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Assessment of road geometric adequacy in São Paulo's bikeway network

Avaliação da adequação geométrica da malha cicloviária de São Paulo

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ABSTRACT
To encourage and increase bicycle use in the cities, it is necessary to offer cycling paths with adequate geometric dimensions. This study aimed to contribute to the evaluation of the geometric adequacy of São Paulo cycle tracks and cycle lanes. To this end, a pilot area was subdivided into segments in the bicycle network so that three aspects could be evaluated: width, slope and speed. The average widths and slope were measured for each segment and the speed limits of the adjacent streets were identified for comparison with reference ranges. These values were integrated into the Bikeway Geometrical Adequacy Indicator (IAGVC), which showed that no segment of the pilot area is fully inadequate, but only 28.95% were classified as fully adequate.

RESUMO
Para o incentivo e aumento do uso da bicicleta nas cidades, é necessária a oferta de vias cicláveis com geometria adequada. Este trabalho teve como objetivo contribuir para a avaliação da adequação geométrica das ciclovias e ciclofaixas de São Paulo. Para tanto, foi delimitada uma área piloto subdividida em segmentos da rede cicloviária para que três aspectos pudessem ser avaliados: larguras, declividades e velocidades. Foram coletadas as larguras médias e calculadas as declividades de cada segmento e observadas as velocidades máximas permitidas dos automóveis das vias adjacentes para comparação com intervalos de referência. Estes valores foram integrados no Indicador de Adequação Geométrica de Vias Cicláveis (IAGVC) que mostrou que nenhum segmento da área piloto é plenamente inadequado, porém apenas 28,95% foram classificados como plenamente adequados

1. INTRODUCTION

In the largest Brazilian cities, the motorized modes of transportation have resulted in several conflicts and urban issues: air pollution, difficult access to the city by non-motorized commuters, the increase of land value, gentrification and hard traffic (GUALDA, 1994; ITDP Brasil, 2015).

Active modes of transport ensure more possibilities for commuting in cities and represent an alternative that complements and even subverts the traditional logic of urban planners and can be a way to reduce dependence on cars (AMIGO, 2018). In addition, the positive impacts of encouraging bicycle use in cities go beyond the ability to transport people, including economic, political, energetic, social, public health and environmental advantages (CALLIL, 2018; COMISSÃO EUROPEIA, 2000; GÖSSLING & CHOI, 2015; HÖLZEL, 2012; IDAE, 2007; IEMA, 2009; ITDP Brasil, 2013; TORRES-FREIRE *et al.*, 2018).

However, for these benefits, it is necessary that citizens make daily use of the bicycle and, for that, a quality cycling infrastructure is necessary to increase the attractiveness of this mode of transport. The creation of the Brazilian Traffic Code (BRASIL, 2020) was a major step forward in instituting rules that consider the circulation of bicycles on urban roads; however, it is still necessary to build cycle paths to ensure greater safety for cyclists (Vasconcellos, 2014).

Furthermore, even with the existence of a bicycle network, minimum technical requirements are necessary to effectively encourage the circulation of cyclists in the city. Amigo (2018), in a research on adherence to the cycle modal in São Paulo, indicates that there are strong perceptions of vulnerability and insecurity even with already implemented bike paths: there are excessive motorized vehicles moving at high speeds and exhibit aggressive behavior in traffic, deterring the decision to use the bicycle.

In this way, this work intends to discuss the critical points of bikeway geometry that are most related to the guarantee of cycling operation and safety, in addition to presenting the application of geometric cycle adequacy indices in a pilot area of the city of São Paulo, Brazil.

2. BIKEWAY GEOMETRY

DiGioia *et al.* (2017) summarize the objectives of geometric road designs that focus on reducing the number or severity of collisions between motorized and non-motorized vehicles as follows: a) increase segregation between bicycles and motor vehicles in space and time; b) improve visibility between vehicles and cyclists; c) decrease intermodal interactions; and d) reduction of motorized vehicle speed.

Specifically, on the last topic, the authors also state that, when collisions occur, the lower the speed differential between cars and cyclists are, the lower severity and probability of death. Based on this understanding, many cities in the world have implemented traffic calming initiatives by reducing the maximum speed limits for motor vehicles in their urban perimeter. Not only for regulatory purposes, these strategies have generated effective results in driver behavior: in Montreal (Canada), where since 2009 speed limits has been reduced from 50 km/h to 40 km/h on local roads and in Boston (USA) where the same decrease was taken in 2017, there were effective reductions in practiced speeds by vehicles (HEYDARI *et al.*, 2014; HU & CICCHINO, 2018).

The elaboration of geometric designs for bikeways must consider the slope for the implementation of a road in an appropriate shape, regarding the very steep ramps can hinder and even block the bicycle traffic upwards. There are many parameters described in manuals and academic papers about the most preferred or limiting slope thresholds for cyclists. The Canadian manual of public bicycle cycling planning (TRANSPORT CANADA, 2010) indicates that roads with slopes of less than 4% do not significantly affect the use of bicycles, while on roads with slopes greater than 8% little or no bicycle traffic is expected. The less restrictive US manual (AASHTO, 2012) indicates that, even if shared roads (in the case of São Paulo, cycle lanes and cycle routes) follow the slope imposed by the adjacent road, the 5% slope limit must be followed.

The work of Koh & Wong (2013) contributes to this theme by presenting results about the choice of bikeways assessment in Singapore. In their results, the flat ways, low or medium slopes (below 8%) showed greater preference among users in the survey. The Spanish guide for implementation of public bicycle systems (IDAE, 2007) does not fully discourage the installation of bicycle infrastructure on slopes over 8% but suggests the offer of an electric bicycles fleet to solve this characteristic. However, there is also an understanding that cyclists prefer shorter but steeper ways to very long routes with intermediate slopes: traveling on high slopes for a few meters becomes acceptable compared to extensive journeys on softer reliefs (MILAKIS & ATHANASOPOULOS, 2014). Accordingly, the Brazilian reference manual for cycling planning (GEIPOT, 2001) presents an inverse relationship between slopes and distances: the greater the slope, the shorter the route to be taken. As an example, a 5% slope is acceptable on a 2 m course but is not recommended on a stretch of more than 4 m. Thus, ramps with high slopes may be accepted in cycle planning, but they should represent a small part of the bikeway network.

In addition to the difficulties that cyclists must overcome uphill, the Dutch manual for bicycle traffic (CROW, 2007) warns about aspects of bicycle traffic on descents. In the downward direction and in high slopes, attention should be paid, since without the difficulty of overcoming gravity, the cyclist can reach high speeds (35 to 40 km/h), increasing the risk of accidents.

The bikeway width strongly influences cycling safety: bicycle use requires a space for maneuver and circulation that is not limited to the width of the tires, but also considers the width of the handlebars, the driver and the sinuous movement necessary for circulation. This movement is determined by the skills of the cyclist and the speed adopted: the less fast a bicycle is, the less stability is also required, requiring a greater lateral space (AASHTO, 2012; CROW, 2007).

Much is discussed about what minimum widths are necessary to ensure the safe circulation of bicycles. In the American manual (AASHTO, 2012), minimum widths are indicated depending on the type of bikeway: from 1.2 m (on shoulders available for bicycle use) to 1.8 m (on roads without segregation by parking). The Dutch manual (CROW, 2007) indicates minimum widths of 1.5 m, but also relates them with the type of bike path (unidirectional, bidirectional etc.) and the volume of bicycle traffic (ranging from 2.0 m and 4.0 m). The São Paulo Traffic Engineering Company (CET, 2014), adapting the indications of the reference Brazilian cycle planning manual (GEIPOT, 2001), also proposes minimum widths based on bicycle traffic on unidirectional and bidirectional bikeways, varying from 1.2 m to 4 m.

Bicycle safety can also be affected by the relationships between different urban transport systems. Sheresck & Lerner (2015) relate the operational speed and the traffic volume of motor vehicles on roads adjacent to the bike paths as parameters to define what type of bicycle infrastructure is needed. Low-volume car routes do not require a specific cycling infrastructure, whereas roads with a high volume of traffic require cycle tracks and cycle lanes, which in many cases can create many conflicts with the already built and consolidated urban space.

3. SÃO PAULO BIKEWAY NETWORK

Throughout the development of the city of São Paulo, individual motorized modals were privileged: heavy investment in a roadway network with the creation and expansion of streets, avenues, and expressways in the city's history for motor vehicles traffic. However, the recent implementation of 400 km of bike paths in São Paulo (which makes the city with the largest permanent cycling system in Latin America) has consolidated changes not only in technical terms, but in cultural, economic and political aspects for the city and its transport systems (ITDP BRASIL, 2015; ROSIN, 2018).

According to TONOBOHN (2016), until 2012 there were several bikeway plans in São Paulo linked to many urban projects, for example: urban requalification (Água Espraiada, Nova Luz); road extension (Faria Lima Avenue); public park construction (Parque Várzeas do Tietê); subway and train extension (Line 2-Green and Line 9-Emerald). However, these projects were scattered and not integrated, which made them unreliable as belonging to a bicycle network itself. Based on this scenario and with the goal of implementing 400 km of bikeways, from 2013 to 2016, these various bike path construction plans were unified, which contributed to the current 513 km São Paulo cycle network extension: with 482 km of cycle tracks and cycle lanes and 30.3 km of cycle routes (CET, 2020).

In this process, in addition to public infrastructure, bike sharing systems were also regulated. There are bicycles located in many terminals throughout the city where a user can borrow a bicycle and return it to a station near his destination. Several cities in the world have such a system that subsidizes the movement of local citizens and tourists through some form of registration at low or no cost. These systems, in general, are composed of four main elements: a) customized bicycles (mainly to prevent theft and vandalism); b) fixed and automated stations for making bicycles available; c) tracking technology to control bicycle use; and d) real-time information system that provides the location and quantity of bicycles available at each station (DECASTRO, 2018). In São Paulo, fixed station and dockless systems were implemented, in which there are no physical stations: only a perimeter of performance where bicycles can be borrowed and returned and are managed by embedded geolocation systems.

There is no specific international convention to distinguish and name the different types of bike paths (which can be differentiated by their types of construction materials, their levels of segregation and sharing with other modes, their volumes and traffic speeds, etc.). According to CET (2014), there are three groups of bikeways in São Paulo: cycle tracks (Figure 1 left), cycle lanes (Figure 1 right) and shared use paths.

The cycle tracks have the characteristics of greater segregation in relation to other paths and are built on different vertical level, in addition to being associated with railings and fences. They represent the greater safety infrastructure for cyclists. However, they need a larger free area between the sidewalk and the motorway and higher costs and time of implementation. Cycle lanes, on the other hand, are part of the roadway itself, but are intended exclusively for locomotion of cycles. Its implementation occurs through vertical, horizontal signaling in addition to auxiliary devices such as raised pavement marker. Thus, they present a smaller segregation in relation to the car traffic when compared to cycle tracks; however, their implementation is flexible, and they are built with lower costs and time.

The third type are the shared use paths that are intended not only for bicycles, but also for motor vehicles and pedestrians. They are subdivided in two types: a) cycle routes, which are streets with lower operational speeds and safer characteristics for cycling and their implementation occurs through vertical and horizontal signs; and b) operational cycle lanes, which are activated only at certain times and days, depending on a specific demand. As an example, there are leisure cycle lanes, which are enabled with the help of traffic cones and vertical signs.

In addition to the paths themselves, it is very important to consider bicycle loading in other modes. Due to its flexible characteristics, the bicycle can stop being a vehicle and become a load that the commuter carries in part of path because of increase of difficulty in locomotion (due to the distance or the lack of bicycle infrastructure, for example). In São Paulo, bicycles can be transported at designated times and spaces in public transport (bus, subway, and train) and in individual motorized transport (taxis with support for bicycle loading).

Figure 1. Paulista cycle track (left) and Artur de Azevedo cycle lane (right)

4. MATERIAL AND METHODS

Based on characteristics (collected in February/2019) that indicated qualitative similarities with the entire cycle network of São Paulo (Figure 2), the bikeways of a pilot area were selected for this study (26.7 km of extension or 5.2% of the whole cycle network). The pilot area provides access to 20 transportation structures, including subway, train, and urban bus terminals, which indicates a high attraction for cyclists: it is possible to transport bicycles on rail network at certain times, and folding bicycles can be carried on buses or keeping them in bike racks (in general, associated with these structures). This information is also influenced by bike sharing systems in São Paulo: the pilot area includes 45 stations (of 231 active) in the *BikeSampa* network, 11 stations (of 17 active) in the *CicloSampa* project and were within the operation area of Yellow and Grin dockless system (of bicycles and electric scooters).

Also, the relief were considered: São Paulo has many flat areas, due to the flooding system of its rivers, but also hills, which result in medium and high slopes. The pilot area contemplated these characteristics with examples of notably flat roads, such as the cycle track of Faria Lima Avenue (which is parallel to the Pinheiros River) and the cycle lane of Consolação Street, which links the downtown of São Paulo (district of the Republic) to the Paulista Avenue (in Jardim Paulista district), on a high hill.

The pilot area also provides access to various sports, leisure and cultural establishment, which, in addition to attracting more users to the cycling system, also favors the inclusion of more types of cyclists (such as children, the elderly, sportspeople, etc.) with others travel reasons (such as leisure, tourism, etc.). In the pilot area and its surroundings are Ibirapuera Park, Povo Park, Água Branca Park, Trianon Park, Roosevelt Square, Paulista and Sumaré cycle lanes (leisure operational lanes), Pinheiros Club, Hebraica Club, Ibirapuera Gymnasium, the Sesc Units (Pinheiros, Paulista, Consolação, Pompeia), Museums and culture houses as Masp, Itaú Cultural, Moreira Salles Institute, Casa das Rosas, Japan House among others.

For the best execution of the analyzes and the organization of the collected and produced data, a segmentation was defined and was oriented by the intercessions or nodes of the network. The cycle paths were divided into units of analysis, here called segments, which respected the limits of the adjacent blocks or "natural breaks", such as sharp curves, resulting in 156 segments distributed in eleven ways, seven of which are cycle lanes and four cycle tracks (described in Table 1). The data of this work were collected in surveys carried out in February 2019.

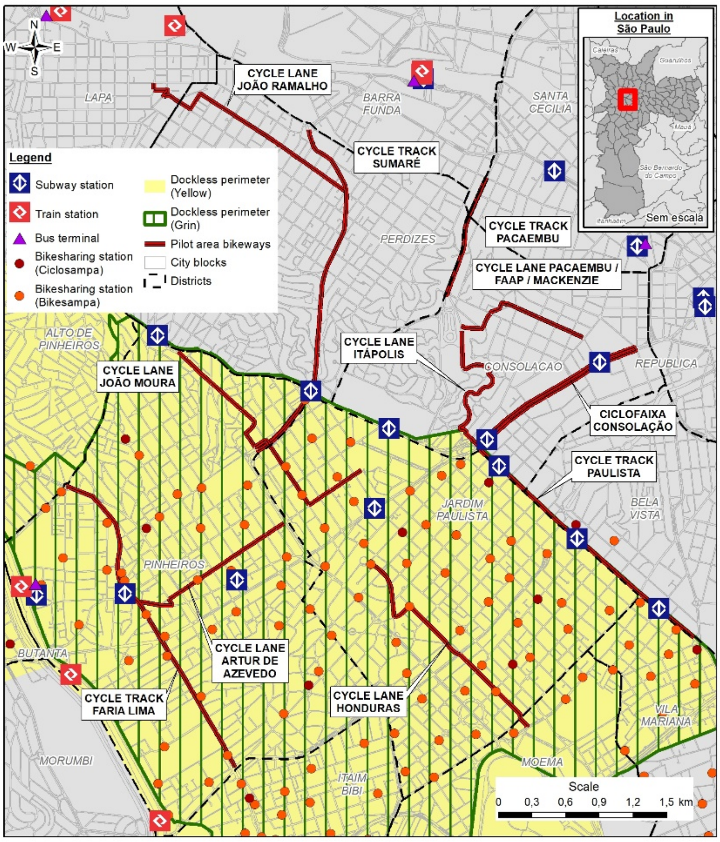

Figure 2. Pilot area map

Table 1 – Pilot area bikeways and segments

Bikeway and extension	Number of segments	Average segment extension (m)
Cycle lane Artur de Azevedo (1,6 km)	14	114,22
Cycle lane Consolação (3,3 km)	14	237,91
Cycle lane Honduras (2,3 km)	15	152,65
Cycle lane Itápolis (1,5 km)	5	300,49
Cycle lane João Moura (2,6 km)	19	135,57
Cycle lane João Ramalho (2,3 km)	20	112,47
Cycle lane Pacaembu / Faap / Mackenzie (1,3 km)	8	161,59
Cycle track Faria Lima (3,0 km)	18	169,26
Cycle track Pacaembu (2,2 km)	6	373,14
Cycle track Paulista (2,7 km)	18	149,97
Cycle track Sumaré (3,7 km)	19	196,19
Pilot area (26, 5 km)	156	191,22

For an integrated assessment, the Bikeway Geometrical Adequacy Indicator (from Portuguese, "IAGVC"), was proposed based on three sections that synthesize the main influences of geometry on comfort and safety on bikeways. The first one is represented by the values collected from the average widths of each segment of the road studied, for purposes of comparison with the ideal values defined based on the previously presented bibliography, as shown in Table 2.

Table 2 – Reference values for the width indicator

Bidirectional	Unidirectional	Width indicator
Greater than or equal to 2,51 m	Greater than or equal to 1.51 m	Fully adequate
From 2,26 m to 2,50 m	From 1,35 m to 1,50 m	Partly adequate
From 2,01 m to 2,25 m	From 1,21 m to 1,34 m	Partly inadequate
Less than or equal to 2.00 m	Less than or equal to 1,20 m	Inadequate

The second section relates to the maximum speeds allowed on streets and avenues adjacent to bike paths. The higher the speed of motor vehicles, the more difficulties are posed to perceive the existence of cyclists, for braking or maneuvering detours, which increases the chances of conflicts and accidents. Thus, from the observation of the maximum regulatory speeds of cities in which traffic calming initiatives were applied and the maximum speeds already applied in São Paulo, the ideal maximum speeds allowed by cars and the type of the bikeway are shown in Table 3.

Table 3 – Reference values for the speed indicator

Type	Maximum allowed speed of adjacent road
Cycle track	Suitable up to 50 km/h
Cycle lane	Suitable up to 40 km/h

The bike paths slope values were included in the third section, which considers the cyclists difficulty to overcoming ramps and the problems of increasing speed and deceleration when going down steep slopes. This section contributes to safety assessment: cycle lanes in a downward direction with high and narrow slopes located next to an avenue with very high car speed, present an increased risk to the cyclist, considering maneuver space has been reduced, which increases the possibility of losing control of the bicycle and the invasion of the carriageway.

To obtain the slope values of each segment, a Digital Terrain Model was generated (Figure 3) to show the pilot area elevation. The inputs used for processing were the vectors of the contour, on a scale of 1: 1,000 and equidistance of 1 m, from the Digital Map of the City (SÃO PAULO, 2008).

The model was made using the *Topo to Raster* interpolator, from the *Spatial Analyst* module from *ArcGis* platform (ESRI, 2016), which generated a raster layer of 5 meters of spatial resolution based on contour lines and quoted points. Then, it was possible to calculate the slope value (D) of each segment using the following procedure:

a) Collecting the initial (z1) and final (z2) elevation values with the tool *Feature Vertices To Points* from module *Data Management Tools* and the tool *Extract by Points* from module *Spatial Analyst Tools,* both from platform *ArcGis* (ESRI, 2016);

b) Absolute value from the difference between the initial (z1) and final (z2) elevation values, divided by the horizontal distance of each segment (L), multiplied by 100.

$$D = \frac{|Z1-Z2|}{L}.100 \tag{1}$$

It is important to note that the results do not include the direction of the road (keeping in mind that the cyclist does not necessarily transit respecting the mandatory direction of the road network) and the values adopted for the analysis started from 0% (totally flat relief) to higher slopes. The ranges for classification were defined based on the observation of the sample of data from the pilot area and the bibliography previously presented as inversely proportional to the geometric adequacy values (the greater the slope, the less favorable it will be for the cyclist's comfort and safety):

a) Less than or equal to 2,99% as fully adequate segments;
b) From 3% to 4,99% as partly adequate segments;
c) From 5% to 7,99% as partly inadequate segments;
d) Greater than or equal to 8% as inadequate segments.

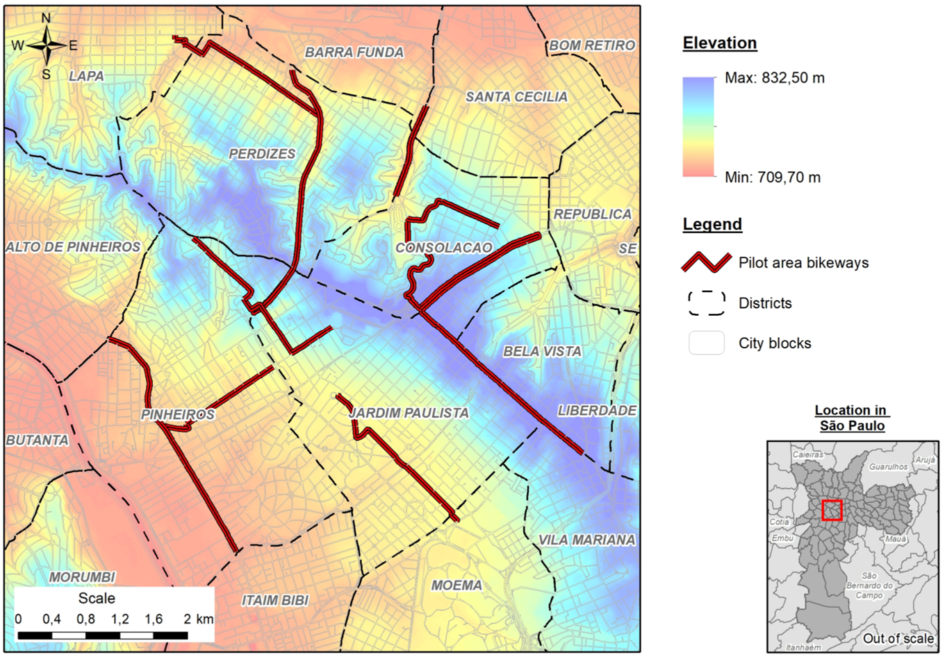

Figure 3. Pilot Area Digital Terrain Model

5. RESULTS

The assessment of geometric adequacy was composed by three indicators. The first considers the widths of the bike paths and the minimum values that guarantee the cyclist safety. The second is the result of observations of the maximum permitted speed of motor vehicles on the streets and avenues bordering the cycle paths. The third one evaluated the slopes of bikeways considering that steep areas are less attractive (given the difficulty in overcoming them) and safe (due to the cyclist's high speeds on the descent).

The widths of the cycle tracks were collected in full, while the widths of the cycle lanes were separated from the width of the street gutter: however, much cyclists may come to use the street gutter, it was disregarded in this analysis. The average widths identified in the bidirectional cycle lanes were 1.48 m and in the unidirectional 0.83 m (both classified as “inadequate”). The average widths of the bidirectional cycle tracks were 2.43 m and the one-way lanes were 1.45 m (both classified as “partially adequate”). Table 4 shows that more than 70% of the pilot area does not meet the proposed width criteria.

The speed indicator evaluated the cyclist's safety in relation to the motor vehicles on the adjacent road. Thus, the adequacy criterion was up to 50 km/h for cycle tracks and 40 km/h for cycle lanes without specific segregation. All roads were considered adequate, except Consolação Street, which was inadequate in terms of these criteria (is a road with a maximum speed of 50 km/h bearing a cycle lane).

Table 4 – Bikeways width geometric adequacy for pilot area

Width adequacy	Number of segments	Extension (m)	% of Pilot Area
Inadequate	108	18710,01	70,46%
Partially inadequate	21	3206,66	12,08%
Partially adequate	7	1479,19	5,57%
Fully adequate	20	3156,65	11,89%

The result of the slope indicator is presented in Table 5, which shows that the majority (72,50%) of cycle paths are “fully adequate” for cycle traffic in terms of their slope values. Only five segments were classified as “inadequate”, with four located on João Moura's cycle lane, and one on João Ramalho's cycle lane.

Table 5 – Bikeways slope adequacy for pilot area

Slope adequacy	Number of segments	Extension (m)	% of Pilot Area
Inadequate	5	459,97	1,73%
Partially inadequate	12	1945,35	7,33%
Partially adequate	25	4895,84	18,44%
Fully adequate	114	19251,37	72,50%

The average, maximum and minimum slope values for each bike path are described in Table 6, which shows an acceptable value for the pilot area (2.22%), according to the previously established criteria. However, maximum inadequate values stand out, as in the cycle lanes João Moura (10.26%) and João Ramalho (8.25%), which indicate significant differences in the evaluated area and that cannot be classified as fully adequate.

Table 6 – Average, maximum and minimum slope values (%)

Bikeway	Avg	Min	Max
Cycle lane Artur de Azevedo	2,04	0,09	7,06
Cycle lane Consolação	3,13	0,25	5,88
Cycle lane Honduras	0,71	0,02	1,91
Cycle lane Itápolis	2,75	0,19	5,42
Cycle lane João Moura	4,98	0,71	10,26
Cycle lane João Ramalho	3,33	0,04	8,25
Cycle lane Pacaembu / Faap / Mackenzie	2,54	0,15	5,66
Cycle track Faria Lima	0,99	0,03	3,62
Cycle track Pacaembu	0,94	0,81	1,13
Cycle track Paulista	0,48	0,07	1,31
Cycle track Sumaré	1,87	0,16	4,65
Pilot area bikeways	2,22	0,02	10,26

In order to make an integrated assessment of the three presented geometry indicators, scores were defined for each of the classes: a) “Fully adequate”, score 1; b) “Partially adequate”, score 0,75; c) “Partially inadequate”, score 0,5; and d) “Inappropriate”, score 0,25. Thus, the average of the three indicators for each bike path segment was calculated, generating the Bikeway Geometrical Adequacy Indicator (IAGVC), which is represented in Table 7 and in Figure 4.

It was not found no fully inadequate segment, however there is a high concentration of “partially inadequate” segments on the cycle lane Consolação, which has an average IAGVC of 0,53 and has the lowest value of the entire sample (0,42). As shown in Table 7, the Pilot Area is, in large part, classified as partially adequate (62,11%) and as fully adequate (28,95%).

Only 8,94% of the roads are partially inadequate, which indicates that the pilot area has a good geometric adequacy.

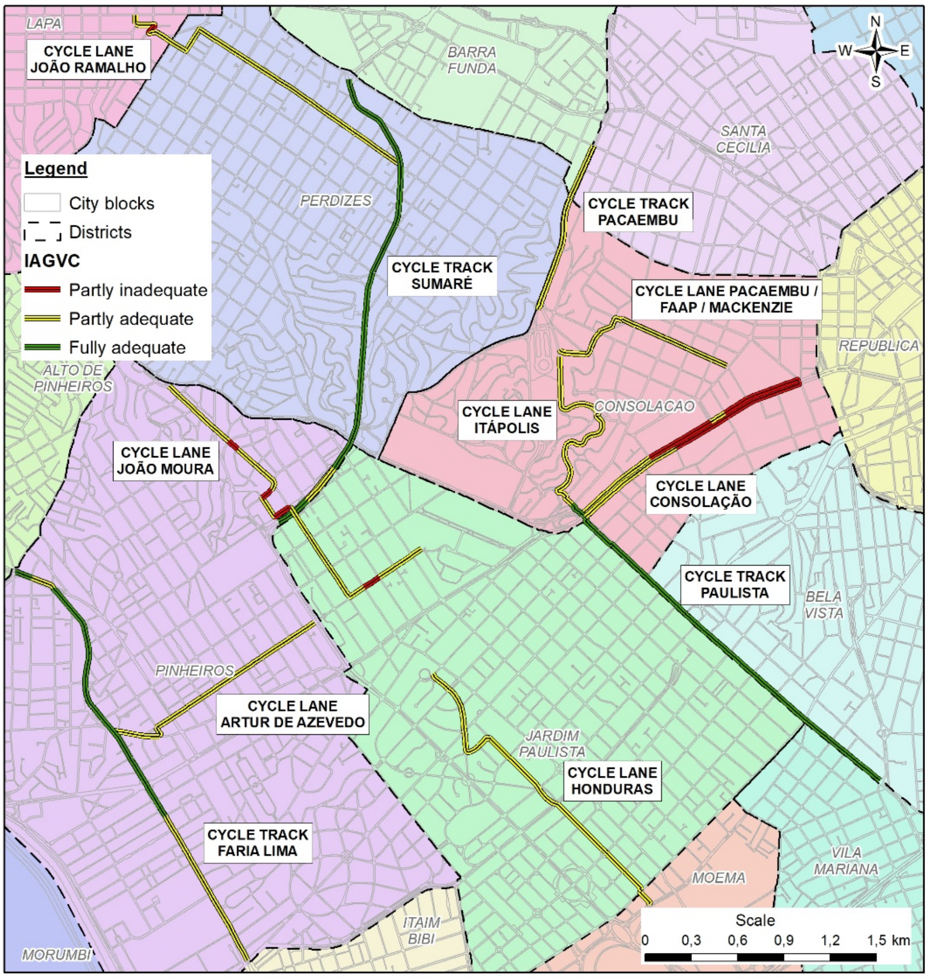

Figure 4. Pilot area IAGVC map

Table 7 – Pilot area IAGVC description

IAGVC	Number of segments	Extension (km)	% of Pilot Area
Fully adequate	47	7,69	28,95%
Partly adequate	97	16,50	62,11%
Partly inadequate	12	2,37	8,94%

6. FINAL CONSIDERATIONS

Bicycle transport has a high potential to positively influence the economic, environmental, health and psychosocial aspects of a community. It does not happen in the city just by the existence of bicycles and cyclists, but also by ensuring a quality, safe and secure infrastructure with proper maintenance.

About the geometric aspects of the cycle paths in the pilot area, three main parameters were approached: the slopes, the widths, and the speeds. Each one influences individual's adherence to the bicycle modal and their safety. The high slopes make it difficult to move upwards and, in the downwards direction, induce the cyclist to reach high speeds. Bikeways with reduced widths increase the vulnerability of cyclists by not providing essential space for maneuvering, inducing them to circulate on streets and avenues. High speeds practiced by automobiles, especially on streets with cycle lanes, increase the chances of accidents with cyclists and its severity. Therefore, it is important to consider speed reduction policies for motor vehicles to increase the safety of cyclists.

It is important to note that, as the three indicators have the same weight in the proposed analysis, this evaluation model can be revised to be more robust. The high values of the slope and speed indicators may have minimized the importance of the width indicator, which is very significant for the evaluation of bicycle safety. Thus, other approaches to these indicators are suggested in future works: such as the incorporation of traffic volume data and the speeds practiced by automobiles. In addition to the formal aspects, this research also intended to contribute to future projects that improve quality and guarantee bikeways safety are developed for São Paulo and other cities in the world.

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