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Accessibility analysis as an urban planning tool: Gas station location.

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Abstract

We apply geo-statistical techniques to find relationships between the geographic location of urban "Gas Stations" (GS) and operational features offered by the transport network in Manizales (Colombia). This research is built upon primary information collected during a period longer than one year using GPS (more than 18 million data points). The methodology consists of i) The set-up of the entire urban transport infrastructure network, ii) The calculation of the average operating speeds in the links, iii) The calculation of the global average accessibility offered by the infrastructure network in different transport modes, iv) The calculation of the Spatial Coverage Index, area, population and number of houses covered by the curves of travel time. Graphical results explain the average times invested in reaching a particular GS, and quantitative comparisons between different types of stations are studied. Thus, we establish which sectors of the city are deficient in coverage of this type of activity. The overall results reveal the possibility of reaching a GS in Manizales in an average travel time between 4 and 22 min.

JEL Classification: R32, R41

Keywords: Gas Stations, Accessibility, GPS, coverage, urban mobility, operating speeds, Geostatistics.

Résumé

Nous appliquons des techniques de géostatistique pour trouver des relations entre la localisation géographique des "Stations-service" urbaines et des caractéristiques opérationnelles offertes par le réseau de transports à Manizales (Colombie). Cette recherche est fondée sur des informations originales recueillies pendant une période supérieure à un an, en utilisant le GPS (plus de 18 millions de points de données). La méthodologie consiste en: i) La mise en place de l'ensemble du réseau d'infrastructures de transport urbain, ii) Le calcul des vitesses moyennes dans les liens, iii) Le calcul de l'accessibilité moyenne totale, offerte par le réseau d'infrastructures dans les différents modes de transport, iv) Le calcul de l'Index de Couverture Spatiale, de l'aire totale, de la population, et du nombre de maisons couvertes par les courbes de temps de déplacement. Les résultats graphiques expliquent les délais moyens pour arriver à une station-service particulière, et des comparaisons quantitatives entre les différents types de stations sont étudiées. Ainsi, en établissant quels secteurs de la ville sont déficients en couverture de ce type d'activité. Les résultats complets montrent la possibilité de parvenir à une station service à Manizales, dans un temps de trajet moyen entre 4 et 22 min.

Mots-clé: Stations-service, accessibilité, GPS, couverture, mobilité urbaine, géostatistique.

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1. Introduction

The city of Manizales is located in the centre-west region of Colombia, at 5.4º latitude north and 75.3º longitude west), along the prolongation of the Andean Mountain Range, at 2150 metres above sea level. This research provides an accessibility analysis relating geo-spatial locations for Gas Stations (GS) and the operative characteristics of the road network, with a view to calculating the geo-spatial coverage index of each activity node. To process the data, we used TransCAD® and Surfer® software. Accessibility as a tool has been used infrequently in Colombia, yet its importance is such that it must be understood as an unperceived secondary necessity (Halden, 2011); not an end in itself but rather a medium to achieve essential civic aspects (health services, education, the job market, etc.). In general, accessibility can be considered a crucial competitiveness factor for different regions (Biehl, 1991), thus, those populations that exhibit higher levels of accessibility should over time have accounted for a greater economic success. This close relationship between accessibility and competitiveness means that the improvement of transport infrastructure becomes an essential component of economic development (Holl, 2007). Nowadays, gas can be considered a primary necessity for many people and so must be guaranteed as accessible and attainable. Crucial transport policies in a variety of countries aim at reducing inequality by – among others – guaranteeing greater access to primary necessity goods and services (Jones, 2011). Moreover, we are aware of the fact that ordinary tools for evaluating transport projects often do not reliably measure their contribution to the accessibility levels (to services and opportunities), and in turn to the social implications of this (Bocarejo and Oviedo, 2012). As such, we intend to contribute with evidence on using accessibility analysis as an urban planning tool. The structure of this paper is as follows: section 2 presents a brief literature review; section 3 explains the methods used for calculating the geospatial coverage indices, and overall accessibility. In this section we also describe the construction of the database used; in section 4 we explain the results in detail; followed by the main conclusions in section 5.

2. Literature Review

Accessibility has increasingly become a focus point in territorial planning studies, for both urban and regional transport, during the last 50 years. This approach was initially introduced in the 1920s, in the context of regional economic planning and area location theories (Batty, 2009). Accessibility has been often defined in different ways, and for different academic purposes. For instance, in the transport field, as a measure of the ease in connecting human settlements and activities using a certain mode of transport (Morris et al., 1978), (Zhu and Liu, 2004); however, we are aware of several other accepted definitions for this concept (Pirie, 1979; Jones, 1981; Martellano et al., 1995), with Hansen's (1959, 73) definition being the classic one: "… *the potential of opportunities for interaction*". Accessibility analysis for a territory can be advanced using graph theory (Petrus and Segui, 1991). This implies the application of a morphometric analysis of networks (explanatory assessment) to understand, via partial databases, which is the aspect of the complete network structure; we can thus identify those zones that are characterized by minor accessibility possibilities in relation to the location of one or many particular activity nodes. These types of accessibility analyses are increasingly becoming more important in the evaluation of infrastructure plans and projects (Gutierrez et al., 2010), often implying that the improvement in accessibility levels, is one of the key criteria frequently used in these evaluations. There are various approaches to use accesibility analyses as evaluation tools. Often born out of the conceptual frameworks of urban and regional planing, these approaches aim at a variety of criteria, related with spatial distribution of economic activities (Krugman, 1991; Fujita et al., 1999), economic development (Rietveld and Nijkamp, 1993; Vickerman et al., 1999; MacKinnon et al., 2008), land appreciation and urban density (Alonso, 1964; Kotavaara et al., 2011), sustainability (Cheng et al., 2007; Vega, 2011; Escobar et al., 2013), operativity in modes of transport (Geurs K. & Van Wee B., 2004), social cohesion (Schürman et al., 1999; López et al., 2008), marketing (Geurs K. & Ritsema Van Eck, 2001), tourism (Kastenholz et al., 2012), social networks (Sailer et al., 2012), etc.

Powerful informatics tools have been developed during the last decades to generate spatial analyses, by studying the relationship between geographical databases (Zhu X. & Liu S., 2004). These tools have positively impacted the analytical capabilities of researchers, allowing for the integration of activity node geographical data with other data regarding transport infrastructure, demographics, socioeconomic and geospatial characteristics, etc. In this research we used Geographic Information Systems (GIS) to collect data from various activity nodes identified as gas stations throughout the urban areas of the city of Manizales. When linking these to specific operational characteristics of the transport infrastructure network, and additional socio-demographic data, we were able to integrally analyse the spatial coverage indices, and thus, generate more accurate values in relation to the actual coverage that the transport infrastructure offers to the local community, in terms of the geographical location of gas stations, and specific structural variables such as area, population and housing units. Using the geospatial visualization capabilities of the GIS, we produced geographical distribution maps of gas stations. These maps allowed us to perform the geospatial coverage index analyses, as proposed by the current literature. Some examples of geospatial coverage analyses, also performed using various informatics developments include the areas of: location and service provision studies (Calcuttawala, 2006; Higgs et al., 2012; Park , 2012), natural resources and agriculture (Gellrich, M. & Zimmermann N., 2007; Tassinari et al., 2008; Arcidiacono, 2010); urban and demographic growth (Huiping, L. & Qiming, Z., 2010); regional studies (Straatemeier, 2008); health (Hernández et al., 2002); amongst others. We have developed a number of interrelated stages in this research. First, we optimized the data pertaining to the full transport infrastructure network, hence going through data collection phases, and an update of the georeferenced network. Secondly, we relate the calculations for the average arc operational speeds. Thirdly, we calculate the Average Overall Accessibility offered by the infrastructure network in the various transport modes analysed; and finally, we calculate percentages for area, population, and housing units which are covered by the average travel time curves obtained through the accessibility analysis, and their relationship with the geospatial location of the gas stations.

3. Methodology

Our methodological approach is composed by five key steps.

3.1. Data collection

A detailed fieldwork was advanced to identify all gas stations located within the urban areas of the city of Manizales, dividing them according to the gas type these distribute, and verifying the correctness of their geospatial location using GPS tracking devices. The data collection took place during a twelve-month period between 2010 and 2011. The GPS tracking devices were activated during normal business hours.

3.2. Update of the georeferenced network

We analysed the current road network, as provided by the municipal administration, and complemented the supplied data with the fieldwork done using the GPS devices. This allowed us to correct and validate the geographical information supplied. The city of Manizales exhibits a network composed by more than 12000 arcs and approximately 9000 nodes.

3.3. Calculating operational speeds and instantaneous speed

GPS tracking devices were installed in different vehicle types (private car, motorcycle, taxi, truck, and public transport buses). We were thus able to record satellite positioning data along a predetermined time interval (every one second). Using this approach, we are able to calculate the average operation speed for each of the arcs that compose the system. Operational speeds were calculated based on the actual direct monitoring data, and reflect the true operational characteristics (including slopes, jam, etc.) of the arcs that compose the network. This is an extraordinary contribution, as accessibility analyses are often performed using assumed operational speeds, depending on the road category (Burns & Inglis, 2007); Nonetheless, other recent accessibility studies also use real vehicle speeds (Li et al., 2011). In order to process the collected data we applied a variety of algorithms. First, to calculate the operational speed for each time interval between two points, we used Equation (1). This parameter is useful when establishing speed variations in a particular arc, and to determine the number of stops.

$$v_i = \frac{3.6}{t}\sqrt{(y_2 - y_1)^2 + (x_2 - x_1)^2} \qquad (1)$$

Where: v_i = Speed in km/h; x_1, y_1 = Coordinates for point 1 in metres; x_2, y_2 = Coordinates for point 2 in metres; t = Time interval in seconds between data points.

Secondly, to calculate the average operational speed of a trip for a given *nth* arc, we used Equation (2). This speed was obtained by examining the relation between arc length and the difference in passing times for the starting and ending node.

$$v_i^a = 3.6\frac{l_a}{t_2 - t_1} \qquad (2)$$

Where: v_i^a = Speed *i* in an arc *a* (km/h); l_a = Longitude of the arc *a* in metres; t_1 = Passing time in beginning node; t_2 = Passing time in ending node.

Finally, to calculate the average speed within an arc, for a given time period, we used Equation (3). We calculate this speed to establish network impedances, and used it as an input to develop the average time travel prediction model.

$$\overline{v_a} = \frac{\sum_{i=1}^{n} v_i^a}{n} \qquad (3)$$

Where: $\overline{v_a}$ = Average operational speed within arc *a*; n = Number of registered speed data points within arc *a*, during a given time period.

3.4. Calculating Overall Average Accessibility

For this, we base our calculations on the average trip time vector (*Tvi*), which represents the average travel time from node *i* to all other nodes in the network. It is widely known that this indicator tends to favour those nodes located towards the centre of the network, since travel times from those nodes to all others are shorter, due precisely to their geographical location. To obtain *Tvi*, we first calculate the uni-modal distance matrix. Then, after compiling average operational speeds for each arc, we generate a minimum average travel times matrix, in order to minimize average travel times between all nodes in the network. Then, the average trip time vector (*nx1*) is related to the specific geographical coordinates (lat. and long.) for each node. This becomes the ordering matrix (*nx3*), with which we are able to generate isochronous curves for average travel times. We used this approach to analyse four gas station contexts: Context 1, considers all gas stations, without regard for the type of fuel; Context 2, considers only those gas stations distributing ordinary gasoline and Diesel fuel; Context 3, considers only those gas stations distributing premium gasoline; and, Context 4, considers only those gas stations distributing natural gas for vehicular use.

3.5. Calculating the spatial coverage index

The urban area of the city of Manizales comprises 35.1 Km^2, and its population for 2010, totalled 361.422 inhabitants. The number of housing units accounted for in this area corresponds to 83.868 units, which are distributed throughout 115 neighbourhoods. These data were correlated, via the use of GIS, with the average time travel curves, obtained for the aforementioned contexts. The Spatial Coverage Index – SCI, is defined by Equation (4), and is developed through equations (5) and (6):

$$SCI =_{V_x} \left[Accessibility\right]_{C_k}^{G_t} \quad (4);$$

Where; C_k =Percentage coverage of K; K= 1, 2, …, 31 Gas stations; G_t =5, 10, …, 50 isochrones curve; V_x = population, area and housing.

As variables of area, population and number of housing units are accounted for in this index, these will represent a greater impact, as each average time travel curve refers greater coverage. The coverage index varies from 0 to 1; being 1 the greatest spatial coverage. Hence, we were able to estimate the percentages of area, population and number of housing units covered by a particular isochronous curve, which ultimately defines the coverage values for each average time travel curve.

$$C_{k,v} = \left(\%V_x \middle| V_x \in C_t \right) \quad (5);$$

Where; $C_{k,v}$ = Percentage of coverage for each Gas Station and for each analysed variable, given an score from cero to one; cero for min. C_v and one for max. C_v

$$SCI = \Sigma \frac{1}{2^n} * \Sigma P_v * \frac{C_v - \min(C_v)}{\max(C_v) - \min(C_v)} \qquad (6);$$

Where; n = number of isochrones curves; P_v =weight for each analysed variable (population 40%, housing 40% and area 20%).

4. Main results

There are a total of 31 gas stations in the city. The specific results from each of the studied contexts allow us to illustrate the overall relationship between the gas station locations and the operative characteristics of the road network.

4.1. Context 1: Gas Stations without regard for the type of fuel

Initially, we analysed the geospatial location of all gas stations, without focusing on the types of fuel these distribute. The area reporting the greatest accessibility refers an average travel time of 4 minutes (see Figure 1a), thus extending around an ample central sector of the city, and expanding to each side of the main arteries. When analysing the total urban area, we find that in order to reach a gas station it is necessary to invest between 4 and 22 minutes of average travel time, approximately. Figure 1b shows the accumulated percentage of area, population and housing units that is covered by the isochronous curves, where we can perceive similar behaviours from these three key variables. The coverage analyses as referred to the time curves provide us with a better diagnostic on the geospatial location of the gas stations, for the area and housing units variables; the 6 minute curve being the one showcasing a major coverage percentage in this case. For the population variable, however, we find that the 10 minute curve covers the greatest number of people.

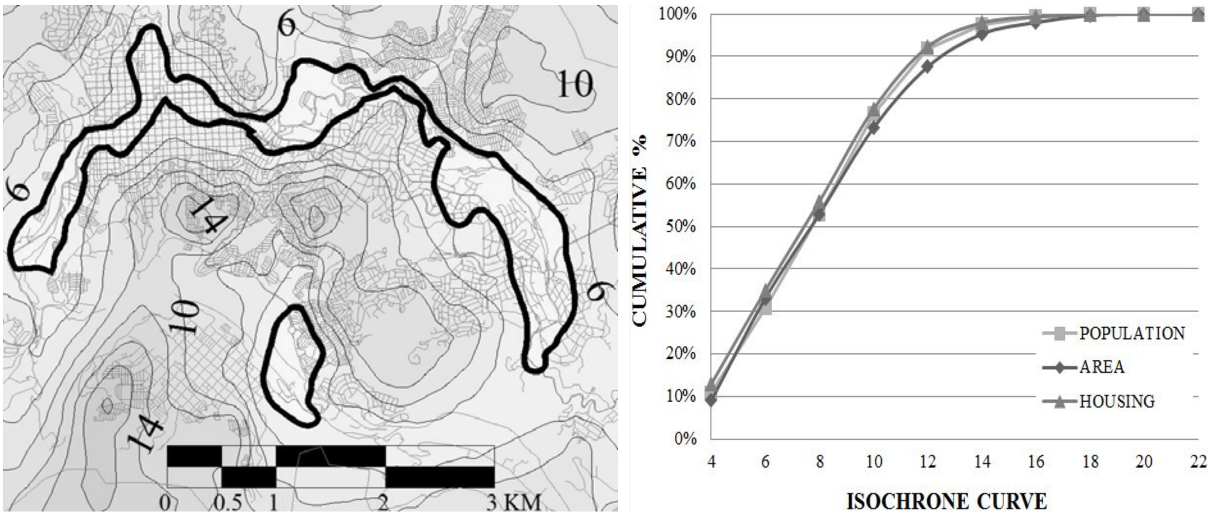

Fig. 1. (a) Isochrone curve; context 1. (b) Cumulative percentage vs. average travel time, isochronous curve; context 1. Source: authors' elaboration.

We can conclude that 50% of the total population can reach a gas station if 7.7 minutes of average travel time are invested; this number decreases to 7.4 minutes when analysing only housing units. We can conclude that 50% of the total population can reach a gas station if 7.7 minutes of average travel time are invested; this number decreases to 7.4 minutes when focusing only on housing units. The north-west, north-east, and south sectors of the city show the greatest coverage times, which ultimately means these are the areas from which it is hardest to access a gas station.

4.2. Context 2. Gas Stations distributing ordinary fuel and Diesel.

Out of the 31 gas stations, 30 of these distribute ordinary gas and 29 distribute Diesel. Our results do not exhibit major differences from those previously obtained in context 1. However, we can observe that the west and south sectors of the city reveal the most deficient coverage times.

4.3. Context 3 Gas Stations distributing premium fuel.

58% (18) of the gas stations in the city distribute premium fuel. The shortest average travel time that must be invested in order to reach a gas station of this type is 4 minutes (see Figure 2a). Within this context, we find that the city is covered by curves corresponding to average travel times between 4 and 34 minutes (see Figure 2b); the 10 minute curve is the one referring a greater percentage for the three variables (area, population, housing units).

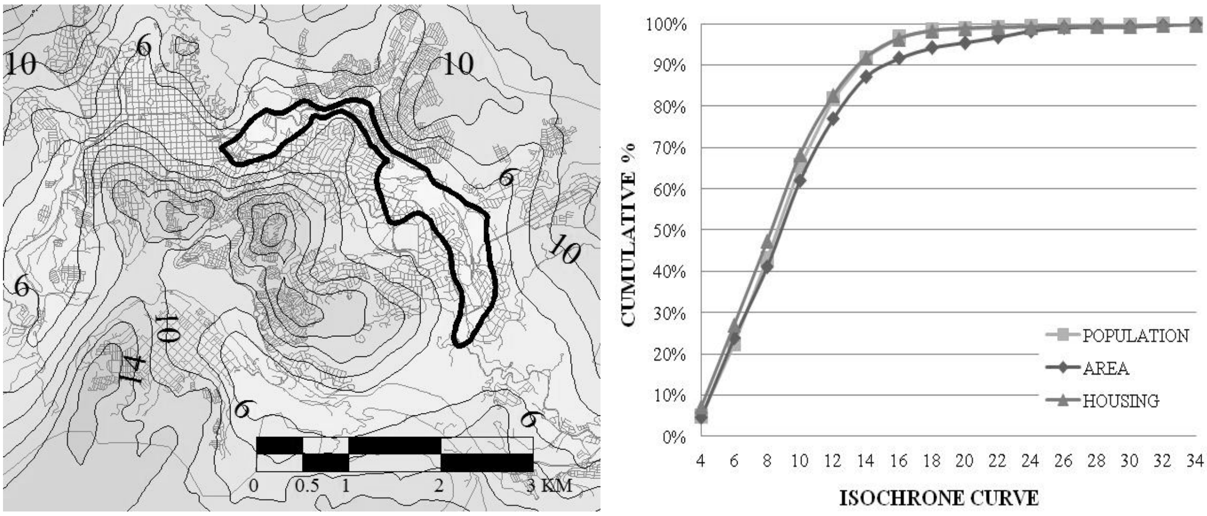

Fig. 2. (a) Isochrone curve; context 3; (b) Cumulative percentage vs. average travel time, isochronous curve; context 3.
Source: Authors' elaboration.

When comparing the results form contexts 1 and 3, and focusing on the population variable, we observe that within context 1, 100% of it is covered by an average travel time of 18 minutes, while for context 3, only 985 of the population is covered by the same time curve; thus representing a difference of 7950 inhabitants. Furthermore, for the 4 minute curve, context 3 refers a greater coverage difference, with respect to context 1, this time represented in 23150 inhabitants. We can conclude that 50% of the total population can reach a gas station if 8.6 minutes of average travel time are invested; this number decreases to 8.3 minutes when focusing only on housing units. These findings indicate that it is necessary to make greater time investments to find a gas station that distributes premium fuel, as compared to context 1. The central and western sectors of the city showcase the greater operative limitations to reach a premium fuel gas station, which is not the case for the eastern sectors of the city. It is appropriate to mention here, that it is this eastern sector of the city, which hosts a vast percentage of high socioeconomic strata lands.

4.4. Context 4 Gas Stations distributing Natural Gas for Vehicular Use (CNG).

39% (12) of the gas stations in the city distribute CNG. The shortest average travel time curve corresponds to 4 minutes, extending over the main corridor between the eastern sector of the city and the CBD. In this specific context, the city is covered by average travel time curves between 4 and 40 minutes. Hence, in order to reach a gas station distributing CNG, the maximum travel time corresponds to approximately 40 minutes. The 8 minute curve showcases the greatest coverage percentage for the population and housing units variables. Similarly, we find that 90% of the population can reach a CNG distributing gas station investing a maximum average travel time of 16 minutes. When comparing the obtained results with the previously analysed contexts, and focusing on the population variable, we observe that while 100% of the population (in contexts 1 and 2) is covered with 18 minutes of average travel time, for context 3, this same time curve only covers 98% of the population. Moreover, for context 4, we find that this number only corresponds to 93%. For this fourth scenario we find that 50% of the population can reach a CNG gas station if 8.9 minutes of average travel time are invested; a number which decreases to 8.6 minutes when focusing only on housing units. This provides clear indication that it is necessary to invest greater travel times to reach a CNG gas station than one distributing ordinary or premium fuel. Likewise, we highlight the fact that most of the CNG gas stations are located along the main east-west corridor (and vice versa), denoting a significant deficit of CNG gas stations along the north-south corridor.

4.5. Spatial Coverage Indices (SCI)

To calculate the spatial coverage indices for each gas station, we took the coverage percentages obtained in Context 1, for the three key variables (area, population, housing units). Applying the previously described methodology, we found a variation for the SCI ranging from 0.06 to 0.85. Figure 3 describes the spatial location of all gas stations analyzed in this research, graphically distinguishing between those obtaining a high SCI (SCI> 0.75; rhombi), and those with a low SCI (SCI < 0.1; stars).

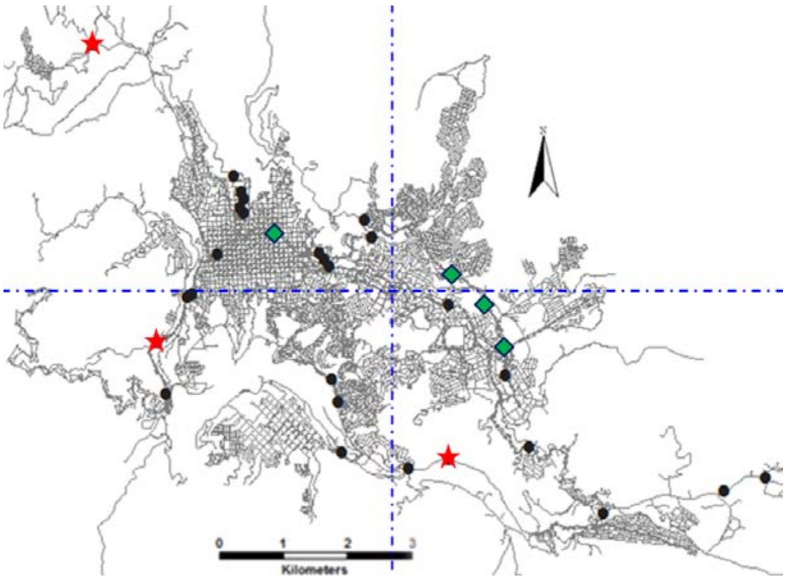

Fig. 3. Spatial location of all gas stations. High SCI (rhombi); low SCI (stars). Source: Authors' elaboration.

Overall, both high SCI and low SCI gas stations are located across the main vehicular corridor of the city. However, we find that four of these showcase a very high SCI, while three of these exhibit a very low SCI. By dividing the city in quadrants, we are able to highlight the following key points:

- The quadrants with the greater number of gas stations correspond to the northwest and south east quadrants, with a total of 13 and 10 gas stations, respectively.
- The northeastern quadrant showcases only one gas stations; nevertheless, this precise one reports a significantly high SCI of 0.76.
- Out of all gas stations, only 35% (11) of these report an SCI higher to 0.5, out of which seven are located within the northwestern quadrant; hence, 54% of the gas stations located within this quadrant have an SCI greater to 0.5.
- Through a cumulative distribution function, we find that 50% of the gas stations in the city, showcase SCI values lower tan 0.35, which is considered to be a low value in this case.
- All gas stations located in the southeastern quadrant report SCI values lower tan 0.29.
- When calculating an average SCI for each quadrant, we obtain the following order: northeast (0.76), northwest (0.48), southeast (0.41) and southwest (0.17). If we ponder these values by the number of gas

stations, the values would otherwise be: northwest (0.2), southeast (0.13), southwest (0.04) and northeast (0.02).

5. Conclusions

It is possible to reach a gas station in the city of Manizales within an average travel time of between 4 and 22 minutes. The worst scenario is found for CNG stations, as reaching one implies an average time investment of between 4 and 40 minutes. The importance of the location patterns of activity nodes has been recognized as one of the crucial factors influencing local and regional economic development. This is applicable both to urban and regional levels.

Through analysing Spatial Coverage Indices, we can conclude that there are two specific sectors of the city where it is feasible to locate a new gas station; namely the southwestern and northeastern sector. We also conclude that those gas stations reporting greater coverage levels, thus implying a better relationship between their geospatial location and the operative characteristics of the city's road network, are located in the central and eastern sectors.

From a social perspective, we know that a greater accessibility in transport contributes to greater social inclusion, as it allows for greater access to the typical activities of society (Farrington and Farrington, 2005). Therefore, activity nodes must be adequately distributed within a territory in order to maximize accessibility. In this respect, we observe that the northwestern sector exhibits sub-sectors with a highly biased vocation towards gas distribution. Although this can be explained due to the specific economic activities performed in this zone, it does not represent a distribution aiming to supply a service provision need.

We further observe that those gas stations reporting a lower SCI are located along heavy traffic corridors, providing an entrance or exit to the city. Hence, it is crucial that future research on this topic considers the inclusion of additional variables such as daily average traffic flows for those roads reaching gas stations, as well as the stock of private cars in the city. Both of these variables, for instance, could provide a greater range to examine the optimal locations for such activity nodes.

We propose that future contributions in this arena consider being complemented with visual tools that clearly represent the effects of accessibility changes. This would allow a better understanding – from the perspective of mobility planning – of the sectors towards which a greater impact in terms of social coverage is expected.

Analyses such as this are useful to complement urban planning activities in general, and permit issuance for urban infrastructure interventions, in particular. Likewise, we propose the construction of an intervention plan or activity node expansion, based on the application of the SCI hereby described. Such an activity (and considering the recent trends in sustainable energy for transport) would probably demonstrate a need for a systematic definition of the best locations, for stations providing vehicular electric charging. In such a case, this research could be replicated and applied. This research was presented to Public Authorities.

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