Multilayered Analysis of Urban Mobility

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Abstract

This study analyzes the urban mobility of Curitiba through the use of public transit by the population divided into socioeconomic strata. To study the established mobility graph and its spatio-temporal patterns, a multilayered approach called Multi-Aspect Graph (MAG) with four aspects is applied. The results detail patterns that cannot be observed in a traditional graph, such as the most frequent routes and the most central points of the city, taking into account all the modeled aspects. The model used allows a strategic understanding of the use of the beneficial public transit system for different applications, such as actions in emergencies and outbreaks of rapidly contagious diseases.

Keywords: transit, social stratification, network analysis.

1 Introduction

The debate on urban mobility in Brazil has been a much-discussed topic among public administrators in large cities [12] [13]. Urban mobility refers to the ease of movement of the population and goods in the geographic space of cities, constituting a component of the quality of life aspired by its inhabitants [1]. A possible model to represent urban mobility is through graphs, mapping the system elements into vertices and edges. However, the dynamics of urban mobility can be studied from several aspects, such as time and space. To enable all its nuances to be analyzed simultaneously, it is necessary to use a multilayer approach instead of a traditional graph. Such a structure is known as a Multi-Aspect Graph (MAG), an extension of traditional graph theory that allows analyzing the interaction between the layers of a complex system. Despite such studies dating back decades, multilayer graphs have become one of network science's most important recent directions.[4].

This work aims to use a MAG to characterize a complex system, in this case, urban mobility using public transit in the city of Curitiba. In this sense, we make a comparison with the results presented in our previous work [14], in which we created a model representing the origin and destination routes of public transit users in Curitiba using a traditional graph structure. From this structure, we extract spatio-temporal patterns considering subsets corresponding to socioeconomic strata. The results of this work show, for example, the most frequent movements by specific periods and socioeconomic class, in addition to identifying central points of the city taking into account the modeled aspects simultaneously. We observe that the non-consideration of aspects such as socioeconomic class or time representing the partial understandings of the phenomenon under study, which can lead to wrong conclusions. The results also suggest that the proposed model provides important knowledge of mobility using public transit that can be beneficial in different applications, for example, in interventions in emergencies, such as the pandemic generated by COVID-19.

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2 Related Works

Given that urban mobility is a fundamental part of the functioning of cities, many recent studies focus on understanding this phenomenon from different perspectives, from the mobility of groups [11] and taxis [7] to mobility considering public transit in various ways [2, 8]. In an application to understand mobility using a spatio-temporal representation, Marques-Neto et al. [6] used cellular records to analyze the spatio-temporal dynamics of the movement patterns of event participants large scale. Relying on three different types of events: a big football match, a rock concert and a New Year's celebration, the authors were able to improve the understanding of human mobility caused by these events and developed an app to help telephony companies to plan their infrastructure for major events.

With an approach to mobility in different socioeconomic strata, Xu et al. [17] use information from cell phones and propose an analytical framework to better understand human mobility patterns in different socioeconomic strata of the population. The same is true of the study by Lotero et al. [5], which analyzes urban mobility between two Colombian cities using an origin-destination survey and coupling information on socioeconomic classification.

Our previous study [14] analyzed urban mobility in Curitiba through public transit in the city. We used the city's neighborhoods to establish the mobility graph, where the vertices represented the neighborhoods and the edges represented the existence of a route between them. In that study, we divided public transit users into subsets corresponding to socioeconomic strata and explored spatio-temporal patterns in an aggregated fashion. According to the results, we conclude that morning activity is postponed to wealthier strata, and the spatial distribution of trips becomes more localized. The present study also analyzes urban mobility in different social strata. Still, it incorporates a technique not explored in the cited works, which is an approach that uses the Multi-Aspect Graph (MAG). We compare some results of this study with the one presented previously [14], identifying the nuances that the MAG allows in a more detailed study of urban mobility in Curitiba.

3 Data Description and Methodology

In this study, the criterion used to classify society according to family income is the rule of the Secretary of Strategic Affairs (SAE), an institution from the federal government established in 2012 [10]. Income information was acquired through the 2010 Brazilian Demographic Census carried out by IBGE [3]. In Brazil, social classification according to family income is divided into the upper class, middle class, and lower class. Based on the studies carried out by SAE, these groups were subdivided, leaving the lower class and the middle class in three groups and the upper class in two groups. According to this classification and the estimated income by neighborhood, Curitiba has only four of the eight classes: Lower Middle Class, Middle Class, Upper Middle Class, and Lower Upper Class.

The public transit base for analysis of urban mobility developed in this study is provided by URBS [1] and is available for the general public without restrictions. The information contained in this database is from the daily smart card records, and each of these records has seven fields: Line Code, Line Name, Vehicle Code, Card Number, Date of Use, Date of Birth and Gender. Additionally, we use two complementary datasets related to public transit in Curitiba: Vehicles and Stop Points. The Vehicles dataset contains the location of all vehicles that circulated in Curitiba and the Stop Points dataset contains the information of all existing bus stops in the city. The smart card entries represent 17,511,710 records and the Vehicles dataset 129,461,200 records, totaling 69 days analyzed.

To infer in which neighborhood each card entry was made, we search a correspondence in the Vehicles dataset using the bus line code, vehicle code, approximate date and time, thus obtaining the latitude and longitude of each card entry. We associate each pair of latitude and longitude to the bus stop closest to the specific line of the smart card entry. At the end of this stage, we infer the neighborhood for 5,388,638 smart card records. We needed to associate a neighborhood of origin for each smart card, which we called the user's home. For this, entries between 5 am and 10 am were considered, as this is a period in which people usually use public transit to work or study. By recovering the most frequent neighborhood in the group from 5 am to 10 am by card, we obtained 14,632 exclusive smart cards with an associated neighborhood of origin.

Considering a Multi-Aspect Graph or MAG, a structure capable of representing a time-varying multilayer network, the proposed MAG model is given by $H = (A, E)$, where E is the set of edges and A the list of aspects that make up the model. Each aspect $\alpha \in A$ is a finite set, and the number of aspects p represents the order of the MAG. Each edge $e \in E$ is a tuple with $2 \times p$ elements. All edges have the form $(a_1, ..., a_p, b_1, ..., b_p)$, where a_1, b_1 are elements of the first aspect of H, a_2, b_2 are elements of the second aspect from H and so on, up to a_p, b_p, which are elements of the p-th aspect of H [16].

We create a MAG to analyze the mobility of public transit in Curitiba with the order $p = 4$, that is, four aspects. These aspects are: the socioeconomic class of the user who is carrying out the route, that is, the class of the user's residential neighborhood, being CMB (Low Middle Class), CM (Middle Class), CMA (Upper Middle Class) and CAB (Upper Class Lower); the city's neighborhoods; 24 moments of time (each moment corresponds to 1h of the day) and socioeconomic class of the neighborhood, being 4 (Low Middle Class), 5 (Middle Class), 6 (Upper Middle Class) and 7 (Upper Low Class). Figure 1 illustrates this model and the six types of edges present, knowing that all types of edges can occur with all classes of users. It is also worth mentioning that the proposed model captures users' route between neighborhoods of different socioeconomic classes, regardless of the user's class. The types of edges present in the model are listed below:

- orange: same neighborhood at the same instant of time;
- red: same neighborhood at different instants of time;
- blue: between neighborhoods of the same class at the same instant of time;
- green: between neighborhoods of the same class at different instants of time;
- purple: between neighborhoods of different classes at the same instant of time;
- brown: between neighborhoods of different classes at different instants of time.

This model can retrieve the most central vertex by determining the degree of the vertices. The general degree of a vertex v is the number of edges incident to that vertex, the in-degree is the number of edges pointing to v, and the out-degree is the number of edges leaving v . Another way to retrieve the most central vertex is by the betweenness value, which measures the importance of vertices in relation to the flow of information between all pairs of vertices, assuming that information flows mainly along the shortest paths between them [9].

[1]URBS (Urbanização de Curitiba S/A): company that manages public transit in Curitiba [15].

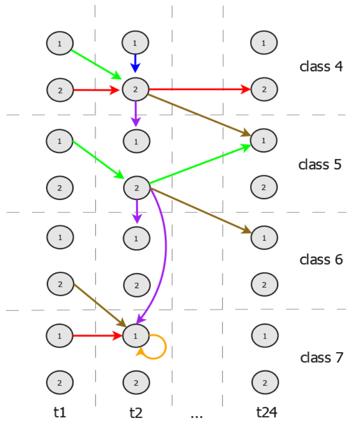

Figure 1. Representation of the general structure of the graph using MAG with 4 aspects. The vertices correspond to the city's neighborhoods and are separated into 4 layers, according to their socioeconomic classification. The edges illustrate the routes between the neighborhoods, which can occur at any 24 instants of time, where each instant corresponds to 1h of the day.

4 Results

We obtain a structure with 4,204 vertices and 63,718 edges (directed and weighted) by establishing the general graph using MAG. The direction of the edges identifies the direction of route, whereas the weight corresponds to the number of routes between two vertices. We decide to extract the 20 heaviest edges of the model in order to verify a small portion of the densest routes and identify patterns that compose it. Besides that the weight of the twentieth edge corresponds at 23.5% of the weight of the heaviest edge, that is, the routes already become much less dense in the sequence. So, by extracting the 20 heaviest edges, we observe the predominance of the Centro neighborhood, both as origin and destination, that is, the greatest amount of routes occur within this neighborhood, composing the ten heaviest edges of the model and obtaining the highest single weight, 1034 routes. The second most dominant neighborhood is Cidade Industrial, appearing on four edges as its origin, with the Centro being its destination. The neighborhoods Capão Raso, Água Verde, Vista Alegre and Bairro Alto still make up the most intense routes, with edges weighing less than 294. This result also characterizes the mobility graph created from users' origin and destination matrix in our previous work[14]. However, with the MAG it is possible to identify the socioeconomic class of the user and the times when these more intense routes occur. Of the 20 heaviest edges, 16 are CAB class, and 4 are CM class. The trips start at 6 am, 7 am, or 8 am, with the return from 12 am.

To analyze the mobility of public transit in the different socioeconomic strata of Curitiba we consider four groups of edges, where each group corresponds to the routes of users of a class, preserving the aspects of the four layers as the socioeconomic class of the neighborhood (4, 5, 6 and 7), the 24 moments (each moment corresponds to 1h of the day) and the neighborhoods of the city. In each group, we recover the most central vertex considering the degree of vertices (general, input, and output) and the betweenness value.

We notice the predominance of early morning hours (6 am and 7 am) when considering the vertex with the highest general degree and the highest degree of output in each class, as well as a high occurrence of late afternoon hours (5 pm and 6 pm) in vertices with the highest degree of entry, reinforcing the temporal patterns found in [14], which shows two relevant peaks in the day, one in the early morning and the other in the late afternoon. However, with the MAG, it is possible to observe, simultaneously to the time, the neighborhood present in these central points, showing a strong route with origin in Tatuquara for the CMB class, Cidade Industrial for the CM class, Santa Cândida for the CMA class and Centro for the CAB class.

The vertices with the highest betweenness centrality are the same for the CM and CAB classes, Centro at 12 am. Centro is also the most important place for the CMA class, but at 5 pm, which reinforces the dominance of this neighborhood in participating in intermediate and final destinations, for 3 of the 4 socioeconomic classes. We analyze more carefully the presence of the Campo de Santana neighborhood at 5 pm for the CMB class to understand why this neighborhood appears in this analysis. Observing the complete routes that have this vertex as an intermediate destination, we detect that individuals carry out routes within this neighborhood, one in the morning and another in the late afternoon (precisely at 5 pm) because they probably work in the same neighborhood where they live, and after work move to other neighborhoods in the city, which are closer to the central region, such as Centro Cívico, Água Verde and Bairro Alto, possibly to have access to places and services, such as colleges and universities, not available in their region (remembering that Campo de Santana is located at the southern end of the city) and later returning to their homes.

Analyzing the ten heaviest edges by class, we identify a pattern concerning the start times of routes, showing that with increasing richness, the morning activity is postponed, in the same way that we inferred in our previous work [14]. Predominantly, in the CMB class, routes originate at 5 am in Tatuquara, in the CM class at 6 am in Cidade Industrial and in the CMA class at 7 am in Capão Raso and Bairro Alto. In the CAB class, it also occurs at 7 am, but in the Centro. As you can see, we could enrich the time information with the MAG, concomitantly extracting the data from where such routes begin.

With the aspect of the individual's socioeconomic class it is possible to capture the diversity of behavior in each socioeconomic strata. Analyzes with this detail can be useful, for example, for public administrations, as an indication of where disease prevention and vaccination campaigns would reach a larger audience and, consequently, the largest territorial part of the city.

5 Conclusion

This article presents a study on urban mobility in Curitiba using a multilayer resource. And to highlight the advantages of using a MAG, we make comparisons with the results obtained in our previous work, in which a model was created representing the origin and destination routes of users of public transit in Curitiba using a traditional graph.

The general mobility graph characterizes urban mobility under four aspects, allowing the joint analysis of time (hourly), space (neighborhoods), and socioeconomic class, performing routes between the four layers corresponding to the socioeconomic class of the neighborhoods. All this information cannot be extracted with a single traditional graph since it considers the spatio-temporal routes in a grouped way. When studying the graph by socioeconomic class of the individual, many results reinforced temporal patterns found in our previous study [14]. Still, with the MAG, it is possible to verify, simultaneously with the time, the neighborhoods present in these central points of each class. At these times and places, therefore, a greater agglomeration of people is detected, and this result is capable of helping public transit companies to plan fleet increases at these points and times, guaranteeing to serve the entire city of Curitiba since, in this analysis, it was possible to consider the behavioral breakdown by socioeconomic class. This action can be essential in helping combat a pandemic such as COVID-19, which requires the elimination of groups of people to reduce contagion. Still, in this context, this model can help evaluate vaccination strategies.

An overview of urban mobility under spatial and temporal aspects, considering the socioeconomic strata of the neighborhoods and of the individuals who carry out the routes, can benefit the work of several professionals, such as urban planners, sociologists, engineers and epidemiologists, giving directions to places and times of greater agglomeration, in addition to identifying strategic routes for the formulation of new bus paths. With MAG, there is the possibility of working with all these aspects in a single model, guaranteeing a detailing of the retrieved information and flexibility in creating derived models when the need for integrated perspectives arises concerning some particularity, thus constituting some of the advantages over a traditional model.

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