

## Article

# The Barrier Effect and Pedestrian Mobility/Accessibility on Urban Highways: An Analysis Based on the Belo Horizonte/Minas Gerais/Brazil Ring Road

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**Abstract:** Historically, public policies in Brazil and many developing countries have prioritized individual motorized modes of transport. The urban space of Brazilian cities has been repeatedly remodeled, often to meet the demands of vehicle flow, to the detriment of spaces for pedestrian use. Part of the transport infrastructure, particularly the highways, are obstacles to the population's mobility, constituting the barrier effect and expanding the physical separation of the communities that reside or transit between the adjacent neighborhoods. Based on the proposed mobility and accessibility indicators extracted from the Origin and Destination Survey databases, this article aims to analyze pedestrian mobility and access to cross the Celso Mello Azevedo Ring Road, located in Belo Horizonte/Brazil. The results indicate that, over the period analyzed, the flows of foot crossings were significantly reduced, even in areas where population growth was recorded. The evidence also shows the prevalence of crossings by motorized modes, whose mobility and access are characterized by a tangible inequality in spatial distribution, linked to the occupation pattern of the surroundings, one consequence of which is the expressive volume of accidents involving pedestrians on the highway.



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**Keywords:** barrier effect; pedestrian mobility; accessibility; urban highways; spatial segregation

## 1. Introduction

Pedestrians are frequently penalized when they travel through urban space, often risking their lives due to repeated conflicts and disputes with vehicles over space and the lack of safe, convenient, and inviting walking conditions. This unfavorable scenario directly impacts the population's (micro)accessibility as the organization of road use in Brazil and many countries has historically prioritized the use of individual motor vehicles. Among other constraints, this reduces social interaction and the use of public spaces on roads in their surroundings, augmenting the occurrence of the "barrier effect".

Conceptually, the barrier effect is the consequence of socio-spatial separation or disruption. It is a discontinuity in the urban structure caused by transport networks, impacting the perceptions, behavior, and wellbeing of the population and results in repressed travel, a risk to pedestrians, and environmental effects on individual health and social networks [1,2]. Ancaes [1] (p. 5) defines the barrier effect as follows: "transport-related community severance is the variable and cumulative negative impact of the presence of transport infrastructure or motorised traffic on the perceptions, behaviour, and wellbeing of people who use the surrounding areas or need to make trips along or across that infrastructure or traffic." The "variable" and "cumulative" impacts differ for individuals with different needs (age, sex, socioeconomic status, and other characteristics) and vary according to the number of destinations and alternative routes [1]. The period elapsed since the barrier was

created is also considered as people adapt their behavior over time. The barrier effect can, therefore, occur in three ways: by the installation of the transport infrastructure, known as the physical barrier; by the traffic flow using the road, causing a traffic flow barrier; and by the annoyance and discomfort they cause the population, thus generating a psychological barrier [2].

In certain places, the barrier effect is so intense that the dynamics of pedestrian mobility are imposed by the transportation infrastructure, as in the case of highways inserted in urban areas [3]. It translates into a major challenge for pedestrian displacements, including danger when crossing the road [4], longer walking trips [2], and an unpleasant walking environment due to noise and air pollution [5]. There is an increased inequality in the use of the street, particularly by people with disabilities, children, the elderly, and women [5]. Urban permeability is reduced, which particularly impacts neighborhoods located along the highway [5], and there is an increase in the pedestrian accident rates [6]. Therefore, an environment prevails in which a series of conflicts and contradictions related to the (re)production of urban spaces is observed and is materialized by the current dichotomy between vehicle flows and people.

The impacts of the barrier effect on urban areas have been the object of study and concern for urban transport planners and managers since 1960 [1]. Studies in specific literature on the barrier effect and the transformations caused by highways inserted in the urban environment are not uncommon. Usually, the methodologies and approaches found in the literature evaluating the barrier effect on pedestrian displacements seek to establish a link between transport and public health [5–9]. This relationship usually occurs by quantifying traffic accidents. Furthermore, also noteworthy are studies that address monetary and social costs caused by the phenomenon [10,11], as well as the application of behavioral models [12] and geospatial analyses to identify the reduction in the population interaction considering the restrictions to pedestrian mobility caused by these infrastructures [3]. The impacts of the barrier effect on pedestrians can also be investigated using participatory mapping, questionnaires with local residents, the analysis of research data, and the development of walking models and indices [13]. Although this subject is widely addressed in research abroad, there is still a significant lack of studies on the subject in the Brazilian scenario. In this case, we can find studies about the impacts of urban highways from the perception of pedestrians using an opinion survey [14] and a theoretical analysis of the barrier effect in peripheral neighborhoods [15]. However, no proposals appear to evaluate the barrier effect using mobility and accessibility indicators based on the analysis of pedestrian displacements between the margins of roads in urban areas.

Pedestrians are the most vulnerable group, not only in places where the barrier effect occurs, but in the entire urban mobility system. In this regard, several studies can be found with the objective of understanding its characteristics and behavior in the walk. Children, for example, are even more vulnerable because they have certain cognitive skills that are less developed than adults, such as peripheral vision and color perception [16]. Another peculiarity that can increase pedestrians' traffic risk is the use of cell phones for texting and listening to music [17]. Therefore, "building public education policies on traffic safety, developing traffic safety infrastructure, improving the traffic management system, and strengthening urban traffic safety legislation" are highly important as the main strategies to promote pedestrian safety [18] (p. 5).

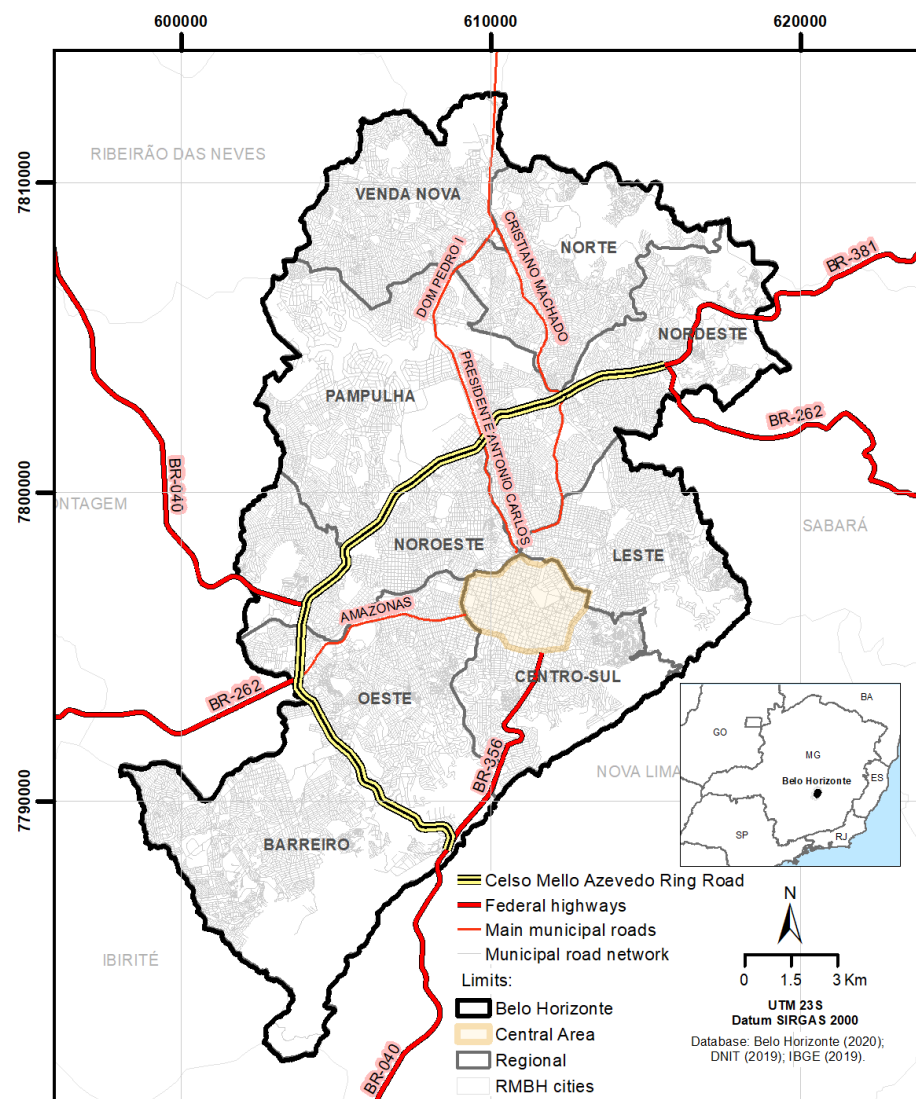
In this way, this article aims to analyze pedestrian mobility/accessibility and the occurrence of the barrier effect in urban highways using the indicators extracted from the Origin and Destination Survey databases. For this, the study was carried out on the Celso Mello Azevedo Ring Road, located in Belo Horizonte/Brazil. It is one of the most important highways in Belo Horizonte's urban space, which includes intense regional traffic and accesses in the metropolitan space [19]. As a result of the growth of the fleet of cargo and passenger vehicles and the expansion of the local urban fabric linked to the flow of Belo Horizonte, the road has become responsible for a significant share of traffic accidents in the municipality, mainly fatal pedestrian accidents. Several events exposed in the media and

shared as common knowledge have made the road notorious (not unjustifiably) as a tragic circulation zone in the state capital. Understanding how this highway acts as a barrier and its effects on the mobility and accessibility of pedestrians in its environs is a fundamental task of municipal management and planning, reaching beyond the transportation system.

## 2. Materials and Methods

### 2.1. Study Area

The Belo Horizonte Road Ring, officially called the Celso Mello Azevedo Road Ring, was inaugurated in the early 1960s to divert the growing volume of vehicles circulating in the Central Area of Belo Horizonte, the capital of the State of Minas Gerais [19]. Currently, the Ring Road connects the highways that cross the capital and extends for 26.2 km, from the junction with the BR-040 highway (towards Rio de Janeiro-RJ), in the region of Olhos D'água neighborhood, in the south of the municipality, to the fork with the BR-262 (direction Vitória-ES) and BR-381 highways (direction São Mateus-ES), in the neighborhood Nazaré, located in the northeast (Figure 1).



**Figure 1.** Location map of the Celso Mello Azevedo Ring Road in the municipality of Belo Horizonte (MG). Database: [20–22].

Since its creation, the highway and its surroundings have undergone several transformations, due primarily to the increase in mostly irregular residential buildings in the adjacent neighborhoods and on the sides of the highway itself. In addition, due to the growth of the fleet and expansion of the urban border, the Belo Horizonte Ring Road has taken on the function of the population's urban displacement, which contradicts its original purpose. According to the National Department of Transport Infrastructure [20], 105 thousand vehicles/day travel on the highway in both directions, with the highest flow section located between Av. Amazonas and BR-040. It is the main interregional cargo corridor, which added to the internal flow of approximately 40 thousand trips/day, makes the Ring Road the most important route for transporting the RMBH's products and goods [23].

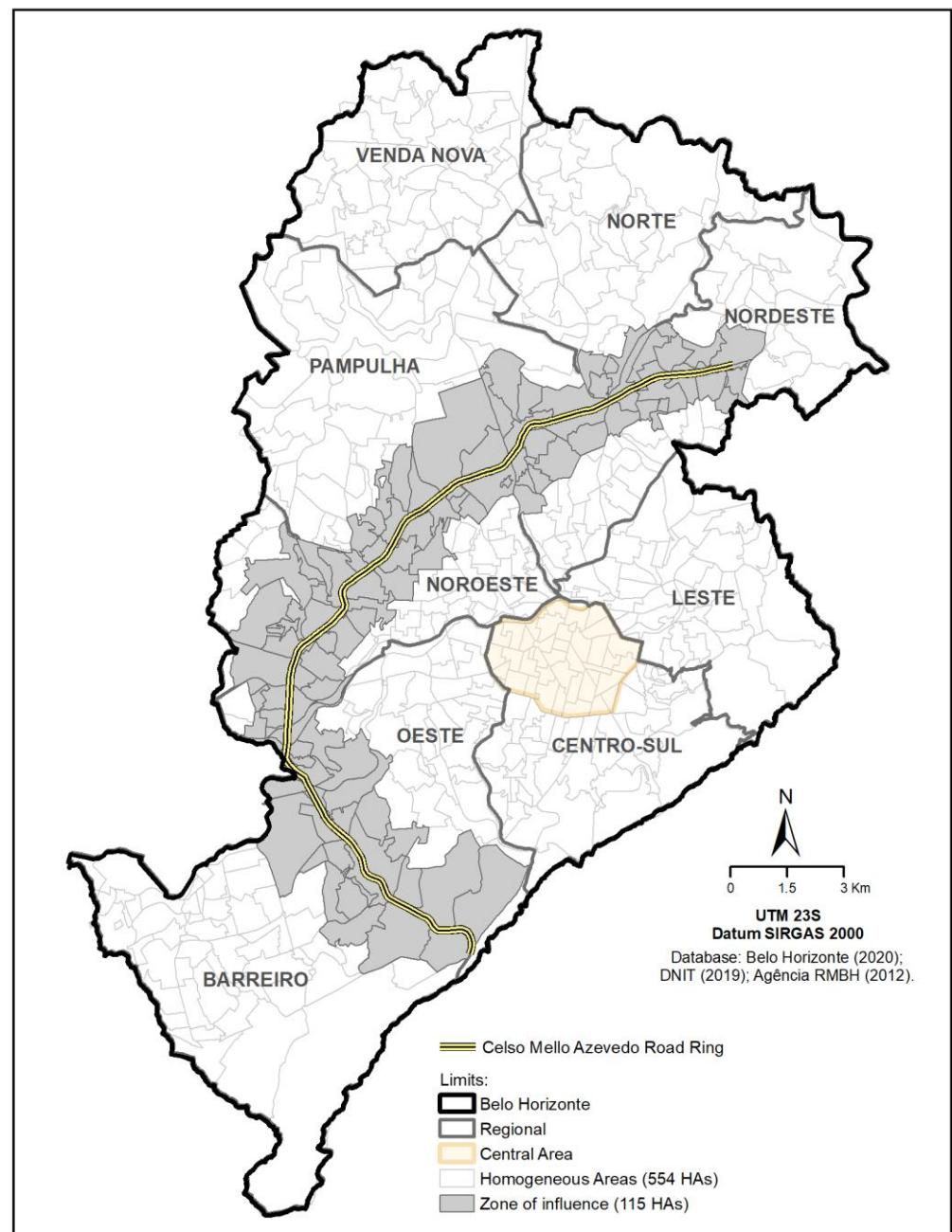
The urban traffic on the Ring Road has intensified considerably over the past few years. However, the low investments in local maintenance have made the highway infrastructure outdated, as evidenced by the discontinuity of the hard shoulder, narrowing of the central lanes at the intersections with urban corridors, and limited footbridges [24]. The preference for individual motorized transport, responsible for 36.5% of the Belo Horizonte population's daily commute [25], means the highway has become a central urban avenue, particularly at peak times, with high rates of congestion and accidents [26].

## 2.2. Databases, Cuts, and Spatial Analysis Units

The primary source of data in this study was the Origin and Destination Survey (OD) of the Metropolitan Region of Belo Horizonte (RMBH). OD Surveys are essential to evaluate a given region's mobility and socio-spatial transformations as the resulting data allow us to understand the characteristics of daily population displacements and socioeconomic and demographic aspects [25]. Since 1972, the OD Survey has been carried out in the Metropolitan Region of Belo Horizonte using samples and decennial data collections. The most recent data available are for 2012 [27], which are used to obtain the number of trips to apply the proposed indicators.

The spatial cuts used to analyze the results in the study area (Celso Mello Azevedo Road Ring) were the administrative regions and neighborhoods of Belo Horizonte. The analysis used the spatial units named in the OD of Homogeneous Areas (HAs) and the segments of the Road Ring, which were part of the research's methodological procedures. The HAs are aggregations of census tracts and the lowest spatial disaggregation level used in the origin and destination surveys [25]. Using them as a spatial unit of analysis makes it possible to obtain more detailed pedestrian flows, following the System of Spatial Units established for OD Surveys of the Metropolitan Region of Belo Horizonte. Although the municipality of Belo Horizonte is subdivided into 554 HAs, only a portion of these intersect directly (border or proximity) with the Ring Road.

In selecting the highway's zone of influence and defining the segments of the Ring Road for analysis, it was necessary to propose mobility and accessibility indicators. Thus, a 600 m buffer was established because it is a parameter used in Belo Horizonte as the maximum travel distance for pedestrians to access public transport [28]. Based on this parameter, the zones of influence of the potential crossing areas were outlined from the main axis of the Ring Road, using the QGIS buffer tool (Figure 2), by the topological border ratio to select the respective homogeneous areas that intersect the highway, employing the 'select by location' tool. For the HAs located immediately at the ends of the highway, an additional selection criterion was used by verifying whether they touched the edge of the Road Ring. If they did not, the HAs were excluded from the selection. In this way, the zone of influence comprises 115 HAs, as presented in Figure 2.



**Figure 2.** Location map of the Celso Mello Azevedo Ring Road in the municipality of Belo Horizonte (MG). Database: [20,21,25].

### 2.3. Mobility and Accessibility Indicators Proposed to Evaluate the Pedestrian Barrier Effect

Indicators are aggregate and complex measures that allow a phenomenon to be described and evaluated, considering its nature, state, and evolution [29]. They have been widely used as tools to assist in understanding urban dynamics to guide public policies and decision-making in the most diverse areas of knowledge, including urban mobility and accessibility [30]. From this context, four indicators are proposed to analytically identify the levels of the mobility and accessibility of the population in the area of influence of the Ring Road: Pedestrian Mobility Ratio (PMR), Pedestrian Mobility on the Highway (PMH), Pedestrian Crossing the Highway (PCH) and the Footbridge Access Indicator (FAI).

The PMR (Equation (1)) allowed us to verify the participation of the walking mode in the total internal trips to the area of influence (HAs) of the highway.

$$PMR_i = \frac{Va_i}{Vt_i} \quad (1)$$

where  $Va_i$  is the total of walking trips and  $Vt_i$  is the total trips including all modes of transport except on foot, originating in an  $HA_i$  and destined for an  $HA_j$ .

The PMH indicator (Equation (2)) measures the relevance of the pedestrian crossings between the sides of the highway on walking trips:

$$PMH_i = \frac{Vp_i}{Va_i} \quad (2)$$

where  $Vp_i$  is the total of crossing trips by foot mode and  $Va_i$  is the total walking trips, originating in an  $HA_i$  and destined for an  $HA_j$ .

The PCR indicator (Equation (3)) verifies the prevalence of walking displacements in relation to motorized modes (individual and collective) in the crossings between the sides of the highway.

$$PCR_i = \frac{Vp_i}{Vm_i} \quad (3)$$

where  $Vp_i$  is the total of crossing trips by foot mode and  $Vm_i$  is the total of crossing trips by motorized modes, originating in an  $HA_i$  and destined for an  $HA_j$ . The number of internal trips and those between the highway sides was extracted from the RMBH Origin and Destination Survey.

In the context of the pedestrian crossings on the Ring Road, it is considered that better accessibility is directly related to a higher supply of footbridges, as these are the on-site structures for crossing the highway with relative safety. The distance between the structure and the origin of potential users is also relevant for accessibility analysis; the greater the distance, the lower the access to the opposite side. Therefore, the Footbridge Access Indicator (FAI) (Equation (4)) is calculated as follows:

$$FAI_i = \frac{\sum_i^n p_i}{D_i} \quad (4)$$

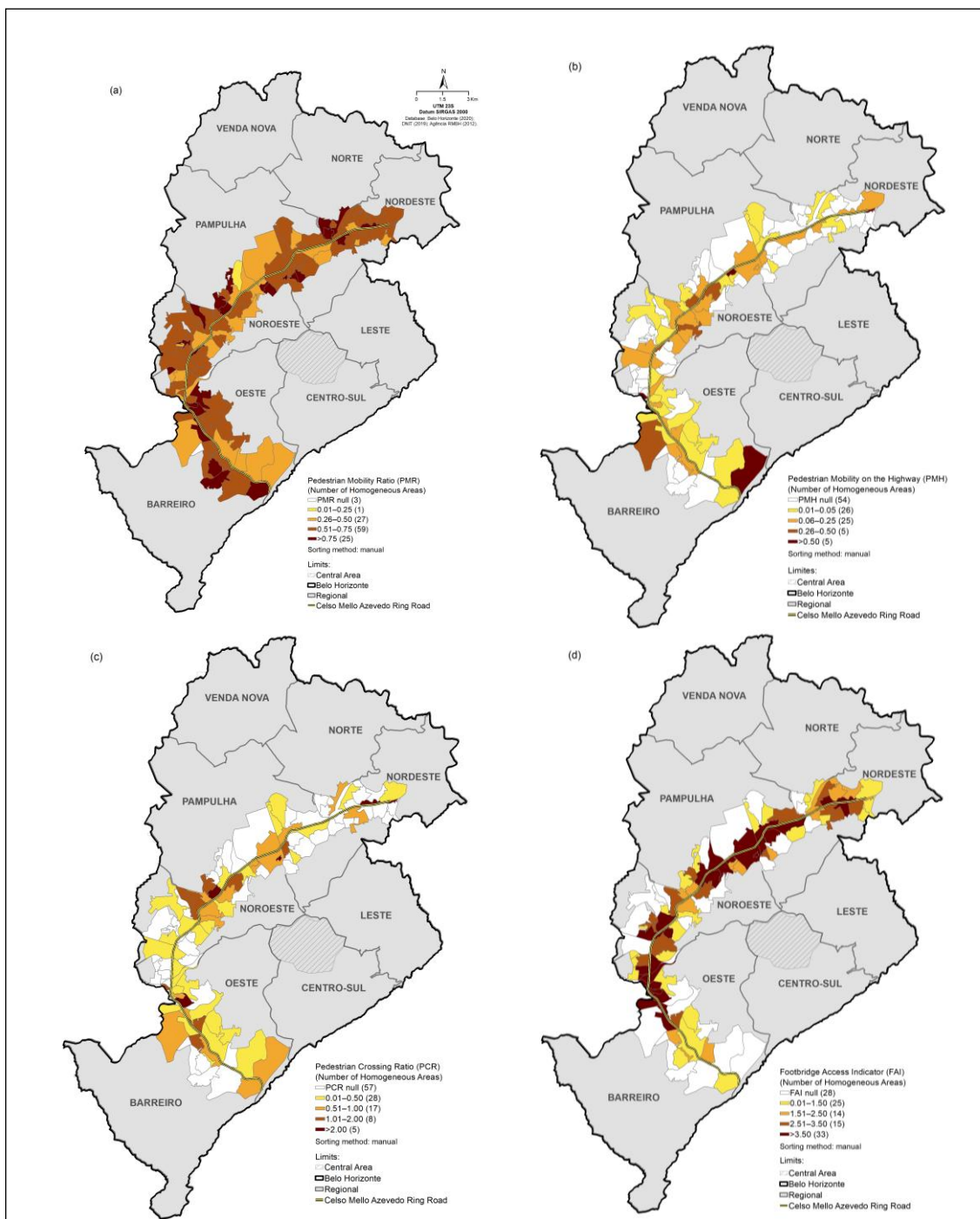
where  $p_i$  is the total of footbridges that effectively attend an  $HA_i$  and  $D_i$  is the minimum distance of access between the nearest footbridge and the centroid of an  $HA_i$ , in kilometers.

The number of footbridges that effectively attend certain HA was established by a Euclidean distance matrix of 1000 m from the HA centroid to the available footbridge, based on the DNIT [20] guidelines for Brazilian highway projects in urban areas. In turn, the calculation of the shortest distance between the nearest footbridge and the HA centroid was performed using the 'MMQGIS' complement available for QGIS.

### 3. Results

In 2012, there were 14,122 crossings on foot in the 115 HAs selected from the 600-m area of influence from the highway axis: 7163 from the right to the left side and 6959 from left to right. Excluding trips with the purpose of 'residence,' which involve the origin and destination of the respective trips, the main reasons for crossing the highway are 'work' (35.3%) and 'study' (29.2%).

In general, due to the differential occupation of the territory, there is no uniform spatial distribution of pedestrian mobility along the Ring Road when analyzing the results of the PMR indicator. As highlighted in the cartograms in Figure 3, there are portions in which walking trips (internal or crossing) are more relevant. However, it is noteworthy that walking displacements prevail in most HAs around the highway. The contribution of foot mobility is less than 0.50 in only 28 HAs, where pedestrian displacements do not stand out from those of the other modes.



**Figure 3.** Cartograms representing the results of the (a) Pedestrian Mobility Ratio (PMR), (b) Pedestrian Mobility on the Highway (PMH), (c) Pedestrian Crossing Ratio (PCR), and (d) Footbridge Access Indicator (FAI) in the Celso Mello Azevedo Ring Road. Database: [20,21,25].

According to the PMH indicator, in most HAs, crossings do not predominate in the displacements on foot. Thus, walking journeys are frequent in the HAs around the highway but rarely involve crossing them. Foot crossings represent more than 50% of the trips by foot mode in five HAs, including HA #1394, located in the Noroeste Regional, with an PMH value equal to 1.00; this means that all of the foot trips recorded in this area cross to the opposite margin of the Ring Road (Figure 3).

The PCR indicator identified that, in 13 HAs, crossings of the sides of the Ring Road on foot exceeded motorized crossings (collective and individual), as highlighted by the

last two classes. Still, in 57 areas, the PCR result was null as no foot and/or motorized crossings were identified. In most areas where there were records of trips (45), there is a predominance of motorized displacement between the margins of the highway. Among the areas in which the values identified for the PCR indicator were greater than 1.0 (prevalence of foot crossings), HA #1395 has the highest weight of foot mobility in crossings on the Ring Road. HA #1395 is located in the Noroeste Regional, with a PCR equal to 5.21; that is, crossings on foot exceed motorized crossings for trips from this location by more than five times. Other areas also have a predominance of foot crossings, in the Oeste Regional (HA #1111, PCR 2.58; HA #1138, PCR 1.17; HA #1155, PCR 1.01), Pampulha Regional (HA #1315, PCR 4.84; HA #1388, PCR 1.03; HA #1305, PCR 1.03; HA #1303, PCR 1.01), Nordeste Regional (HA #1661, PCR 2.04; HA #1664, PCR 2.13, HA #1615, PCR 1.51), Noroeste Regional (HA #1316, PCR 1.56), and Barreiro Regional (HA #1246, PCR 1.07).

Within the scope of accessibility, the Footbridge Access Indicator (FAI) was used to evaluate the influence of the physical elements that assist the crossings, which allowed us to verify the areas located closest to the edge of the highway that have better access conditions to footbridges, both in terms of the quantity and the minimum distance required to reach them. Approximately 22% of the HAs in the Road Ring's zone of influence (25) have a low accessibility level, with FAI values below 1.50, highlighted in light yellow on the cartogram (Figure 3). In these cases, the low FAI value is because there is only one footbridge available for pedestrians at a distance greater than 600 m from the centroid of the HA. Of these HAs #1388 (Pampulha Regional) and #1215 (Barreiro Regional) are notable for their higher ratio of foot crossings to motorized vehicles, as indicated by the PCR mobility indicator. In total, 2635 crossings between the sides of the Ring Road, in both directions, are compromised by the low access from these 25 HAs to footbridges, equivalent to 19% of daily commutes. Furthermore, the average minimum distance of access to the footbridges is 745 m. It is an average Euclidean (linear) distance, which disregards the road system's access routes and the ramps and stairs to access these infrastructures. Therefore, in practice, the conditions of the pedestrian crossings may (and should) be more critical than shown by the indicators.

In turn, FAI values above 3.51 generally indicate the availability of two or more footbridges less than 600 m from the HA centroid. This indicator identified 33 HAs, of which six areas had positive results. Concomitantly with good access to the footbridges was the prevalence of foot displacements over motorized modes (individual and collective) in the crossings of the Ring Road, which are located in the Nordeste Regional: HA #1615, with PCR 1.51 and FAI 14.18; HA #1395, with PCR 5.21 and FAI 6.49; HA #1316, with PCR 1.56 and FAI 5.05; HA #1664, with PCR 2.13 and FAI 4.20, and in the Oeste Regional: HA #1111, with PCR 2.58 and FAI 6.61; HA #1155, with PCR 1.01 and FAI 7.87. The absence of crossings on foot in 11 HAs (33.3%) considered to have better accessibility is also noted.

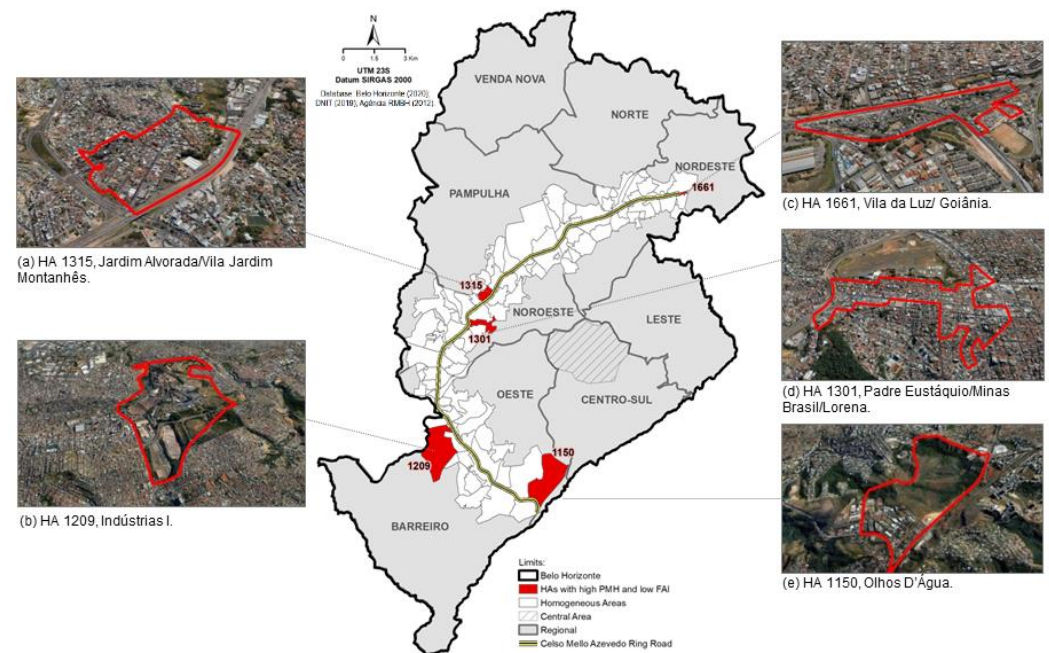
#### 4. Discussion

With the intensification of urban road space occupation, vehicle traffic has substantial impacts, particularly when analyzed in the light of the insertion of highways in the urban space. At the same time, there is a mutual and complex influence between the built environment and different transport modes, which strengthens when motorized modes become dominant in these spaces [31]. When highways cut through densely populated urban areas, physical obstacles arise, either by the infrastructure or by the flow of vehicles, which impair the local population's mobility and accessibility. Thus, barriers are formed that often produce the effect of community separation. Rajé [4] emphasizes that this phenomenon produces a series of adverse problems in the urban environment, such as reducing social interaction and the use of public spaces and facilities, thereby restricting pedestrian access. Thus, this is one of the conflicts generated by urban highways: the "barrier effect". Jacobs [32] states that urban highways and expressways have "eviscerated cities" and generated consequences for urban life, such as environmental degradation, impacts on land use, and community separation. The limited access that highways impose

on the urban layout creates barriers that reduce one of the city's essential characteristics: its vitality [33].

The discontinuity in the urban fabric caused by the installation of this type of infrastructure directly impacts the surroundings' access and mobility dynamics, as can be seen when applying the indicators proposed in this article. The results highlight the significant number of areas considered "inaccessible" (28 areas), mainly due to the absence of footbridges less than 1000 m away from the HA centroid. These areas with zero FAI indicate that potential crossings may be affected by a lack of infrastructure, putting pedestrians crossing the highway at a high level of risk. In total, there are 2010 estimated daily crossings in these areas, in both directions of travel, equivalent to 14.2% of foot journeys. The most critical situations are those with the highest figures and a greater number of foot crossings than motorized ones. The areas affected include HA #1150 and HA #1133 (Oeste Regional), HA #1305 (Pampulha Regional), and HA #1209 (Barreiro Regional).

In addition to the Ring Road's mobility and accessibility indicators, an evaluation was carried out from the intersection between the FAI and the PMH. A grouping was created that correlated the HAs with higher levels of mobility ( $PMH \geq 0.26$ ) and lower levels of accessibility ( $FAI \leq 2.50$ ). This assessment indicated the locations where the access infrastructure (footbridges) does not adequately meet the demand for trips crossing the highway. As a result, five HAs were identified (Figure 4) where the barrier effect seems to be significant in pedestrian mobility, given the lack of adequate access for those who want (or need) to cross the Ring Road. Two of these five HAs (#1150 and #1209) were identified in the accessibility analysis because they have null PAI values due to the absence of footbridges less than 1000 m away.



**Figure 4.** High mobility areas (PMH) and low accessibility (FAI) in the Belo Horizonte Road Ring. Database: [20,21,25].

Generally, 319 crossings per day originate in the areas with PMH values of 0.56 and 0.30, respectively. The other HAs identified as having low accessibility and high mobility have 2495 total crossings, corresponding to 18% of the daily walking trips between the sides of the Ring Road (HAs #1301, #1661, and #1315). The former covers the Padre Eustáquio/Minas Brasil/Lorena neighborhoods in the Noroeste Regional and is served by a footbridge 890 m away. In HA #1661, in the Vila da Luz/Goiania neighborhoods (Nordeste Regional), the nearest footbridge is 610 m away. In HA #1315, located in the Pampulha Regional with coverage of the Jardim Alvorada/Vila Jardim Montanhês neighborhoods, the

nearest footbridge is 520 m away. Identifying these areas with greater mobility (demand for crossings) and low accessibility (through footbridges) prioritizes locations for government intervention to induce mobility and/or facilitate accessibility. Furthermore, it spotlights potential areas for the construction of new footbridges, particularly near the HAs where the service was not identified (FAI null).

Before the context, the results indicate that due to its infrastructure, location, and traffic flow, the Celso Mello Azevedo Ring Road is a significant barrier to the crossing of pedestrians who circulate in its surroundings. The application of the proposed indicators shows a prevalence of crossings by motorized modes in the study area and inequalities in access to footbridges. Consequently, the risks to foot-travelers crossing are raised, a scenario confirmed by the significant occurrences of accidents involving pedestrians, which are indications of the implications of this barrier on the mobility of pedestrians who reside or transit in the highway's surroundings. In 2018 alone, 61 people were hit by cars on the Belo Horizonte Ring Road, of whom 11 were fatal victims [28]. In the same year, fatal accidents involving foot-travelers on the Ring Road corresponded to 25% of all pedestrian deaths in the municipality for the year in question. This is a warning about local walkability conditions, evidencing that focusing solely on footbridges for crossing highways is insufficient.

The PMH indicator also confirms the inhibitory effect of the Ring Road on crossings from one side to the other. The data show the low relevance of foot crossings as a proportion of total displacements on foot. As predicted by Mindell and Anciaes [5], these results evidence a low flow between communities located on the opposite sides of the highway. It was also possible to verify the relevance of foot crossings by pedestrians from HAs that include areas of greater social vulnerability, which demonstrates the selective impact of the effect. HA #1661 (Vila da Luz) and #1155 (Sport Club) stand out as areas where foot crossings seem to be part of the residents' daily routine. However, these areas of towns and slums are primarily situated in irregular occupations on the margins of the highway, which under current legislation, are considered non-buildable domains.

## 5. Conclusions

It is essential to highlight the need to evaluate the barrier effect of urban highways on foot crossings and in their surroundings and this article showed a new possibility to carry out this type of analysis. For this, the use of the OD Survey and the proposed indicators can be considered an important contribution to evaluate the barrier effect, particularly between the edges of urban highways. The proposed indicators can be used strategically for future actions and public policy formulation, as it was possible to identify risk areas and potential interventions to improve mobility and accessibility.

Despite the good results obtained with the proposed methodology, it is important to emphasize the limitations of this work. The most expressive is the limitation of the time and spatial frame, mainly due to the unavailability of more recent data. As a result, some methodological adjustments were necessary, as explained in Section 2. In this way, it is suggested to continue investigating the barrier effect based on the data from the OD Survey, as well as the need to update the results to the present day as soon as they are available. We also consider it important to analyze the impacts of the COVID-19 pandemic on urban highways in future studies, as changes in the mobility and accessibility patterns of the world's urban population are clear.

In this research, the focus was on physical accessibility. However, a new perspective can be given to the study if the perceived accessibility is also considered, which is a research limitation and also a future research direction. Conventionally, accessibility studies do not consider user perceptions to understand factors such as travel time and distance [34]. However, this modern and careful point of view on accessibility is even used as a good indicator for the fairness of the transport system [35], which expands the potential application of the methodological proposal of this article for future directions of research.

Moreover, despite the physical and psychological obstacles caused by the barrier effect, it is only one of the manifestations of the recurrent conflicts and social contradictions resulting from the production and appropriation of urban space. In this study, there is a conflict between two territories: vehicles and people; and two uses: the flow and lived experience. In the case analyzed herein, the territory of vehicles and flows seems to have prevailed.

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