Capacity of Roadway Infrastructure and its Relation with Functional Urban Regions

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Abstract

This study proposes a roadway infrastructure supply index that considers road capacity for the analysis of its relation with the metropolization process. An exploratory analysis using ESDA (Exploratory Spatial Data Analysis) techniques was conducted in São Paulo state for comparing the index values if calculated with and without road capacity data. The results suggest that the identification of homogeneous urban regions is improved when such data are considered. Therefore, the inclusion of qualitative characteristics has not only contributed to the determination of the index, but also made clear they significantly reflect the intense interactions among the municipalities of a region.

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1. Introduction

The organization of cities in networks of cooperation and interaction is due to the existence of important infrastructures for the socioeconomic maintenance and growth of a region. Examples of such infrastructures are power and telecommunication grids and transportation systems. The latter, in particular, are responsible for the physical integration of the cities and provide their exchange of goods, people, services and opportunities. As such interactions, in general, depend on both the hierarchical structure of the cities and characteristics of the available infrastructures, regions with greater power to attract people and goods can be spotlighted in a regional or national scenario. A result of this process is the formation of Functional Urban Regions (FURs), an expression used in this study to refer, in general, to metropolitan regions, urban agglomerations and conurbations.

Over the past years, the number of studies on FURs has grown due to the increasing urbanization of the planet (UNFPA, 2011) and efforts have been devoted to the development of methods and models to represent the existing interrelations within the complex and multidimensional FUR's structures. Interactions do not result only from the geographic proximity among the municipalities. According to Rodrigues da Silva et al. (2008), they are also a consequence of spatial, economic, political, social and demographic relations observed in those FURs. This context brings a challenge to urban planners and urban managers, namely the definition or delimitation of the FURs. On the one hand, the administrative limits of the FURs often exceed the limits of the individual cities that form them. On the other hand, they are often not large enough to match the boundaries of the superior administrative subdivisions, i.e. states or provinces.

Williams et al. (2012) argue that the FURs have been conceptualized mostly in terms of functional linkages (i.e. flows of people and goods). This is the criterion used in both Europe (Cheshire and Hay, 1989) and the United States (Office of Management and Budget, 2000). In Europe, FURs comprise at least one core "urbanized area" with 20,000 or more jobs as well as any adjacent NUTS3 (NUTS, or Nomenclature of Units for Territorial Statistics, is a hierarchical classification of administrative boundaries developed by Eurostat, the European Office for Statistics) regions from where more workers commute to that core than to any other location. Similarly, in the United States, the Metropolitan Statistical Areas comprise at least one core city with a population of 50,000 or more, as well as any adjacent counties from where at least 25 % of the employed residents commute to the core city's county.

However, this approach based on commuting flows has faced some criticisms (Duranton and Puga, 2004; Coombes and Overman, 2004; Rosenthal and Strange, 2004; Duranton, 2006; Bode, 2008). The authors argue that the commuting intensity itself does not show the degree of economic integration between a metropolitan center and its hinterland. The approach developed by Bode (2008), for example, uses the fraction of land prices attributable to economies of urban agglomeration. Despite the theoretical robustness of the model and the good results achieved in the empirical study, such an approach is not easily applied because the data required for its application are often unavailable or outdated in some countries.

Another alternative found in the literature is to analyze satellite images for the identification of the urban areas of a region (Weber, 2001; Huang et al., 2014; Niemeyer et al., 2014). The advantage of approaches in remote sensing is they indicate the exact delimitation of the entire urbanized area, no matter where they are located within the municipal boundaries. Similarly, spatial metrics have been used to determine the urban form and its morphology (Bereitschaft and Debbage, 2014). However, statistical factors that really show the mutual influence of urban settlements, such as economic relationships, commuting flows, etc. cannot be captured by those approaches, which make their isolated application insufficient.

The concept of FURs is not simple and additional approaches can also be found in Cheshire and Carbonaro, 1996; Champion and Hugo, 2004; Robson et al., 2006; Ferreira et al., 2010; Haisch and Müller, 2013. However, as previously mentioned, some of those methods cannot be applied, given the absence of specific data in some countries. In such cases and according to the recommendations of the Office of Management and Budget (1998), population density becomes the alternative for the definition of FURs. Traditionally, the statistical census has been regularly conducted in most countries with fairly reliable results. This variable, however, can be analyzed in several ways for the purpose of defining FURs, as shown by Ramos and Rodrigues da Silva (2003 and 2007), Ramos et al. (2004) and Manzato et al. (2007). The authors have based their studies with the variable on branches of spatial analyses, like spatial statistics and spatial modeling.

Besides population density, other alternatives are also indicated. Coombes (2004), for example, suggested the analysis of job distribution or the use of roads or service networks, like bus services, as a proxy for data on actual patterns of interaction. In this sense, Manzato et al. (2006) tested the viability of using transportation infrastructure supply indexes to define FURs. Their conclusions pointed out to a combination of both transportation infrastructure supply and population indexes, based on the evidences about the role played by transportation infrastructure in the development of FURs (for an overview, see Lin, 1999; Boarnet and Haughwout, 2000; Baum-

Snow, 2010). Manzato and Rodrigues da Silva (2006, 2007 and 2010); Pereira and Rodrigues da Silva (2010); Ajauskas et al. (2012 and 2013) and Rodrigues da Silva et al. (2014) explored such a hypothesis. In general, the conclusions of these studies indicate that the use of both transportation infrastructure supply and population indexes combined with spatial analysis techniques, especially spatial statistics and spatial modeling, can lead to a promising approach for the definition of FURs.

Nevertheless, there is no general agreement on the transportation infrastructure supply indexes applied in such studies. According to Magalhães et al. (2004), such indexes comprise road extension (when the total road extension within a region is obtained), spatial density of the road network (when the total road extension within a region is divided by the area of the region), population density related to the road network (when the total road extension within a region is divided by the population of the region), and indicator for the coverage of the roadway infrastructure. The latter determines the area influenced by a transportation system composed of bands or buffers around the system. Regarding the roadway infrastructure system, the determination of such indexes is based mainly on the road extension. Qualitative factors associated with the roads, as capacity, for example, are usually not taken into account. In this case, capacity can be differentiated between two-lane and multi-lane roadways. Multi-lane roadways can also be differentiated by the number of lanes.

The objective of this research was to develop an exploratory study about the influence of the roadway infrastructure capacity on metropolization. The idea is to incorporate the data on road capacity to the roadway infrastructure supply and verify this relation based on the definition of FURs. A new structure for a transportation infrastructure supply index, in which road capacity data are introduced, was tested. Among the existing indexes, we adopted the indicator for the coverage of the roadway infrastructure, because it considers the influence of the infrastructure around the system. ESDA (Exploratory Spatial Data Analysis) techniques were used for a case study developed in São Paulo state, Brazil.

This paper is organized as follows: section 2 presents the methodology and the data used for the case study; section 3 provides the results and discussions; finally, section 4 addresses the conclusions and suggestions.

2. Methodology and Case Study

The methodology used is based on ESDA techniques. Its theoretical basis is presented in this section along with the indicator for the coverage of the

roadway infrastructure adopted. The data used for the case study, as well as the proposed structure for the indicator for the coverage of the roadway infrastructure also include road capacity.

2.1. Theoretical Basis

In the application of ESDA techniques, each zone (or municipality, as in this study) is classified regarding a given attribute value and in relation to the overall average value and the average value of the adjacent zones. The results, represented in four quadrants of the Moran's scatterplot and also on maps (the so-called Box Maps), can be classified as follows:
1. High-High (HH): for zones with positive value for the zone and positive average value for contiguous neighbors. Positive values are always above the overall average value.
2. Low-Low (LL): for zones with negative value for the zone and negative average value for contiguous neighbors. Negative values are always below the overall average value.
3. Low-High (LH): for zones with negative value for the zone and positive average value for contiguous neighbors.
4. High-Low (HL): for zones with positive value for the zone and negative average value for contiguous neighbors.

    As previously mentioned, the index of infrastructure supply regards the indicator for the coverage of the roadway infrastructure (Magalhães et al., 2004), shown in Equation 1. This indicator refers to an area under the influence of a particular transportation system (in this case, the roadway network) and is composed of weighted buffers around the system. We used a set of 10 buffers evenly spaced, which each buffer had a width of 4 km.

$$IC_x = \frac{\sum_1^n \gamma(i) * A_i}{A_x} \tag{1}$$

where:
IC_x indicator for the coverage of the roadway infrastructure for zone x;
$\gamma(i)$ function that determines the weight of each buffer, such as $\gamma(i) \in [0,1]$;
A_i area of each buffer comprised in a zone x;
A_x area of zone x;
n number of buffers.

2.2. Data

A geographic database obtained from the State Roadway Department was used for the analysis of the roadway infrastructure in São Paulo state. This database contained information about the type of road, i.e. two-lane or multi-lane roadway. For the latter, additional information about the number of existing lanes was collected from the analysis of the satellite images available in Google Earth.

Equation 1 shows the indicator for the coverage of the roadway infrastructure is obtained for a given zone *x*. Therefore, the administrative limits of the municipalities, as well as a geographic database comprising the 645 municipalities of São Paulo state were used.

2.3. Proposed Structure of the Indicator for the Coverage of the Roadway Infrastructure considering the Road Capacity

The proposed version of the indicator for the coverage of the roadway infrastructure is based on the idea of incorporating the road capacity in its structure. In this case, the road capacity is represented by the specification of the number of lanes in the roadways. In the original version, all roadways displayed the same characteristics (i.e. not taking into account the differences between two-lane and multi-lane roadways, neither the data about the number of lanes).

The new version has been determined in parts, according to the number of lanes in each roadway link. In other words, values for IC_x (Equation 1) are obtained for the links with 1 lane, 2 lanes, …,*m* lanes. At the end, a weighted average composed of the partial values of IC_x (Equation 2) is obtained.

$$IC_{CAP} = \frac{w_1 * IC_{x_1} + w_2 * IC_{x_2} + \cdots + w_m * IC_{x_m}}{w_1 + w_2 + \cdots + w_m} \tag{2}$$

where:
IC_{CAP} indicator for the coverage of the roadway infrastructure considering the road capacity;
IC_{x_m} indicator for the coverage of the roadway infrastructure for roadway links with *m* lanes, which is obtained by Equation 1;
w_m weight of each IC_{x_m};
m   number of lanes.

3. Results and Discussions

The data on the road capacity in São Paulo state indicated that, in general, the two-lane roadways have links with 1 lane (per direction) and the multi-lane roadways have links with 2 to 4 lanes (per direction). An occasional third lane for the two-lane roadways was not significant. The links with more than 4 lanes, also assumed to be insignificant, were considered links of 4 lanes.

Therefore, the indicator obtained by Equation 2 refers to the capacity of the roadways with up to 4 lanes per direction (i.e., $m = 4$). Regarding the weight of each IC_{x_m} (w_m), we adopted values 1, 2, 3 and 4 for w_1, w_2, w_3 and w_4, respectively.

Two functions were explored for parameter $\gamma(i)$, which provides the weight of each buffer in Equation 1: a linear form and a polynomial form of 5th degree.

Figure 1 shows the results for each municipality of São Paulo state regarding the indicator for the coverage of the roadway infrastructure, for a linear function and different values of road capacity. The results are represented in a box map, in which the municipalities are classified in one out of the four quadrants HH, LL, LH or HL. The map shows the boundaries of the official FURs (i.e. Piracicaba, Campinas, Sorocaba, Jundiaí, São Paulo, Baixada Santista, and Vale do Paraíba and Litoral Norte).
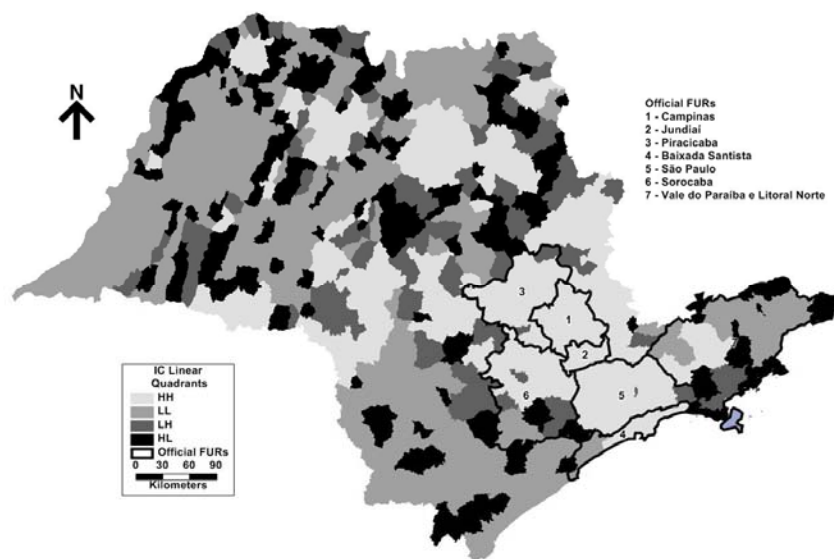
The results for each municipality of São Paulo state regarding the indicator for the coverage of the roadway infrastructure without the data on the road capacity (i.e. as if all roadways were the same) were obtained (box map in Figure 2) for the evaluation of the proposed analyses.

According to the maps in Figures 1 and 2, when the road capacity is considered, the classification of the municipalities in the quadrants is more homogeneous. For example, in Figure 1 the municipalities in quadrant HH, where the indicator has a positive value for the municipality and a positive average value for the contiguous neighbors, form a well-defined area from the East to the North of the state. The same cannot be verified in the results of Figure 2. The analyses of the remaining quadrants (i.e., LL, LH and HL) also show a similar pattern: the set of municipalities classified in these quadrants are better defined in Figure 1 than in Figure 2.

This improvement in the results can also be confirmed by the values of Moran's *I* index. When the road capacity was considered in the determination of the indicator, the index was equal to 0.87; when it was disregarded, the index was 0.39. These results show the value of the spatial autocorrelation was 2.23 higher when the road capacity was considered in the determination of the indicator for a linear function.
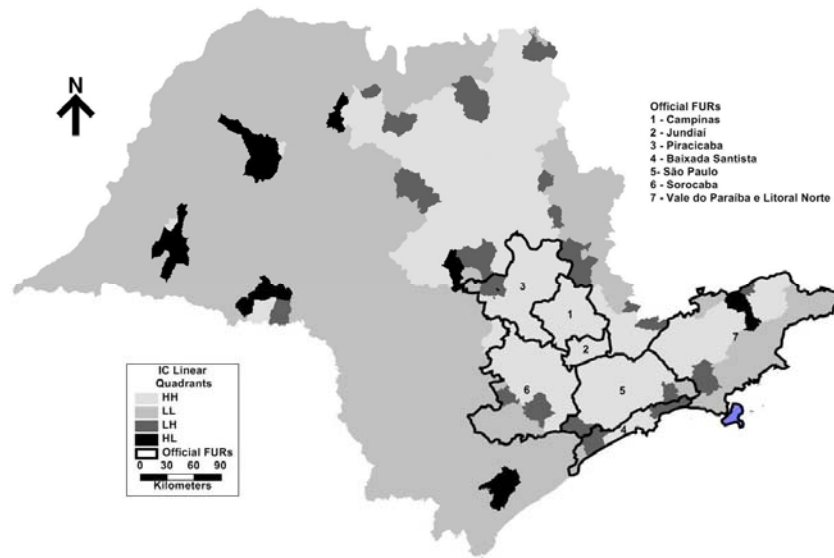
Figure 1. Box map showing the indicator for the coverage of the roadway infrastructure for a linear function (road capacity was considered)

Figure 2. Box map with the indicator for the coverage of the roadway infrastructure for a linear function (road capacity was not considered)

Regarding the results for a polynomial form of 5th degree for function $\gamma(i)$, Figure 3 shows a box map with the classification of the municipalities in the quadrants for the indicator for the coverage of the roadway infrastructure considering the road capacity. Similarly to the linear form, we obtained for the polynomial form of 5th degree the results of the indicator for each municipality without the data about the road capacity. These results are shown in the box map of Figure 4.

According to the results in Figures 3 and 4, the patterns identified for the linear form are similar to those observed for the polynomial form of 5th degree, i.e. if the road capacity is considered, the municipalities in one out of the four quadrants are more homogeneously distributed. When the road capacity is not considered, we can observe a more scattered distribution. This fact can also be confirmed by the Moran's I indexes obtained. The index was 0.73 when the road capacity was considered. If such data are not taken into account, the index is 0.37. The value of the spatial autocorrelation in the case of a polynomial function of 5th degree is almost the double when the road capacity is considered in the determination of the coverage indicator.

As the objective of this study was to analyze the influence of the roadway infrastructure capacity on metropolization, the municipalities classified in quadrants HH and LH deserve special attention. In the first case (HH), the capacity of the roadway supply of the municipalities, and their neighbors, is higher than the average observed in the state. In the second case (LH), the capacity of the roadway supply of the municipalities is lower than the average observed in the state, but these data in their neighbors is higher than the average observed in the state. In general, due to the proximity of the municipalities in quadrant LH to the municipalities in quadrant HH, those in quadrant LH may shift to the set of municipalities in quadrant HH after some time.

Figures 1 and 3 show that the municipalities classified in quadrants HH and LH are, in general, inside or around the official FURs. Although this pattern can be observed when the road capacity is not considered (Figures 2 and 4), the spatial autocorrelation verified in the outcomes is larger when such data are included. Therefore, the road capacity has a significant contribution towards identifying the relationship between the transportation infrastructure supply and metropolization.
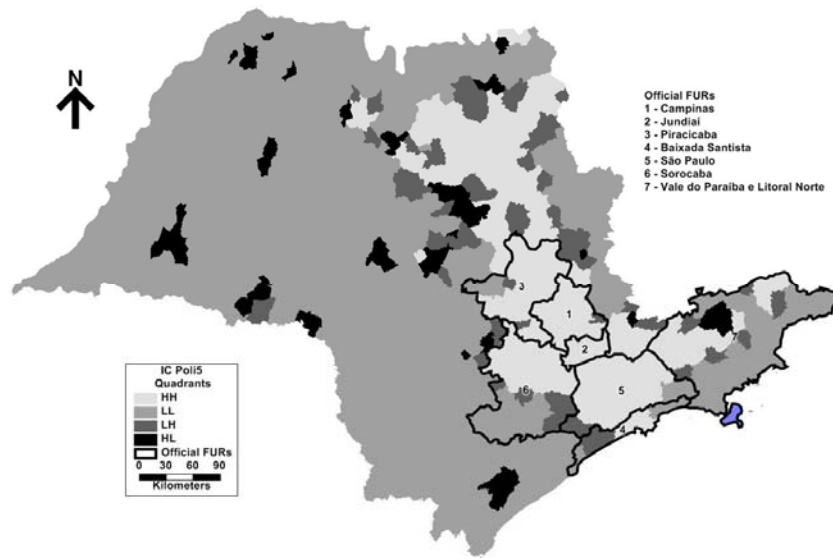
Figure 3. Box map showing the indicator for the coverage of the road-way infrastructure for a polynomial function of 5thdegree (road capacity was considered)
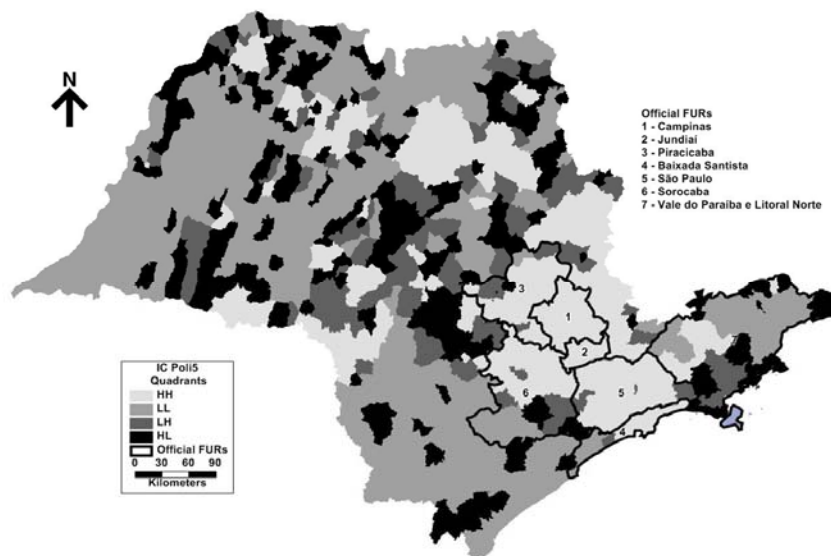
Figure 4. Box map showing the indicator for the coverage of the road-way infrastructure for a polynomial function of 5thdegree (road capacity was not considered)

Table 1 provides an additional evaluation of the analyses conducted that can strengthen the discussions. This table shows the percentage of municipalities in quadrants HH or LH that correspond to the official FURs, according to the results for both linear and polynomial of 5th degree functions, considering or not the road capacity in the determination of the indicator. In general, such a percentage either increases or is preserved when the road capacity is considered for both linear and polynomial functions. There are few exceptions, as the case of the FUR of Piracicaba for the linear function and the FURs of Baixada Santista, São Paulo and Sorocaba for the polynomial function. However, in the analysis of the totals (Table 1), the percentages increase for both linear and polynomial functions when the road capacity is considered in the determination of the indicator. The related increase is very significant for the linear function (i.e. from 77% to 84%).

Table 1. Percentage of municipalities in quadrants HH[1] or LH[1] per official FUR[2]

Official FUR	IC linear		IC polynomial of 5th degree	
	Road capacity not considered	Road capacity considered	Road capacity not considered	Road capacity considered
1 - Campinas	100	100	100	100
2 - Jundiaí	100	100	100	100
3 - Piracicaba	95	91	82	86
4 - Baixada Santista	78	89	78	67
5 - São Paulo	97	97	97	95
6 - Sorocaba	85	85	85	73
7 - V. do Paraíba and L. Norte	26	54	28	41
TOTAL	77	84	76	77

[1] *Quadrants HH and LH refer to "High-High" and "Low-High", respectively, as defined in the methodology section.*
[2] *FUR regards "Functional Urban Region".*

4. Conclusions and Suggestions

The objective of this study was to evaluate the influence of the roadway infrastructure capacity on metropolization. Data about the number of lanes in the roadways of São Paulo state were collected for the determination of a new version of a roadway infrastructure supply indicator that considers road capacity. The use of the ESDA technique enabled the identification of more homogeneous patterns regarding the classification of the municipalities in one out of the four quadrants HH, LL, LH and HL when the road capacity is considered to the determination of the indicator.

Among the forms explored for function $\gamma(i)$, the linear form yielded the best results. This could be verified by the value of the spatial autocorrelation given by Moran's I index, which was substantially higher when the road capacity was considered. Moreover, the identification of the municipalities classified in the quadrants of interest (i.e. HH and LH) that were inside the official FURs was also more evident when the road capacity was taken into account. For the polynomial function of 5th degree, the patterns observed were similar to the ones discussed for the linear function, i.e. the indicator improved when the road capacity was considered. However, in the comparison of both functions, the polynomial form yielded lower results not only for Moran's I index, but also for the percentage of municipalities classified in the quadrants of interest that were inside the official FURs.

Our results suggest when the road capacity is considered in the determination of the indicator for the coverage of the roadway infrastructure the identification of the relationships between the transportation infrastructure supply and metropolization substantially improves. In other words, an intense interaction among municipalities within a region, especially with a metropolitan dynamic, is strongly dependent on the quality of the available infrastructure.

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