Accessibility in commuting systems Network based performance indicators

Andrea De Montis(1)*, Simone Caschili(2), Michele Campagna(2), Alessandro Chessa(3)(4), Giancarlo Deplano(2)

Prepared for NECTAR Meeting
The Future of Accessibility
27-28 June 2008, Las Palmas, Spain

(1)Dipartimento di Ingegneria del Territorio, Sezione Costruzioni e Infrastrutture, Università degli Studi di Sassari, via De Nicola, Sassari, 07100 - Italy

(2)Dipartimento di Ingegneria del Territorio, Università degli Studi di Cagliari, Piazza d'Armi 16, Cagliari 09123 – Italy

(3)Dipartimento di Fisica, INFM, Università degli Studi di Cagliari, Complesso Universitario di Monserrato, Monserrato 09042 - Italy

(4)Linkalab, Center for the Study of Complex Networks, Sardegna - Italy

Abstract

The aim of this paper is to contribute to the discussion on accessibility by adopting complex network analysis as a base for constructing accessibility indicators. In this case, a contribution is offered to the construction of two groups of indicators: travel cost and gravity based indexes. A case study is proposed on the level of accessibility of towns for commuters in the island of Sardinia, Italy.

Keywords: accessibility indicators, travel cost approach, commuting, complex networks

*Corresponding author. E-mail address: andreadm@uniss.it

1 Introduction

In a number of research studies, accessibility is regarded as a complex concept and is defined in a variety of ways. It is a multifaceted characteristic and implies a multidisciplinary approach. In a general perspective for infrastructure planning, the accessibility for a city depends on the nature of the movements people adopt to reach it. Accessibility is a broad and flexible concept while it can be perceived as confusing and complex; Gould (1969) has described accessibility as a 'slippery' concept, which often becomes clear in front of the need to define performance indicators. The studies on accessibility describe integrated systems on the user viewpoint rather than transport modes or service provision. A study by DHC and Transport Studies Group at the University of Westminster (2003) identified several different ways in which accessibility has been used for planning purposes ranging from distribution of transport impacts and new developments to access to opportunities and business travel planning. One of the lessons drawn from this study is that accessibility may become the permanent element of a planning methodology if a clear definition is given about how to define people and places, how to represent transport and communications, at what level of spatial/geographical detail this should be done, and the ways in which current accessibility performance should be expressed.

Regarding the appraisal of the level of accessibility, in a recent review (Baradaran and Ramjerdi, 2001), the performance of many accessibility indicators adopted for European systems is assessed. In this study the indicators are clustered according to their methodological principles in five approaches: travel cost, gravity or opportunity model, constraint-based, utility-based surplus, and composite approach.

Recently, the availability of even larger data sets and the parallel explosion of computer processing power has made the systematic and intensive application of complex network analysis (CNA) to the study of very large networks possible. According to this approach, large systems are characterized by a statistical analysis of their simple elements (the nodes or vertices) and of their relations (the edges or link between the nodes pair wise). A series of measures are calculated to describe the behaviour of complex networks, such as the degree -the level of connectivity of a node- and the clustering coefficient -the level of local connectedness. Beyond the simulations, CNA has been applied to a number of real phenomena, providing with insights into a wide range of questions regarding food webs, human interactions, the Internet, the world wide web, the spread of diseases, population genetics, genomics and proteomics. For a review of these applications, see Albert and Barabási (2002) and Newman (2003).

Also in many fields grouped under the realm of regional science, a number of scholars have begun applying the paradigm of complex network analysis for modeling urban, regional and socio-economic systems (Barrat et al., 2004; Schintler et al, 2005; Reggiani et al., 2008). A number of applications refers to the study of infrastructures and of commuters' complex behaviour (Strano et al, 2007; Porta et al, in press). These works are often developed on the assumption that the emergence of scale free properties is a signature of efficiency in the system general behaviour. Examples are the hub-and-spoke structure invoked for transportation systems and, in particular, for airline networks (O'Kelly, 1998). In the field of the analysis of commuters' behaviour, a weighted network analysis has been applied to the system of inter-municipal habitual movements of the inhabitants of the Italian region of Sardinia, the second largest island of the Mediterranean See (De Montis et al, 2007). Thus CNA has provided an interesting perspective for the characterization of infrastructure and transportation systems.

The aim of this paper is to contribute to the discussion on accessibility by proposing CNA as part of a new methodology for constructing accessibility indicators. In this case, a combined approach is proposed, by integrating CNA with two groups of accessibility indicators: travel cost-based and gravity model-based. The indicators proposed are assessed on the measurement of the level of accessibility to the towns for the commuters of the island of Sardinia, Italy. As in Sardinia inter urban commuters move mostly through the road system, it is possible to analyse their movements by inspecting a network, where the nodes stand for municipal towns and shortest road connections for edges.

The argument is reported as follows. In section 2, an application of CNA to the study of commuting on the road network of Sardinia is described. This study provides with relevant variables that are adopted as input terms for developing inter-urban commuters' accessibility indicators, whose methodological principles are described in section 3. In section 4, the results are presented and a preliminary interpretation is given on the concept of accessibility for commuters in Sardinia. Section 5 concludes this paper with some synthetic remarks which may suggest further research work.

2 CNA and commuting: describing spatial networks

In a study inspired by the analyses developed by De Montis et al. (2007), Campagna et al (2007) investigate on the influence of geography on commuting by analyzing the spatial properties of the road network, the favorite infrastructure for commuters in Sardinia, Italy. In this study, Sardinia is regarded as a closed domain and its inter-municipal commuting system is represented as a weighted complex network. As the topological analysis is concerned, this network displays vertices corresponding to the Sardinian municipalities in 2001, and edges corresponding to a positive commuting relationship among them pair wise. The data source adopted consists of the origin-destination table (ODT) issued by the Italian National Institute of Statistics (Istat, 2001a). The ODT is constructed on the output of a survey about commuting behaviours of Sardinian citizens. This survey refers to the daily movement from the habitual residence (the origin) to the most frequent place for work or study (destination): data comprise both the means used and the time usually spent for displacement. Hence, ODT

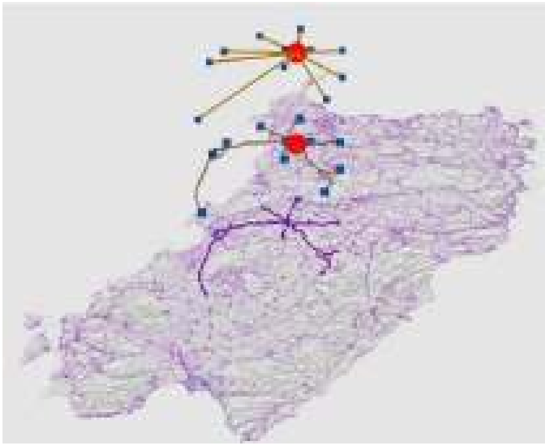

Figure 1: 3D visualisation of Sardinia. On the background the roadways used by the commuters of the town of Sodde highlighted, while the Euclidean distance is drawn on the top and the shortest road distance is floating in the middle (Campagna et al., 2007)

data provides the analysts with information about the flows of commuters who regularly move among the Sardinian municipalities.
In order to inspect the influence of the space, Campagna et al (2007) consider two spatial networks that are isomorphic to the commuting network above, as they display the same topology, i.e. the number of nodes and edges. By contrast, they are different, when regarded as weighted networks, since they show two diverse attributes (the weights of the network) attached to the edges: the Euclidean distance between each pair of nodes (towns), and the length of the shortest road path between them.

As a general result, this study uncovers strong connections between the traffic properties of the system (commuters flows) and the geographical properties. As a special result, Campagna et al (2007) verify that the two spatial networks above display very similar statistical properties and show that Sardinian commuters' flows are similarly correlated to both Euclidean distances and shortest road path distances between pairs of towns.
As far as this paper is concerned, the set of length values of the shortest road path between each pair of towns is assumed as input variable for modeling accessibility, as presented in the next section.

3 Integrating accessibility indicators with CNA: travel cost and gravity model approaches

In this paper, accessibility is in general referred to as the capacity of a given town to be attractive with respect to other towns. In this particular case, the

authors are interested to accessibility for commuters traveling daily mostly in a spatial infrastructure -the road system- described as a network.
While in the literature it is possible to find a number of methodologies to set accessibility indicators (Baradaran and Ramjerdi, 2001), in this paper, the authors aim to measure commuters' accessibility of each municipal town of Sardinia according to two approaches based on the travel-cost-model and a gravity model. According to the first approach, accessibility is measured by taking into account a proxy of the generalised transport cost commuters face to access their habitual place of work or study. In this case, the length of the shortest road path is assumed as relevant proxy. For each municipalities of Sardinia the travel cost model based accessibility obeys to equation (1).

$$A_{TC}(i) = \sum_{j \in \mathcal{V}(i)} \frac{1}{d_{ij}} \tag{1}$$

Where V(i) indicates the set of first neighbours of the municipality i and d_{ij} the shortest road distance between the municipality i and its first neighbour j. According to the second approach, the authors refer accessibility to the behavioural aspects of travel, as in a gravity model the number of trips between each pair of "agents" is estimated invoking the concept of potential of opportunities and friction to the movement caused by physical distance. Thus gravity model based accessibility is assessed starting from equation 2.

$$S_{ij} = K \frac{P_i P_j}{(d_{ij})^{\beta}} \tag{2}$$

where S_{ij} stands for the number of commuters between town i and j, K for the gravitational constant, P_i and P_j for the number of commuters living in town i and j, d_{ij} for the shortest road distance between towns i and j, and β for the impedance to movement, i.e. an empirical constant representing the inhibiting effect of distance. After calibrating the last equation, it is possible to calculate the accessibility according to equation 3.

$$A_G(i) = K \sum_{j \in \mathcal{V}(i)} \frac{P_j}{(d_{ij})^{\beta}} \tag{3}$$

This is the traditional measure of population potential defined originally for geographical systems by Stewart and Warntz (1958) and central to the definition of competition in spatial interaction models (Jiang et al, 1999).

4 Results and preliminary remarks

In the case of the accessibility based on the travel-cost model (A_{TC}), input data on shortest road path length are known, as they have been calculated by Campagna et al (2007). This has enabled the authors to assess through equation (1) the vector of accessibility values corresponding to each town.
In the case of the accessibility based on the gravity model (A_G), a process of

	Value	t-stat	R^2
LnK	8.49	2.37	0.48
β	1.61	86.55	0.48

Table 1: Gravity model: statistics of the estimation

	A_{TC}	A_G
1	Quartucciu	Arzana
2	Elini	Elini
3	Selegas	Oristano
4	Quartu Sant'Elena	Cagliari
5	Settimo San Pietro	Ghilarza
6	Elmas	Selargius
7	Sinnai	Ales
8	Arzana	Abbasanta
9	Sestu	Macomer
10	Maracalagonis	Assemini

Table 2: Ranking of Sardinian municipalities by their commuters' accessibility

calibration is required in order to appraise the parameters K and β in equation (2). This process has been developed by solving an over determined linear system, where K and β are the unknown variables and P_i, P_j and S_{ij} the known terms. In table 1, the statistics of the estimation K and β is reported.

In table 2, the first ten towns of Sardinia are ranked according to their values of accessibility calculated according to both the approaches. In figure 2, a geographical analysis of both the accessibility models is reported.

As a preliminary comment, it is possible to observe that the towns in the neighborhood of Cagliari, the capital center of the Island, display relevant values of the travel cost based accessibility A_{TC} . As far as the gravity model based accessibility A_G is concerned, Cagliari and Oristano - important regional and provincial administrative cities- show high values. The information conveyed in figure 2 suggest two different patterns of accessibility for commuters in Sardinia: it is possible to locate a cluster of towns with a high value of A_{TC} in the Campidano, the main plain of the Island, while the highest values of A_G are displayed by municipalities clustered around the capital city Cagliari. As a general remark, both the values of the commuters accessibility display a similar distribution, even though A_G values signal an higher polarization in the south of the Island, while A_{TC} values display an higher heterogeneity. These similarities are confirmed by the assessment of the coefficient of correlation between the two variables A_{TC} and A_G (equal to 0.501) that reveals a weak positive correlation. Those findings are also confirmed by the presence of two highways -national roads n. 131 and n. 130- that represent relevant backbone connections for the

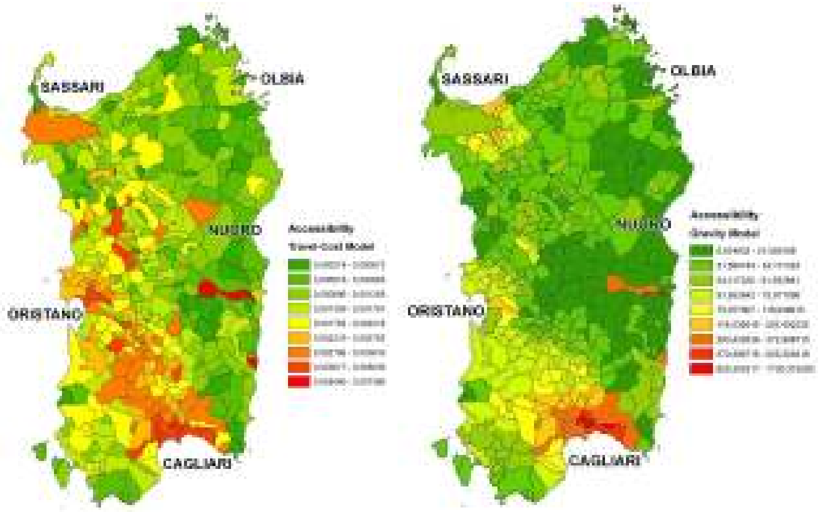

Figure 2: Commuters accessibility for municipalities in Sardinia: on the left, accessibility based on the travel cost model; on the right, accessibility based on the gravity model

whole Sardinian road network.

These preliminary explanations have to be also confronted with relevant demographic elements reported as follows. The population of Sardinia is about 1.6 million resident inhabitants. It is divided into 8 main administrative provinces where most of the citizens, about a half of the total population, live in the metropolitan area of Cagliari, the capital center with 160000 inhabitants. The last Census (Istat, 2001b) highlights that only 14 municipalities have got more than 20000 inhabitants hosting 42 percent of the whole Sardinian resident population. About 43 percent of the resident population lives in 239 medium-low size towns (10000-1000 inhabitants) while the remaining population lives in small villages sizing less than 1000 inhabitants. According to the Census data, in Sardinia population and productive activities concentrate mostly on the coast line. In figure 4, a geographical representation of the municipal distribution of resident population and commuters in 2001 is reported.

In order to inspect in more detail the behavior of the two variables, in figure 5 their complementary cumulative probability distributions are reported. In the case of the variable A_{TC}, the behavior of the curve displays an exponential decay with a finite and determined mean value equal to 0.002. In the case of the variable A_G, the curve shows a behavior that fits a power law line with exponent α=2.3 ($t - stat = 53.27$, $R^2 = 0.99$): the values are distributed on a broad range and the mean does not represent any characteristic value for the distribution.

In order to analyze the interplay between commuters' accessibility and topo-

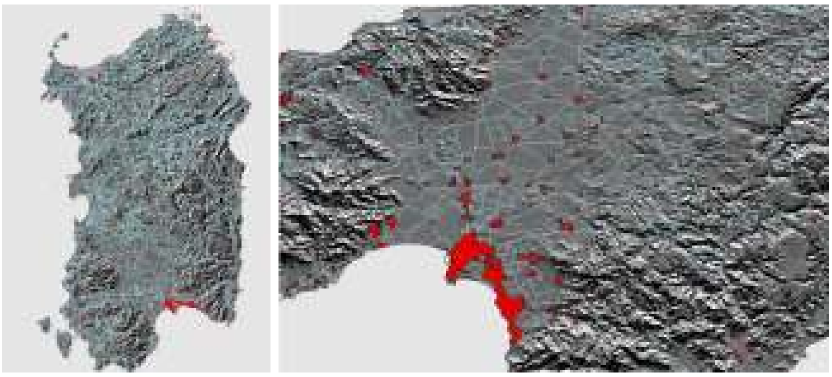

Figure 3: on the left a global view of morphology, road network and urban areas of Sardinia; on the right, a detail of the suburban area of Cagliari.

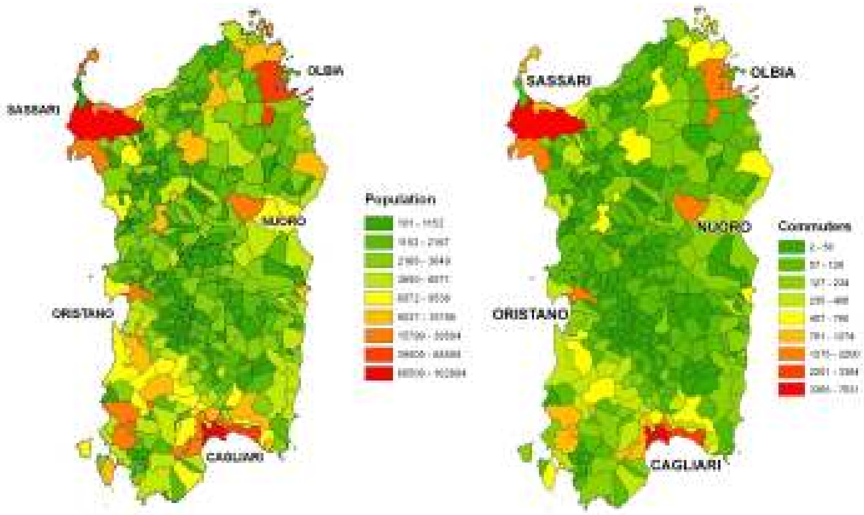

Figure 4: Municipal distribution of resident population (on the left) and commuters (on the right).

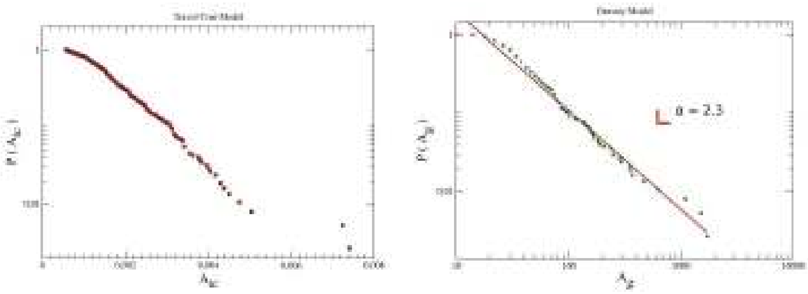

Figure 5: complementary cumulative probability distribution of A_{TC} (on the left) on a lin-log plot and of A_G (on the right) on a log-log plot.

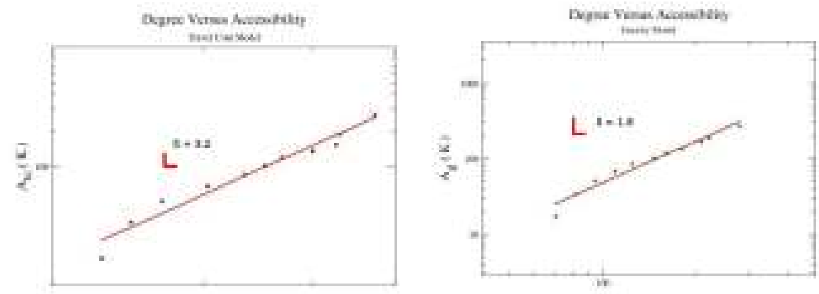

Figure 6: Commuters accessibility versus topologic centrality: log-log plots of A_{TC} (on the left) and of A_G (on the right) as a function of the degree k.

logical centrality of the towns, it is useful to consider the functional relationship between both the accessibility measures A_{TC} and A_G and the degree k, which measures the number of first neighbors of a town. As figure 6 reports, it is possible to obtain an overall representation of that relation by elaborating the log-log plots of the spectrum of the commuters' accessibility measures averaged over the degree values for each municipal center of Sardinia.

As a preliminary comment, it is possible to observe that both the measures of commuters' accessibility scale super linearly with respect to the degree k, while the curves fit a power law line with exponent equal to 3.2 ($t - stat = 15.15$, $R^2 = 0.98$) for $< A_{TC} >$(k) and to 1.8 ($t - stat = 14.12$, $R^2 = 0.98$) for $< A_{TC} >$(k). This evidence suggest that the higher the topologic centrality of a town, measuring its actual capacity to be connected to other towns, the higher, and with an higher pace, its accessibility for commuters in the network. Apparently, the variable $< A_{TC} >$ increases versus the degree with an higher pace than the variable $< A_{TC} >$.

5 Conclusion

In this paper, the authors attempt to integrate complex network analysis (CNA) with accessibility modeling in order to develop two indicators of accessibility for commuters moving on the road system of Sardinia, Italy. The integration implies the adoption of results obtained by means of CNA -i.e. the variable describing the shortest road distances between pairs of Sardinian municipalities- as a relevant input for the construction of a travel cost based and a gravity model based indicator of accessibility.

This work constitutes a contribution for the analysis of accessibility indicators referred to the pattern of interurban commuting. As a preliminary result, it is possible to indicate a number of findings.

First, the indicators calculated should be interpreted as ex post measures of the ability of commuters to access Sardinian towns, as the values of the distances and commuters are given.

Second, the indicators obtained are in general weakly correlated each other, while display different probability distributions: gravity model based accessibility has a cumulative probability distribution with a power law behavior.

Third, both the indicators of commuters' accessibility scale super linearly with the degree k of the towns of Sardinia; a signature of the fact that the higher is the topological centrality of a town the higher its accessibility.

6 Reference

- Albert R, Barabási AL, 2002, "Statistical mechanics of complex networks", Rev. Mod. Phys. 74, 47-97.
- Baradaran S, Ramjerdi F, 2001, "Performance of Accessibility Measures in Europe". Journal of Transportation and Statistics Vol 4 No 2/3 Special issue on Methodological issue in accessibility, 31-48.
- Barrat A, Barthélemy M, Pastor-Satorras R, Vespignani A, 2004, "The architecture of complex weighted networks" Proceedings of The National Academy of Sciences 11, 3747-3752.
- Campagna M, Caschili S, Chessa A, De Montis A, Deplano G, 2007, "Modeling commuters dynamics as a complex network: the influence of space", Proceedings of the 10th International Conference on Computers in Urban Planning and Urban Management (CUPUM), Iguassu Falls, Brasil, July, 11-13 2007.
- DHC and UoW , 2003, "Developing and Piloting Accessibility Planning", Final report for DfT.
- De Montis A, Barthélemy M, Chessa A, Vespignani A, 2007, "The structure of interurban traffic: a weighted network analysis" Environment and Planning B: Planning and Design 34(5), 905-924.

- Gould P, 1969, "Spatial Diffusion", Resource Paper Number 17, Association Of American Geographers, Washington DC.
- Italian National Institute of Statistics (Istat), 2001a, 14^{o} Censimento generale della popolazione e delle abitazioni, Matrice origine destinazione degli spostamenti pendolari della Sardegna (14th General census of population and houses, Origin destination matrix of the commuting movements of Sardinia).
- Italian National Institute of Statistics (Istat), 2001b, 14^{o} Censimento generale della popolazione e delle abitazioni, (14th General census of population and houses).
- Jiang B, Claramunt C, Batty M, 1999, "Geometric accessibility and geographic information: extending desktop GIS to space syntax", Computers, Environment and Urban Systems, 23(2), 127-146.
- Newman MEJ, 2003, "Structure and function of complex networks", SIAM review 45, 167-256.
- O'Kelly ME, 1998 "A geographer's analysis of hubs-and-spoke networks", Journal of Transport Geography 6, 171-186.
- Porta S, Crucitti P, Latora V, "Multiple Centrality Assessment in Parma Campus: a network analysis of paths and open spaces", in press for publication in Urban Design International.
- Reggiani A, Signoretti S, Nijkamp P, Cento A, 2008, "Connectivity measurement for network models in air transport: a case study of Lufthansa", in Stefani S and A Aimzada (eds.) Networks: Topology and Dynamics, Springer Verlag, Berlin.
- Schintler LA, Gorman SP, Reggiani A, Patuelli R, Gillespie A, Nijkamp P, Rutherford J, 2005, "Complex Network Phenomena in Telecommunication Systems" Networks and Spatial Economics 4, 351-370.
- Stewart JQ, Warntz W, 1958, "Physics of population distribution", Journal of Regional Science 1 (1), 99-121.
- Strano E, Cardillo A, Iacoviello V, Latora V, Messora R, Porta S, Scellato S, 2007, "Street centrality vs. commerce and service locations in cities: a Kernel Density Correlation case study in Bologna", Italy, physics/0701111.