Equity issues associated with transport barriers in a Brazilian medium-sized city

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ABSTRACT

Introduction: Transport infrastructures and motorized vehicle traffic in urban areas often act as barriers to walking and cycling. The present study introduces the characterization of this process, also known as "community severance", caused by a railway in a Brazilian medium-sized city. Moreover, it also investigates the equity in the distribution of residents, regarding demographic characteristics, along the railway and around the different types of railroad crossings and segments without railroad crossings.

Materials and methods: Based on census data related to permanent mobility constraints, income level, gender and age, we georeferenced the data and estimated the number of residents living around the railway. In addition, the types of railroad crossings and segments without railroad crossings were classified by means of a qualitative assessment, according to an ordinal scale of relevance. Furthermore, we used the chi-square (χ^2) test of independence and standardized Pearson residual to verify evidence of associations between the variables and to understand the nature and strength of dependence between each category of the variables.

Results: The results provide evidence of associations between the variables and indicate deficits and excesses of residents with certain demographic characteristics in the railway surroundings. They also show that residents with some difficulty in walking or climbing stairs or aged over 60 tend to live nearby the best railway crossings, while residents aged up to 19 tend not to live nearby the best railway crossings. On the other hand, low-income residents (less than R\$ 1200.00) tend to live nearby the worst railroad crossings.

Conclusions: The research indicates that the distribution of the number of residents along the types of railroad crossings and segments without railroad crossings is equitable for residents with permanent mobility constraints, by gender and for the elderly, whereas it is not equitable for low-income residents and aged up to 19 years old.

RESUMO

Introdução: Infraestruturas de transportes e o tráfego de veículos motorizados em áreas urbanas frequentemente atuam como barreiras aos deslocamentos a pé e de bicicleta. O presente estudo introduz a caracterização desse processo, também conhecido como "efeito barreira", causado por uma ferrovia em uma cidade brasileira de médio porte. Além disso, também investiga a equidade na distribuição dos moradores em relação às características demográficas, ao longo da ferrovia e no entorno dos diferentes tipos de travessias e dos segmentos sem travessias.

Materiais e métodos: Com base em dados censitários referentes a restrições de mobilidade

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permanente, faixa de renda, sexo e idade, foram realizados o georreferenciamento dos dados e estimativas do número de moradores que vivem próximos à ferrovia. Além disso, os tipos de travessias e segmentos sem travessias foram classificados por meio de uma avaliação qualitativa, de acordo com uma escala ordinal de relevância. Adicionalmente, utilizou-se o teste de independência qui-quadrado (χ^2) e uma análise do resíduo de Pearson padronizado para verificar evidências de associações entre as variáveis e para compreender a natureza e a força de dependência entre cada categoria das variáveis.

Resultados: Os resultados indicam evidências de associações entre as variáveis e apontam déficits e excessos de residentes com certas características demográficas nas proximidades da ferrovia. Mostram também que os moradores com alguma dificuldade em caminhar ou subir escadas, ou com mais de 60 anos de idade, tendem a morar próximos às melhores travessias, enquanto moradores com até 19 anos tendem a não morar próximos às melhores travessias. Por outro lado, moradores de baixa renda (inferior a R$ 1.200,00) tendem a morar nas proximidades dos piores cruzamentos.

Conclusões: A pesquisa indica que a distribuição do número de moradores ao longo das travessias e segmentos sem travessia é equitativa para moradores com restrições de mobilidade permanente, por gênero e para idosos, enquanto não é equitativa para moradores de baixa renda e com até 19 anos de idade.

R E S U M E N

Introducción: Las infraestructuras de transporte y el tráfico de vehículos motorizados en zonas urbanas a menudo actúan como barreras a los desplazamientos a pie y en bicicleta. El presente estudio presenta la caracterización de ese proceso, también conocido como "efecto barrera", causado por un ferrocarril en una ciudad brasileña de mediano porte. Además, también se investiga la equidad en la distribución de los habitantes con relación a las características demográficas, a lo largo del ferrocarril y en el entorno de los diferentes tipos de cruce y de los segmentos sin cruce.

Materiales y métodos: Con base en datos censales referentes a restricciones de movilidad permanente, grupo de ingresos, sexo y edad, se realizó la georreferenciación de los datos y estimación del número de residentes que viven cerca del ferrocarril. Además, los tipos de cruce y segmentos sin cruces se clasificaron por medio de una evaluación cualitativa, de acuerdo con una escala ordinal de relevancia. Adicionalmente, se utilizaron el test de independencia chi-cuadrado (χ^2) y un análisis del residuo de Pearson estándar para verificar evidencias de asociaciones entre las variables y para comprender la naturaleza y la fuerza de dependencia entre cada categoría de las variables.

Resultados: Los resultados indican evidencias de asociaciones entre las variables y apuntan déficit y exceso de residentes con ciertas características demográficas en las proximidades del ferrocarril. También muestran que los residentes con alguna dificultad en caminar o subir escaleras o con más de 60 años tienden a vivir cerca de los mejores cruces, mientras que los residentes con hasta 19 años tienden a no vivir cerca de las mejores cruces. Por otro lado, los residentes de bajos ingresos (inferiores a R$ 1.200,00) tienden a vivir cerca de los peores cruces.

Conclusiones: La investigación indica que la distribución del número de residentes a lo largo de los cruces y segmentos sin cruce es equitativa para residentes con restricciones de movilidad permanente, por género y para ancianos, sin embargo, no es equitativa para habitantes de bajos ingresos y menores a 19 años.

1. Introduction

Diverse transport infrastructures and motorized vehicle traffic itself often act as urban barriers to cycling, and mostly to walking. This process, also known as "community severance", is a problem that increasingly attracts the attention of urban and transport planners, in part because of the growing need to replace the use of motorized transport with active transport, especially in main urban centers.

Community severance is essentially caused by physical impedances to walking trips (Soguel, 1995; Guo et al., 2001; Mouette and Waisman, 2004; Anciaes et al., 2016a) and to the access to goods, services and people (Scholes et al., 2016; Mindell et al., 2017) due to transport infrastructures, traffic streams and speeds (Guo et al., 2001; Anciaes, 2015; Anciaes et al., 2016a; Scholes et al., 2016). In addition, community severance is related to psychological barriers separating local communities (Taylor and Crawford, 2009; Scholes et al., 2016), affecting the perceptions, behavior, stress (Appleyard and Lintell, 1972; Hine and Russell, 1993; Hart and Parkhurst, 2011), safety perceptions (Hine, 1996; Davis and Jones, 1997; Timperio et al., 2006; Hart and Parkhurst, 2011), wellbeing (Timperio et al., 2006; Scholes et al., 2016; Foley et al., 2017; Nimegeer et al., 2018; Anciaes et al., 2019), health (Timperio et al., 2006; Mackett and Thoreau, 2015; Scholes et al., 2016; Foley et al., 2017; Nimegeer et al., 2018), social interactions (Appleyard and Lintell, 1972; Davis and Jones, 1997; Hart and Parkhurst, 2011; Scholes et al., 2016; Nimegeer et al., 2018) and intensifying social exclusion (Rajé, 2004; Mackett and Thoreau, 2015) of people who live or use the surrounding areas or need to make trips along or across that infrastructure (Anciaes, 2015).

The data collection instruments and analytical tools commonly used in community severance studies include questionnaires (Davis and Jones, 1997; Mouette et al., 2000; Mouette and Waisman, 2004; Timperio et al., 2006; Scholes et al., 2016; Foley et al., 2017; Mindell et al., 2017; Anciaes et al., 2019), interviews (Soguel, 1995; Hine, 1996; Silva Jr. and Ferreira, 2008; Hart and

Parkhurst, 2011; Cantillo et al., 2015; Nimegeer et al., 2018), workshops (Taylor and Crawford, 2009; Anciaes et al., 2016a), focus groups (Cantillo et al., 2015; Mindell et al., 2017), open data (Mouette and Waisman, 2004; Lee and Sohn, 2014; Lara and Rodrigues da Silva, 2018), empirical data collection (Guo et al., 2001; Mouette and Waisman, 2004; Mindell et al., 2017; Lara and Rodrigues da Silva, 2018; Anciaes et al., 2019), video surveys (Hine, 1996; Mindell et al., 2017; Anciaes et al., 2019), participatory mapping, interdisciplinary analysis (Mindell et al., 2017), spatial analysis (Mindell et al., 2017; Lara and Rodrigues da Silva, 2018; Anciaes et al., 2019) and equity analysis (Litman, 2002; Jang et al., 2017; Lara and Rodrigues da Silva, 2018; Pereira, 2018).

The main affected population groups identified in the literature correspond to the elderly, children (Hine, 1996; Mouette and Waisman, 2004), residents who have a long-standing illness (Scholes et al., 2016; Foley et al., 2017), adults who need to accompany another individual with restricted mobility (Mouette and Waisman, 2004), people who have great or some difficulty in walking or climbing stairs and a particular lower income group (Lara and Rodrigues da Silva, 2018). In other words, community severance mainly affects vulnerable social groups (i.e. the elderly, children, people with restricted mobility and low-income people).

According to the urban design concept proposed by Burton and Mitchell (2006), it is reasonable to consider an area of influence (i.e. the area in which the population nearby a transport infrastructure can reach its crossings from their homes within a certain walking distance) compatible with the walking distances of vulnerable social groups. However, studies about community severance do not seem to have a consensus about walking distances, ranging around 300 and 800 m: Anciaes et al. (2019) defined a walking distance of 400 m from busy roads, while Rosenlieb et al. (2018) used a 300 m bandwidth to represent the varying intensity of exposure to traffic with distance and another study of Anciaes (2013) used threshold values of 500 and 800 m.

The impacts of the community severance are related to trip diversion and suppression (Hine, 1996; Guo et al., 2001; Silva Jr. and Ferreira, 2008), poor accessibility and restricted personal mobility in the affected neighborhoods (Guo et al., 2001). There is significant evidence supporting the notion that exercises and physical activities have a positive influence on physical and mental health (Penedo and Dahn, 2005; Reiner et al., 2013), which corroborates the concept that community severance affects residents' health physically and mentally (Timperio et al., 2006; Mackett and Thoreau, 2015; Scholes et al., 2016; Foley et al., 2017; Nimegeer et al., 2018).

Regarding grade railway crossings, the impacts of severance on community cohesion could be positive or negative, since lowering the railway reduces community severance by making surface movement easier for pedestrians, cyclists and drivers and in locations where a road overpass has been built. However, community severance may be worsened due to the intrusion of the elevated structure and its approaches (Taylor and Crawford, 2009). In addition, railway grade crossings affect the accessibility of pedestrians with disabilities or wheelchair users, generally due to rough surfaces and physical obstructions causing travel delay (McPherson and Daff, 2005).

According to Anciaes et al. (2018), the economic value of the negative impacts on transport systems are relevant for decisions about pricing policies and investment in these systems. Under this direction, Anciaes et al. (2016b) proposed guidelines for the consolidation of the wide range of methods found in the literature into a consistent framework to identify and monetarize the effects of severance on communities, people's wellbeing and behavior.

Urban and transport planners are also concerned about inequalities in the distribution of different social groups around transport infrastructures, the quality of these transport infrastructures and the exposure to transport-related externalities. According to Litman (2002), equity could be divided into two categories: horizontal and vertical. Horizontal equity involves the distribution of resources equally to each individual or group, whereas vertical equity implies in the distribution of resources according to each individual's or group's special needs in order to ensure they are not worse off, and that their needs are accommodated. In this study, we used the vertical equity proposed by Litman.

Given the different types and characteristics of the transport infrastructures, the intensity and variability of community severance can be substantially high. In the case of road infrastructures, the intensity of community severance varies substantially. For other transport modes the impact is large, and its variability is smaller, since the physical segregation of the infrastructure is practically unavoidable, as in the case of rivers or railways.

Railways in urban areas are particularly characterized by contributing to community severance, since the passage of pedestrians and cyclists are limited to the points where there are railroad crossings. However, relatively few studies have been conducted on railways (Sousa et al., 2009; Taylor and Crawford, 2009; Chang et al., 2014; Lee and Sohn, 2014; Lara and Rodrigues da Silva, 2018) while there are considerably more studies on urban streets (e.g. Appleyard and Lintell, 1972; Soguel, 1995; Hine, 1996; Mouette et al., 2000; Guo et al., 2001; Mouette and Waisman, 2004; Silva Jr. and Ferreira, 2008; Hart and Parkhurst, 2011; Cantillo et al., 2015; Mindell et al., 2017).

Therefore, community severance is an interdisciplinary effect whose characterization using census data may lead to saving time, effort and financial resources, as it would avoid the need of asking people to fill in questionnaires and finding experienced people to promote field interviews. Even considering that census data are highly aggregated, these databases can help to answer the following important questions: is the distribution of residents near the regions most affected by the community severance vertically equitable? What are the characteristics of these residents?

For this reason, the study presents the characterization of community severance on pedestrians' mobility caused by a railway in a Brazilian medium-sized city based on the classification of the quality of railway crossings. The study does not address psychological aspects of severance, but it analyzes the vertical equity in the distribution of the number of residents along the railway and in the types of railroad crossings in terms of census data regarding permanent mobility constraints, range of monthly nominal income, gender and age of its inhabitants.

The article was divided into five sections. In Section 1, a brief introduction and the contextualization of the problem are presented. Section 2 describes the databases used for the analyses and the analytical procedures applied: classification of railway crossings, chi-square (χ^2) test of independence and standardized Pearson residual. In Section 3, we present and discuss the results and in Section 4, the conclusions are drawn.

2. Materials and method

This study presents an analytical approach to identify possible inequities in the surroundings of a transport barrier located in an urbanized area. In order to do this, the area of influence of the urban barrier was examined, paying particular attention to the region close to the physical elements intended to overcome it. The approach was tested in a specific city, considering that it is sectioned by a railway. In this section, prior to describing the analysis strategy, the study area is characterized, and the databases used are presented.

2.1. Study area

The area selected for the study comprises the urban area of São Carlos, a city located in the state of São Paulo in Brazil with a territorial area equivalent to 83.46 km^2 and an urban population of 205,391 inhabitants, according to the data from the last national demographic census (IBGE, 2010). The urban region is divided into 13 weighting areas. Weighting areas constitute geographical partitions formed by a mutually exclusive group of areas that follow technical restrictions concerning contiguity and size defined by the Brazilian Institute of Geography and Statistics (or IBGE, which in Portuguese stands for Instituto Brasileiro de Geografia e Estatística). The general demographic characteristics of the weighting areas highlighted in the article include: average monthly nominal income of R$ 1601.71, a population of 36,000 inhabitants with some type of self-declared disability (13,213 inhabitants have permanent mobility constraints), 105,026 inhabitants are female and 100,365 inhabitants are male and the average age is 40.1 years old (IBGE, 2010).

The urban perimeter of São Carlos is cut by the Itirapina - Colômbia trunk railway line, operated by the concessionaire ALL (América Latina Logística Malha Paulista S.A.). The railway is at grade and has physical barriers (walls and fences) virtually throughout its entire way, splitting the neighborhoods and limiting their passage to the few points where there are railroad crossings. In addition, it has an average capacity of 11 railway compositions per day and a maximum traffic speed of 10 km/h (maximum speed allowed in urban perimeter). Railroad crossings generally do not have fully segregated pedestrian walkways. This makes pedestrians vulnerable to traffic accidents. Fig. 1 shows the location of the city of São Carlos and the weighting areas, highlighting the weighting areas sectioned by the railway. The city growth was strongly influenced by the railway in the past. As a consequence, the population distribution along the railway within the urbanized region is quite homogeneous.

Additionally, the railway throughout the urban region of São Carlos city includes the following: level crossings (LC), pedestrian crossings (PC), overpasses (OP), underpasses (UP) and segments without railroad crossings (SWC), as shown in Fig. 2.

Some examples of types of crossings along the railway and the segments without railroad crossings, within the urban perimeter, are illustrated in Fig. 3. The segments without railroad crossings (SWC) have physical barriers preventing the passage of pedestrians, motorized and non-motorized vehicles along the whole way, however the material and the height of the barriers vary among segments.

2.2. Databases

The study addresses the urban region divided by the railway and analyzes the vertical equity in the distribution of the number of residents along the railway and the types of railroad crossings regarding permanent mobility constraints, range of monthly nominal income, gender and age.

The databases of the population with self-declared permanent mobility constraints, i.e. those who have difficulty walking or climbing stairs without the help of another person (categorized as: incapable, with great difficulty, with some difficulty or with no disability), the population by range of monthly nominal income and by age range were found by weighting areas, the smallest territorial unit available containing this information. On the other hand, the gender data of the inhabitants were obtained from the database of the statistical grid. The statistical grid comprises a system of regular cells arranged in grid form. Urban regions have dimension cells equal to 200 m × 200 m and rural regions, 1 km × 1 km (IBGE, 2016).
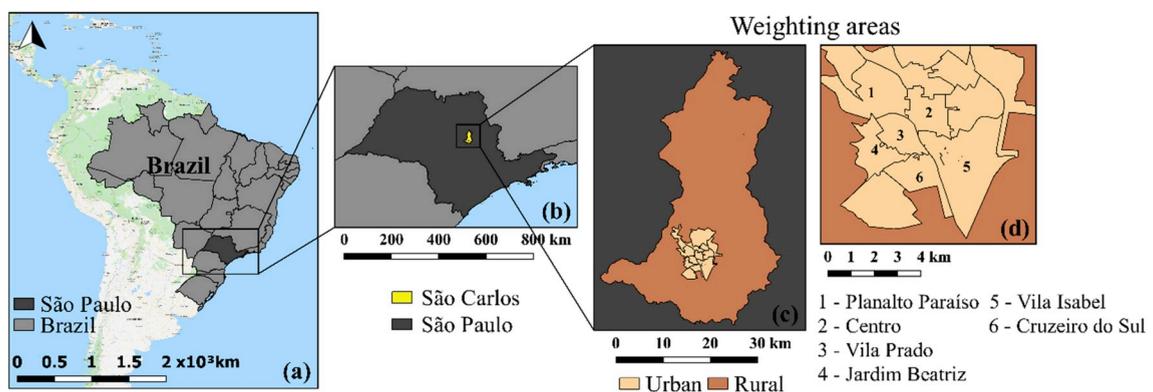

Fig. 1. Location of the state of São Paulo in Brazil (a) and of the city of São Carlos in São Paulo (b). City subdivisions into weighting areas, highlighting urban and rural regions (c) and the weighting areas studied (d).
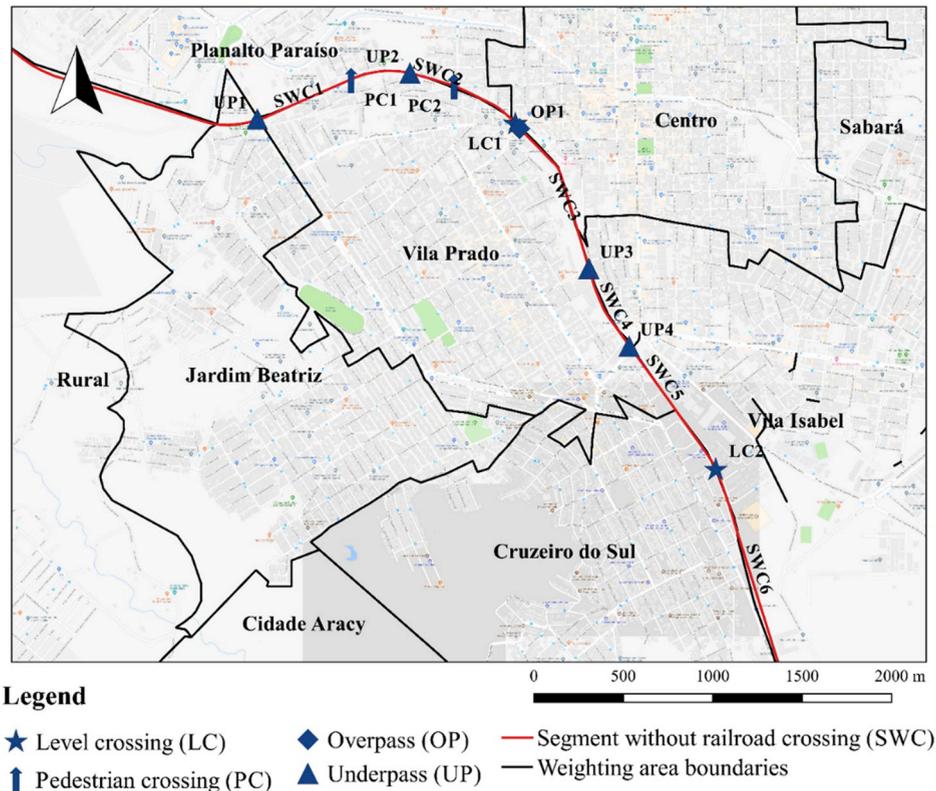
Fig. 2. Location of railroad crossings and segments without railroad crossings.

Thus, four databases were used from the 2010 Demographic Census for the development of the present study: conditions of individual mobility, income, gender and age. Besides the numerical data, we used the weighting areas and the statistical grid from the 2010 Demographic Census in shapefile format.

2.3. Analysis procedures

The railway infrastructure within the urban perimeter of São Carlos city is a physical barrier to the urban mobility. The characterization of this barrier was performed using a field survey, in which the railroad crossings and the segments without railroad crossings were qualitatively analyzed. From the field survey, it is worth noting that only one of the level crossings "LC1" had a segregated pedestrian walkway, but it was not fully accessible and had no handrails. In the regions without railroad crossings, where the barrier was made of metal or chain-link fencing, there were many segments in bad and flawed conditions, which enabled an informal passage of passers-by. However, informal crossings were not considered in this study. Moreover, garbage and high vegetation was found in almost the whole length of the railway, except for the railroad crossings OP1, UP1, UP3 and UP4.

The types of railroad crossings and segments without railroad crossings were classified into classes A, B, C and D according to a qualitative evaluation based on the National Department of Transport Infrastructure (or DNIT, which in Portuguese stands for Departamento Nacional de Infraestrutura de Transportes) Railway Service Instructions (DNIT, 2015a, 2015b; 2015c, 2015d; 2015e). The qualitative assessments were carried out by a specialist in the area of urban and transportation planning, based on the following criteria:

- Level crossing (LC): pavement conservation conditions, rail uniformity, lighting efficiency, pedestrian walkway width, relief conditions, efficiency of the existing signs, salubrity and influence limit (according to ABNT (2017), level crossing should be outside the limit of influence of other types of crossings, i.e. 1500 m from another level crossing, 3000 m from an overpass and 500 m from a pedestrian crossing);
- Underpass (UP): lighting efficiency during the day and at night, pedestrian walkway width, height of guardrail and salubrity;
- Overpass (OP): location attractiveness, pedestrian walkway width, height of guardrail, existence of coverage, lighting efficiency and salubrity;
- Pedestrian crossing (PC): rail uniformity, lighting efficiency, crossing width, efficiency of the existing signs and salubrity;
- Segment without railroad crossing (SWC): type of barrier material, barrier height, efficiency of the existing signs, railway right-of-way and salubrity.

Fig. 3. Examples of types of crossings and segments without railroad crossings. From top left to bottom right: OP1, PC2, UP4 and SWC6 Note: OP - Overpass; PC - Pedestrian crossing; UP - Underpass e SWC - Segment without railroad crossing.

In addition, the criteria evaluated for each type of railroad crossing and segment without railroad crossing received scores ranging from 1 to 3, in which score 1 was assigned to unfavorable conditions for urban mobility and score 3, to favorable conditions. The classification followed an ordinal scale of relevance, according to the percentage of conformance for each set of criteria. Class A corresponds to the most favorable conditions for urban mobility in the area of influence considered, and D, to the most unfavorable conditions.

For the delineation of the area of influence, a band of 500 m was considered for the railway (highlighted in Fig. 4, in green). Within the band, the area of influence for each railroad crossing was also delimited, considering a 400 m radius (highlighted in Fig. 4, in orange). In this case, in order to avoid the overlapping areas of influence we also computed a Voronoi diagram, under the assumption that residents will tend to cross the railway through the nearest railway crossing (for details on the Voronoi diagram see Okabe et al. (2009)). The railway area of influence is slightly larger than the railroad crossings, because it was considered that people who live more than 400 m away from a railroad crossing are as affected as those who live near the segments without railroad crossings.

Based on the population data collected, the characteristics of the railway (layout, railroad crossings and segments without railroad crossings) and the delimited areas of influence, we developed the georeferencing of the study area using the open software *QGIS v.2.18.12*. Besides that, to estimate the number of residents regarding the variables of permanent mobility constraints, income and age, we used factors based on the population distribution provided by the weighting areas, which were later multiplied by the number of inhabitants given in the statistical grid. In the case of the variable *gender*, this approach was not necessary, since gender is provided directly by the statistical grid.

Each variable has a number of factors equivalent to the number of their categories (e.g., permanent mobility constraints have 4 categories - disability, great difficulty, some difficulty and no disability – and, therefore, 4 factors) for each weighting area. Factors were then calculated from the probability of occurrence of the category in the weighting area. Thus, the population was estimated according to its demographic characteristics, for each cell of the statistical grid. Therefore, the variability of the distribution of the estimated population is based on the distribution of the statistical grid, mitigating the limitations resulting from the highly aggregated data, as is the case of the data from the weighting areas.

Hence, through the crossover of the population information (estimated and directly extracted from the statistical grid) with the influence areas of the railroad crossings and the railway, the number of residents by: self-declared permanent mobility constraints, range of monthly nominal income, gender and age range in the areas of interest were computed.

From these values, we conducted an exploratory data analysis to characterize relevant aspects and outline conjectures about the residents alongside the railway. Once the hypotheses were formulated, we conducted the chi-square (χ^2) tests of independence and the calculation of the standardized Pearson residuals regarding the variable of *classification* in relation to the variables of: (i) *number*
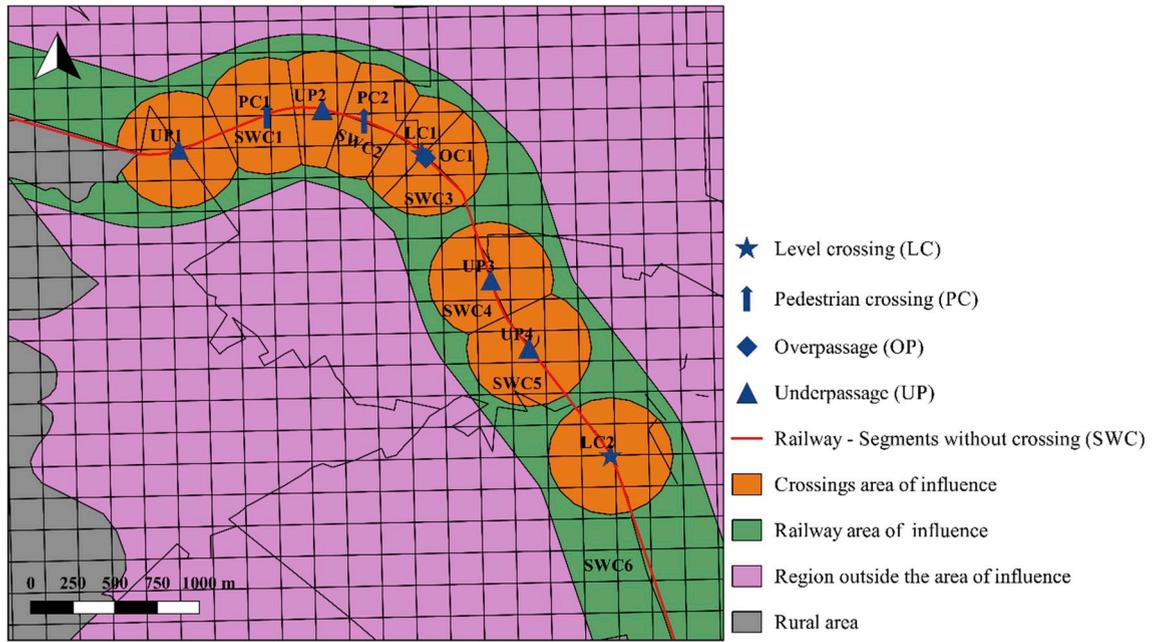
Fig. 4. Areas of influence considered for the railroad crossings and railway.

of residents with self-declared permanent mobility constraints; (ii) *number of residents by range of monthly nominal income;* (iii) *number of residents by gender* and (iv) *number of residents by age range*. Thus, the chi-square (χ^2) test is used to accept or reject the hypothesis of independence between the variables (H_0).

However, the chi-square (χ^2) test of independence is limited, since from the calculated chi-square (χ^2) value and its corresponding p-value, evidence of association can be seen between the variables, but it does not identify the nature or the strength of the association between each category of variables. For this reason, in addition to the chi-square (χ^2) and the p-value, we used Equation (1) to calculate the standardized Pearson residuals in order to make a direct comparison between the categories. Thus, the nature and the degree of dependence between the variables could be better understood.

$$SPR = \frac{Observed - Expected}{\sqrt{Expected \cdot \left(1 - \frac{row_{total}}{Total}\right) \cdot \left(1 - \frac{column_{total}}{Total}\right)}} \tag{1}$$

where *"SPR"* corresponds to the standardized Pearson residual, *"Observed"* corresponded to the observed count and *"Expected"* corresponded to the expected count, *"row_{total}"* indicates the sum of the observed counts in the row, and *"column_{total}"* indicates the sum of the observed counts in the column and *"Total"* indicates the sum of all observed counts.

A standardized Pearson residual that exceeds about 2 or 3 in absolute value indicates that the cell greatly contributes to the chi-square (χ^2) value and does not fit the H_0. Larger values are more relevant when the degrees of freedom are larger, and it becomes more likely that at least one is larger simply by chance (Agresti, 2018).

Thus, we identified deficits and excesses of residents in the surrounding regions of the railroad crossings and segments without railroad crossings, thus answering equity issues in the distribution of the number of residents along the railway and in the distinct types of railroad crossings.

3. Results

Based on the data collected and the delimited areas of influence, we classified the railroad crossings and segments without

Table 1
Classification of types of railroad crossings and segments without railroad crossings according to the percentage of conformance to the analyzed criteria.

Type of railroad crossings	LC		OP	UP				PC		SWC					
	1	2	1	1	2	3	4	1	2	1	2	3	4	5	6
% of conformance	86	71	100	83	83	73	73	80	80	60	63	47	55	50	53
Class	B	C	A	B	B	C	C	B	B	D	D	D	D	D	D

Note: LC - Level crossing; OP - Overpass; UP - Underpass; PC - Pedestrian crossing and SWC - Segment without railroad crossing.

railroad crossings, carried out exploratory data analysis and chi-square (χ^2) tests of independence, and evaluated the standardized Pearson residuals, as detailed in the subsequent subitems.

3.1. Classification of the types of railroad crossings and the segments without railroad crossings

The classification for each type of railroad crossing (LC, UP, OP and PC) and segment without railroad crossing (SWC) was performed according to the percentage of conformance of the qualitative assessments based on a set of criteria (item 2.3). The railroad crossings and segments that met from 90.0% to 100.0% of the established criteria were associated with class A. Those attending from 80.0% to 90.0% were associated with class B, from 70.0% to 80.0%, class C and from 33.0% to 70%, class D. Thus, the different types of railroad crossings and segments were classified, as shown in Table 1.

Therefore, according to the proposed classification, based on the DNIT Railway Service Instructions (ISF - DNIT), only the overpass (OP1) was categorized as class A. The pedestrian crossings (PC1 and PC2), underpasses (UP1, UP2) and level crossing (LC1) located in the *Centro*, *Jardim Beatriz*, *Planalto Paraíso* and *Vila Prado* were categorized as class B. Underpasses (UP3, UP4) and level crossings (LC2) located in *Vila Isabel* and *Cruzeiro do Sul* were categorized as class C, while all segments without railroad crossings (SWC) and only them, were categorized as class D.

3.2. Exploratory data analysis

The exploratory data analysis of the variables of the different databases studied enabled us to describe aspects and make conjectures about the equity in the distribution of the number of residents along the railway and around the different types of railroad crossings.

For this reason, we produced graphs showing the total and partial proportions for each database, shown in Figures A1 to A4 in the Appendix section. Total portions correspond to the analysis including the whole population on the database, whereas partial portions indicate the analysis including only the population of a particular class of railway crossings. Therefore, from Figures A1 to A4 (percentage values), the distribution of the number of residents along the different types of railroad crossings and segments without railroad crossings regarding residents' demographic characteristics can be observed.

With respect to residents with permanent mobility constraints, the largest portion (31.1%) of residents who live near class B railroad crossings are self-declared incapable of walking or climbing stairs without the help of another person, whereas the largest portions of residents with great difficulty or some difficulty or no disability (38.9%, 39.5% and 41.8%, respectively) live near the segments without railroad crossings (class D). Inversely, the smallest portions of residents in this database were observed living around class A railroad crossings, in which the highest portion occurs among residents with some difficulty (4.2%). In addition, once the total proportions are analyzed, it can be observed that a small part of the residents distributed alongside the railway has permanent mobility constraints (8.0%), in which 0.3% are incapable, 2.3% have great difficulty and 5.3% some difficulty. Even though there is a minority of the population living close to the railroad that has some degree of mobility constraints, it is expected that the distribution of these vulnerable groups will be preferred along the best classified crossings. However, it is observed that the distribution of the population along the railway is similar for all groups, except for the self-declared incapable residents whose

Table 2
Squared Pearson residuals (PR²), standardized Pearson residuals (SPR) and chi-square (χ^2) test of independence between the variables of *classification* (types of railroad crossings and segments without railroad crossings) and *number of residents with self-declared permanent mobility constraints*.

Class	Calculations	Permanent mobility constraints (number of residents)			No disability	Total
		Incapacity	Great difficulty	Some difficulty		
A	Observed	2	19	44	501	567
	Expected	2	13	30	522	567
	PR²	0.1691	2.1932	7.0385	0.8044	
	SPR	+0.42	+1.52	+2.77	−3.22	
B	Observed	21	116	278	4396	4812
	Expected	16	113	254	4428	4812
	PR²	1.5245	0.0716	2.2928	0.2308	
	SPR	+1.42	+0.31	+1.78	−1.95	
C	Observed	19	155	322	5920	6416
	Expected	22	151	339	5905	6416
	PR²	0.4819	0.1252	0.7753	0.0386	
	SPR	−0.84	+0.43	−1.10	+0.84	
D	Observed	26	184	420	7757	8388
	Expected	29	197	443	7720	8388
	PR²	0.1892	0.8049	1.1374	0.1807	
	SPR	−0.57	−1.19	−1.43	+1.97	
Total	Observed	69	474	1065	18,574	20,182
	Expected	69	474	1065	18,574	20,182
$\chi^2 = \Sigma$ PR²		18.0581				
p-value		0.0345 (9 degrees of freedom)				

Note: PR² - Squared Pearson residual; SPR - Standardized Pearson residual.

distribution is significant around class B railroad crossings.

In relation to the distribution of income, most of the total number of residents (86.6%) has a monthly nominal income of less than R$ 2550.00, and more than half of the total (55.4%) has a maximum income of R$ 1020.00, nearly 36.3% below the average monthly nominal income of the city (excluding the rural area). The distribution of residents with income over R$ 2550.00 have greater differences among classes A, B and classes C, D. There is a substantially reduced number of residents (1.4%) with a monthly nominal income greater than R$ 10,200.00. Classes C and D have residents predominantly with incomes lower than R$ 1020.00 (59.8% and 57.3%, respectively) and in considerably higher proportions than in the other classes. Meanwhile, classes A and B have the higher portions of residents with income over R$ 10,200.00 (2.0% and 2.5%, respectively) and these proportions are almost twice the proportions in classes C and D. In the case of income distribution, it is expected that residents with lower incomes will be substantial along the best classified crossings, since these groups tend to do more active trips and are also part of vulnerable social groups. However, it is observed that the distribution of the population along the railway is predominantly comprised of residents with low-income. This could be explained by the anecdotal evidence showing that land prices along the railway are around 4 times less than land prices in the central area of the city. Thus, this pattern of residents' distribution could be an indicative that the railway tends to cause urban segregation and marginalization.

The number of women is proportionally higher surrounding class A railroad crossings (56.4%), while in the other classes of railroad crossings there is a slightly higher distribution for female residents (52.1% and 52.9%). It can also be observed that gender distribution along the segments without railroad crossings are balanced (50%, class D). In addition, almost half of the population (20.3% + 20.3%) lives in regions without any railroad crossings (class D), indicating that there may be a need for implementing more railroad crossings.

The distribution of residents who live close to class A and B railroad crossings is slightly higher for the range aged over 60 years old (27.2% and 20.7%, respectively). While in classes C and D, the age ranges from 20 to 29 years old are slightly greater than the other categories (20.1% and 19.8%, respectively). It can also be observed that the age range up to 19 years old presents the lowest values for class A and B railroad crossings (11.7% and 13.7%, respectively). In relation to age, it is expected that children and the elderly will be preferably distributed along the best classified crossings, since these vulnerable groups cannot walk long distances and for long periods. However, our data is aggregated for children and young adults (age range up to 19 years old), thus the results for children are unclear. For the elderly, it is observed that their distribution is considerably higher in the best classified railroad crossings.

3.3. Chi-square (χ^2) test of independence and standardized Pearson residuals

The exploratory data analysis (item 3.2) showed relevant aspects between the variables but it did not validate the hypothesis of association among them, therefore the chi-square (χ^2) test of independence was used as a hypothesis test in contingency tables built from values of the variables of the different databases studied. Thus, the chi-square (χ^2) test is used to accept or reject the hypothesis of independence between the variables (H_0).

The calculations of the standardized Pearson residuals and the chi-square (χ^2) test of independence for the database concerning the variables of *classification* of railroad crossings and segments without railroad crossings and the *number of residents with self-declared permanent* mobility constraints are indicated in Table 2. The chi-square (χ^2) test of independence presented only 6.3% of the total expected counts below 5.0. As the test permits up to 20% of the expected counts less than 5.0, the application of the test in the database was possible. Since the chi-square (χ^2) value (18.0581) matched a p-value of 0.0345 (which is smaller than 0.0500), we

Table 3

Summary of excesses and deficits for the variables of *classification* (of the types of railroad crossings and segments without railroad crossings) regarding *mobility constraints, income, gender* and *age*.

Class		A	B	C	D
Permanent mobility constraints	Incapacity	NR[a]	NR[a]	NR[a]	NR[a]
	Great difficulty	NR[a]	NR[a]	NR[a]	NR[a]
	Some difficulty	Excess (+)	NR[a]	NR[a]	NR[a]
	No disability	Deficit (+)	NR[a]	NR[a]	NR[a]
Range of monthly nominal income	Up to R$1020.00	Deficit (−)	Deficit (−)	Excess (−)	Excess (−)
	R$ 1020.00 to R$ 2550.00	NR[a]	Excess (+)	NR[a]	NR[a]
	R$ 2550.00 to R$ 5100.00	Excess (+)	Excess (+)	Deficit (+)	Deficit (+)
	R$ 5100.00 to R$ 10,200.00	NR[a]	Excess (−)	Deficit (−)	NR[a]
	More than R$10,200.00	NR[a]	Excess (−)	Deficit (−)	Deficit (−)
Gender	Male	Deficit (−)	Excess (+)	Deficit (+)	Excess (−)
	Female	Excess (+)	Deficit (−)	Excess (−)	Deficit (+)
Age range	Up to 19	Deficit (−)	Deficit (−)	NR[a]	NR[a]
	20 to 29	NR[a]	Deficit (+)	NR[a]	NR[a]
	30 to 39	NR[a]	NR[a]	NR[a]	NR[a]
	40 to 49	NR[a]	NR[a]	NR[a]	NR[a]
	50 to 59	NR[a]	NR[a]	NR[a]	NR[a]
	More than 60	Excess (+)	Excess (+)	Deficit (+)	Deficit (+)

(+) Positive effect related to equity in the distribution of the number of residents
(−) Negative effect related to equity in the distribution of the number of residents
[a] Not relevant. The standardized Pearson residual has a small contribution to the chi-square (χ^2) value

reject the hypothesis H_0 with a significance level of 0.05. Therefore, we cannot rule out the possibility of an association between the variables of *classification* and *(i) number of residents with self-declared permanent* mobility constraints.

In addition, based on the standardized Pearson residuals shown in Table 2, it was observed that there is a larger than expected count of inhabitants that is self-declared with some difficulty living near the class A railroad crossings, that is, an excess of residents as can be seen through the value $+ 2.77$ (in absolute values is higher than 2) and the positive sign. For residents with no disability that live in the class A surroundings, there is a smaller than expected count of population, that is, a deficit of residents as can be perceived by the value -3.22 (in absolute values is higher than 2) and the negative sign. In addition, the standardized Pearson residuals found for all permanent mobility constraints categories in classes B, C and D, and residents self-declared incapable or with great difficulty in class A are less than 2 (in absolute values). Therefore, the squared Pearson residuals (PR^2) values of those categories contribute little to the chi-square (χ^2) calculation and are consequently poorly associated with the permanent mobility constraints of the residents who live near the railroad crossings of those classes.

Analogously, we conducted the determination of the squared Pearson residuals, the standardized Pearson residuals and the chi-square (χ^2) test of independence for the databases regarding the variables of *classification* and for the other variables of: (ii) *number of residents by range of monthly nominal income;* (iii) *number of residents by gender* and (iv) *number of residents by age range.*

Therefore, for the database regarding the variables of *classification* and *number of residents by range of monthly nominal income*, the chi-square (χ^2) value obtained was equal to 403.8902 and it corresponds to a p-value of 5.6777×10^{-79} (which is smaller than 0.0250). Hence, hypothesis H_0 is rejected at a level of significance of less than 0.0250, then a possible association between the variables of *classification* and *number of residents by range of monthly nominal income* cannot be ruled out.

For the database related to the variables of *classification* and *number of residents by gender*, considering the result corresponding to 22.7977 and a p-value equal to 4.4500×10^{-5} (which is smaller than 0.0250), hypothesis H_0 is rejected with a significance level of 0.0250. Thus, also in this case the test shows evidence of association between the variables.

Furthermore, the chi-square (χ^2) test of independence obtained for the database regarding the variables of *classification* and *number of residents by age range* was equivalent to 74.7030 and it corresponds to a p-value of 6.4062×10^{-10} (which is smaller than 0.0250). Hence, the hypothesis H_0 is rejected at a level of significance of less than 0.0250, then we cannot rule out a possible association between the variables of *classification* and *number of residents by age*.

Table 3 presents a summary of excesses and deficits of residents with different demographic characteristics that live surrounding the distinct classes of railroad crossings and segments without railroad crossings. It also brings information about the positive ($+$) or negative ($-$) effect of the excess/deficit to the vertical equity in the residents' distribution along the railway. This happens because excesses/deficits of residents living near a determined class of railroad crossing or segment without a crossing could denote a positive or negative effect to vertical equity depending on which social group it is related to.

Concerning the variable permanent mobility constraints, the excess of residents with some difficulty of walking or climbing stairs that live in the class A railway crossing surroundings is a positive effect to the vertical equity, since it corresponds to a vulnerable group which cannot walk long distances and for long periods. Therefore, it is expected that this social group distribution will be preferred along the best classified crossings. On the other hand, the deficit of residents with no disability that live around the class A railway crossings is also a positive effect to the vertical equity, since individuals from this group do not have any mobility constraints and can walk greater distances.

With regard to the variable monthly nominal income, the deficit of residents with income less than R$ 1020.00 living in classes A and B surroundings, and the excess of the same social group that lives near classes C and D denote a negative effect to the vertical equity. As in the excess of residents with an income greater than R$ 5100.00 that live near class B railroad crossings, and the deficit of residents of the same social groups living along classes C and D indicate a negative effect to the vertical equity. On the contrary, a positive effect to the vertical equity corresponds to the excess of residents' distribution of the social group with an income between R$ 1020.00 and R$ 2550.00 that live near class B railroad crossings, an excess of residents' distribution of the social group with an income between R$ 2550.00 and R$ 5100.00 living around classes A and B and a deficit of residents with the later income range that live around classes C and D. This is because regarding the vertical equity, it is expected that residents with lower incomes (less than R$ 2550.00) will be preferred along the best classified crossings, since these groups tend to do more active trips and are also considered vulnerable social groups. We also assumed that the excess of residents with an intermediary income (from R$ 2550.00 to R$ 5100.00) is positive.

Regarding residents' gender distribution, for a positive effect to the vertical equity, an excess of men or women living around classes A and B railroad crossings or a deficit of men or women living around classes C and D is desired, and the contrary for a negative effect. Thus, an excess of women in class A, an excess of men around class B, a deficit of men in class C and a deficit of women around class D indicate a positive effect to the vertical equity. On the other hand, a deficit of men in class A, a deficit of women around class B, an excess of women in class C and an excess of men around class D indicate a negative effect to the vertical equity.

Similarly, a positive effect to the vertical equity regarding age involves an excess of residents up to 19 years old or more than 60 years old around classes A and B railroad crossings, or a deficit of residents up to 19 years old or more than 60 years old around classes C and D. Thus, a deficit of residents up to 19 years old in classes A and B indicate a negative effect. On the other hand, a deficit of residents aged between 20 and 29 in class B, an excess of residents aged more than 60 around classes A and B and a deficit of residents aged more than 60 in classes C and D indicate a positive effect to the vertical equity.

4. Conclusions

This study presented a simple and low-cost analytical approach for the assessment of community severance based on the classification of the quality of the facilities intended to transpose a transport barrier. In addition, the analysis of the chi-square (χ^2) tests

of independence and the calculation of the standardized Pearson residuals helped us identify not only evidence of associations between the variables of classification (of railroad crossings and segments without crossings) and demographic characteristics, but also deficits and excesses between them.

The study found evidence that residents with some difficulty in walking or climbing stairs tend to live near the best class of crossings, low-income (less than R$ 1020.00) residents tend to live around the worst classes of crossings and segments without crossings, while high-income (greater than R$ 5100.00) inhabitants tend to live around one of the best classes, men or women tend to live near the best classes, residents aged up to 19 tend not to live in the surroundings where the best classes are and residents aged more than 60 tend to live near the best classes. Particularly, the population who live near the segments without railroad crossings (class D) are prone to traveling longer distances in order to transpose the railway. This could be an indicative that this population is more susceptible to active trip diversion or suppression, thus their health and well-being condition could tend to be more affected.

In summary, residents with permanent mobility constraints, high-income, men or women, or aged above 60 years old are well assisted in relation to urban mobility. Moreover, residents with a low income or aged up to 19 years old are poorly assisted in relation to urban mobility. Therefore, vulnerable social groups are partially well assisted in relation to urban mobility, since residents with a low income and aged up to 19 years old are poorly assisted.

Hence, even with the limitation of aggregated data, the research responds to the questions formulated in Section 1, indicating that the distribution of the number of residents along the types of railroad crossings and segments without railroad crossings is vertically equitable for residents with permanent mobility constraints, by gender and for the elderly, whereas it is not vertically equitable for residents with a low income and aged up to 19 years old.

Although this study has focused on a very specific type of transport infrastructure, which by its nature is a clear barrier to the trips between the surrounding areas, it is not the only type of barrier produced by transport infrastructures in urban areas. The analysis of these diverse barriers still requires more detailed studies, which may eventually benefit from the methodology developed and tested here. Additionally, the method can assist the decision-making of urban and transport planners in order to assess the community severance caused by a railway, also considering possible vertical inequities in the distribution of the different social groups of the residents along the railway and around the railroad crossings, particularly vulnerable groups.

Acknowledgements

Appendix A

Appendix A is composed of the Fig. A1 to A4 which complement the exploratory data analysis presented in item 3.2. These figures illustrate the distribution of the number of residents along the different types of railroad crossings and segments without railroad crossings regarding residents' demographic characteristics. Thus, Fig. A1 to A4 highlight two patterns of proportions, the first proportion is presented in the bar graph and corresponds to the proportions related to the total number of residents (from each respectively database) distributed per variable category according to the class of railroad crossing and segments without crossings. The second pattern is presented through the sector graph and corresponds to the partial proportions per class of types of railroad crossings and segments without railroad crossings according to the variable category. Total portions correspond to the analysis including all the population on the database, whereas partial portions indicate the analysis including only the population of a particular class of railway crossings.
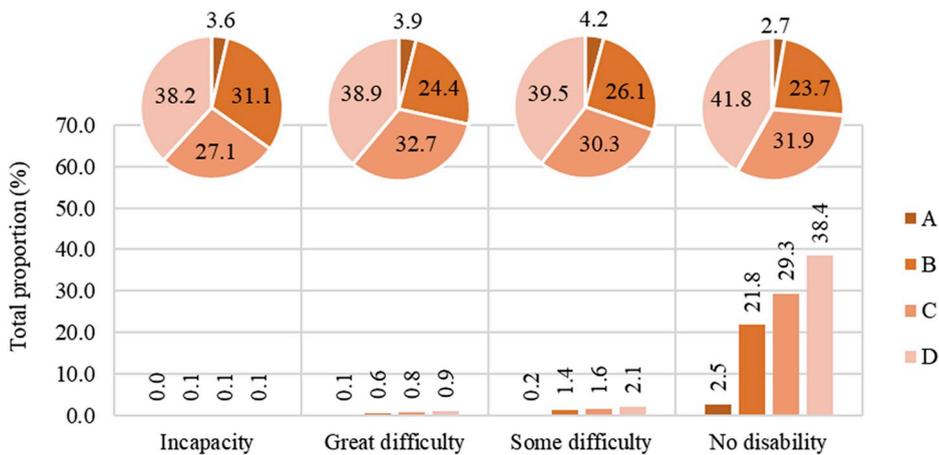

Fig. A1. Total (bar graph) and partial (sector graphs) proportions of the number of residents per class of types of railroad crossings (A is the best and D the worst) and segments without railroad crossings as a function of permanent mobility constraints.
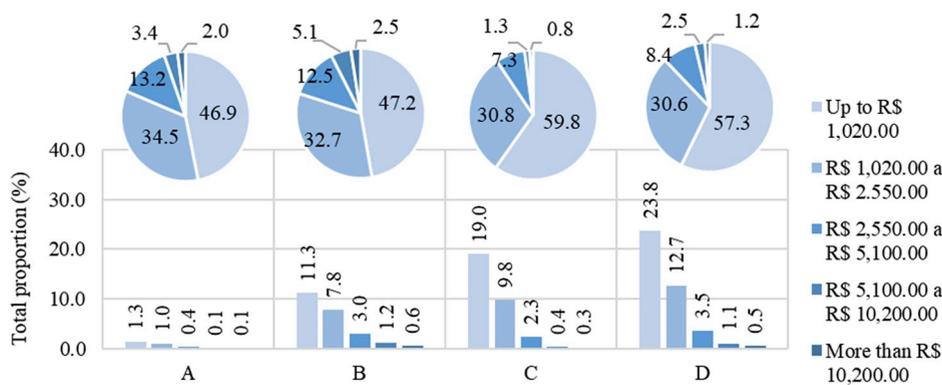
Fig. A2. Total (bar graph) and partial (sector graphs) proportions of the number of residents with income as a function of the different classes of railroad crossings and segments without railroad crossings
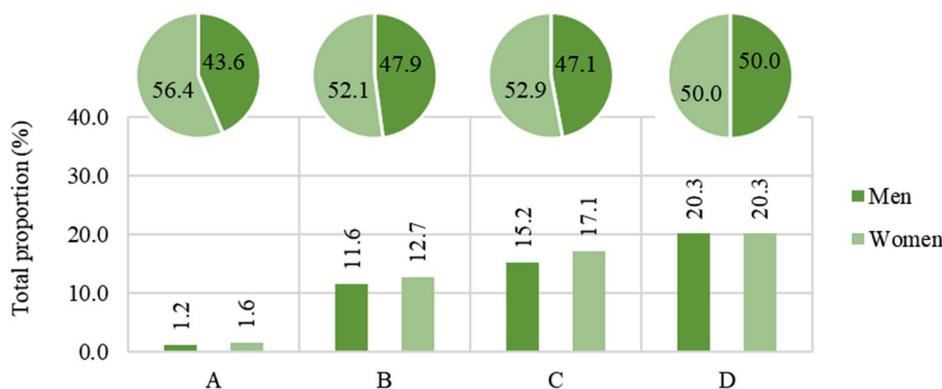

Fig. A3. Total (bar graph) and partial (sector graphs) proportions of the number of residents by gender as a function of the classes of the types of railroad crossings and segments without railroad crossings
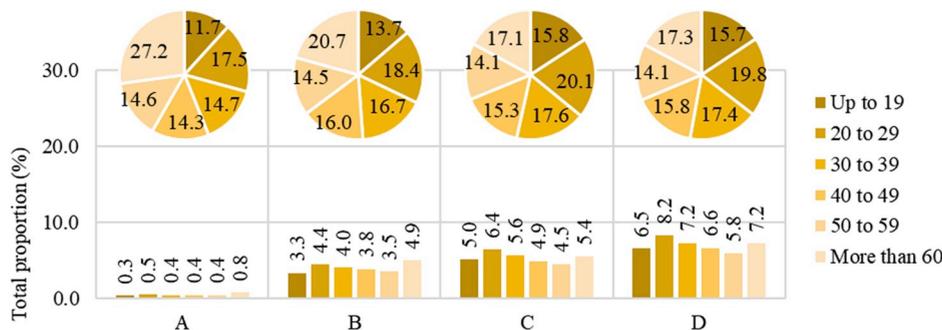

Fig. A4. Total (bar graph) and partial (sector graphs) proportions of the number of residents by age range as a function of the classes of the types of railroad crossings and segments without railroad crossings

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