc = L + E^2/(2R) \tag{17}$$

The second equation is the Gf (a corresponding increase of the vehicle front balance on the curve) calculated by Eq. 18.

$$Gf = \sqrt{R^2 + F(F + 2E)} - R \tag{18}$$

The third calculation is the Fd (dynamic slack) determined by Eq. 19.

$$Fd = v/(2.78\sqrt{R}) \tag{19}$$

The penultimate equation is related to LT (total width of two traffic lanes), exemplified in Eq. 20.

$$LT = 2(Gc + Gl) + Gf + Fd \tag{20}$$

Finally, S (total super width of the track) is represented by Eq. 21.

$$S = 1.50(LT - LB) \tag{21}$$

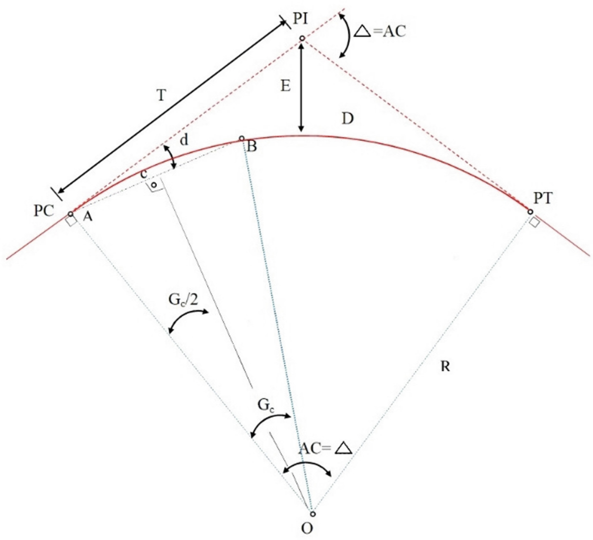

Fig. 4. Other parameters of a transition curve

Finally, we observe Fig. 4, which in summary contemplates all the calculations performed in this work, thus providing a visualization of all the results obtained in this research, and facilitating the identification by readers and researchers in this theme. We also observed that each calculated item makes up an axis of fundamental importance in Fig. 4 so that the construction is carried out in a safe, effective way, providing a lower cost for the implementation of the work, and a reduction of eventual losses of materials and time, thus making the work more effective, safe, and sustainable. All the results achieved in Eqs. 3 to 21 are presented in Table 2.

Table 2.

Variables		Results
Tangent	T	392.33 m
Bend degree	Gc	2°7′19.44″
Arc development	D	678.58 m
Minimum transition length	Lcmin	83.33 m
Maximum transition length	Lcmax	678.58 m
Transition length	Lc	166.66 m
Central angle	Sc	0.1543 rad
Cartesian coordinates of the osculating points SC and CS	Yc Xc	164.09 m 8.56 m
Rectangular coordinates of PC and PT	p q	2.14 m 81.10 m
Tangent of the curved spiral	Ts	474.99 m
Static bodywork of the vehicle on the curve	Gc	2.63 m
Corresponding increase of the vehicle front balance	Gf	0.012 m
Dynamic slack	Fd	0.43 m
Total width of two traffic lanes	LT	7.50 m
Total super width of the track	S	0.45 m

After calculating all the aspects involved in the thematic horizontal curves with transition, as we can see in Fig. 4, the next step for the effective implementation of this project, is the contraction of a topographic study, with technical specialists in this theme, as illustrated in Fig. 5, which aims to study and understand the terrain on which the road will be built. In this stage, the level curve of the site to be implanted is also necessary, as shown in Fig. 6, in order to understand the needs and difficulties of the area. Such form can be requested from the responsible body within the city hall.

Fig. 5. Topographic analysis [36]

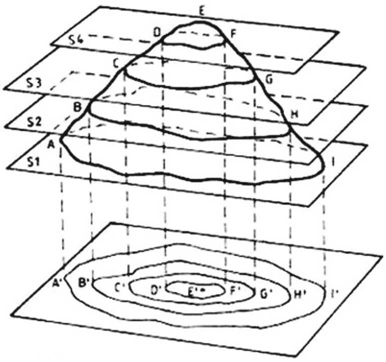

Fig. 6. Level curve [37]

After collecting data in the field, it is necessary to carry out a project, as shown in Figs. 7 and 8 so that the construction of the road comes out according to the guidelines of the calculations, difficulties, and advantages of the local topography to be implemented the project.

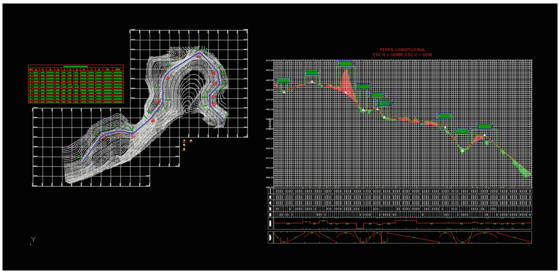

Fig. 7. AutoCAD road design [38]

Finally, we can see Fig. 8, which shows the construction of a road following pre-studied parameters in this innovative article, with a focus on efficient, safe, sustainable construction, in addition, avoiding any losses from altering projects, deforestation, or expropriation needed on the spot. And bringing countless advantages to the municipality and construction company that will have a cost reduction with this pre-project, and we cannot fail to mention the local population, who will take advantage of this bold project, to facilitate the mobilization of all the people who live, work, study, or even use the road eventually.

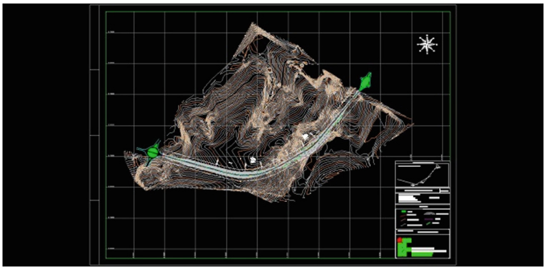

Fig. 8. AutoCAD road design [39]

Fig. 9. Image John Boy Dunlop [40]

4 Conclusion

The studied subject area is very important for academia in the ambit of civil engineering because, nowadays, with the people's latent demand for owning and using transport means, it is essential for the cities, from the smallest to the greatest, to have streets, avenues, roads, and highways that meet the needs of the population. It is of paramount importance to note the relevance of this theme presented in this work since the concept is the basis for the design of roads and aims at the safety of the people who daily use the roads with different objectives (e.g., work, school, and leisure). Besides, a pre-feasibility study of the roads ensures they safely meet the demands of the population and leads the public agencies and the companies specialized in engineering to develop projects thinking in the medium and long terms and facilitate projects that are more efficient and less expensive.

The calculations that were presented in this article are essential for the design of roads because they are required by the city, state, and federal departments of constructions, especially the DNIT, the highest federal agency, which is responsible for the analysis and bestowal of streets, avenues, and roads in the whole

Brazilian territory. In Sect. 3, the work focused on the discussion and calculation, within the case study in the John Boyd Dunlop in the city of Campinas (Fig. 9), its lanes' super width.

The main contribution of this work for the civil engineering segment is the descriptive application of a method that has been improved since the first roads were designed: the mathematical formulation for the construction of avenues considering horizontal bends. This work's main scope is not the case study, but the descriptive approach the authors used for the design of an avenue. The work-group identified a deficiency in the current literature concerning the application of calculations in the design of roads and that is the reason why this article was developed, so that future researchers and engineers may use this work as a reference in their projects, achieving finance and safety benefits.

As future works, the scientific team of this article aims to apply the same methodology in other avenues, streets, and roads in the region of Campinas in order to note the characteristics and similarity in the calculations and their use in a random road, increasingly improving the applied calculus and design and bringing benefits for all three actors (government, population, and the company of civil engineering liable for the construction). The roads that will be analyzed in the future must have the same characteristics as the studied avenue (John Boyd Dunlop), seeking to reinforce the methodology applied in this work.

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