Journal of Transport Geography 46 (2015) 55–66

Contents lists available at ScienceDirect

Journal of Transport Geography

journal homepage: www.elsevier.com/locate/jtrangeo

Understanding road network dynamics: Link-based topological patterns

Susana Freiria [a,*], Bernardete Ribeiro [b], Alexandre O. Tavares [c]

[a] CES, Institute for Interdisciplinary Research, Casa Costa Alemão – Pólo II, Rua Dom Francisco de Lemos, 3030-789 Coimbra, Portugal
[b] CISUC, Department of Informatics Engineering, University of Coimbra (Pólo II), Rua Sílvio Lima, 3030-790 Coimbra, Portugal
[c] CES, Department of Earth Sciences, University of Coimbra (Pólo II), Rua Sílvio Lima, 3030-790 Coimbra, Portugal

ARTICLE INFO

Article history:
Received 1 October 2014
Revised 29 April 2015
Accepted 4 May 2015
Available online 21 May 2015

Keywords:
Road network
Interruption
Graph theory
Dual network analysis
Biclustering analysis
Network performance

ABSTRACT

Road network interruptions caused by natural disasters are becoming more frequent and their consequences are becoming of a wider range. The main goal of this work is to identify the most important roads in a network. Herein, a new model is proposed to evaluate the most important roads in the network through the application of biclustering technique, identifying patterns of attributes (road performance measures) and patterns of roads (connectivity patterns). Thereafter the model presented here is compared with the mean geodesic distance variation. Both methodologies are applied to a case study and the pros and cons are discussed as well. Results point out the alpha index as the topological measure more relevant in the normal network flow; moreover the interruption of the links with highest values of connectivity will have larger consequences in the normal functioning of the network than the links with the lowest levels of connectivity. The approach here proposed is a useful insight of the network dynamics, which allows optimizing the worst-case performance of the system. This work can be useful for risk management actors, for civil protection agents, who need to decide on the effective allocation of human and physical resources and define priority areas, and for the government institutions which design the network of facilities.

1. Introduction

Road network interruptions caused by natural disasters are becoming more frequent with ever wider ranging consequences (EM-DAT, 2013). Roads are a critical infrastructure for the normal functioning of society, connecting people, businesses and services separated in space (Jenelius, 2010; CEPS, 2010). Given the importance of the transport networks for daily travel to work, production logistics, and business travel, the reliability of transport networks is of key interest to transport system users and hence planners at all levels, both in the public and private sectors (Jenelius et al., 2006).

The main function of the road network is to ensure connectivity between points. Connectivity can be defined as the presence of an available or functional path between an origin–destination (O–D) pair (Matisziw and Murray, 2009). The operational consequences of an interruption cause an increase in distance between the points (Jenelius et al., 2006).

Identification of the most important roads and a deeper knowledge of what makes the road network structure more vulnerable provide essential criteria for decision-makers and policy-makers in the course of their policy decision-making process (Murphy and Gardoni, 2007). The development and use of evaluative criteria and performance metrics leading to the most effective prioritization of transportation projects is critical (Novak et al., 2012). Network vulnerability is not just an interesting topic for research by transport network modelers, but is also of great importance to modern society (Taylor and Susilawati, 2012).

The main goal of this work is to identify the most important roads in the network, defined as those whose interruption would cause the most significant consequences assessed in terms of network connectivity loss and quantified based on the average geodesic distance increase among the network's nodes. Furthermore there are two secondary goals: firstly, to identify road network patterns based on its structural properties and second to rank the biclusters according the level of connectivity of the roads integrated in each bicluster. Structural properties, such betweenness, can reflect network configuration that can be utilized for network-based analysis (Zhang et al., 2015). To implement the goals set for this work, a biclustering technique is applied to a real-world road network followed by a linear regression analysis. Biclustering technique permits one to find road bicluster patterns of road indicators (attributes) with roads (samples) within a real-world network. In the excellent review made by Murray

* Corresponding author.
E-mail addresses: susanaf@ces.uc.pt (S. Freiria), bribeiro@dei.uc.pt (B. Ribeiro), atavares@dct.uc.pt (A.O. Tavares).

http://dx.doi.org/10.1016/j.jtrangeo.2015.05.002
0966-6923/

et al. (2014) concerning spatially significant cluster detection it can be verified that biclustering technique has been disregarded in spatial analysis. However, as this work demonstrates, biclustering techniques application is more advantageous than traditional clustering techniques. For start, biclustering technique can solve two issues associated with a priori structured approaches pointed by Murray et al. (2014). The first is related with challenge of spatial data clustering, the use of pre-defined geometric shapes can mask the actual spatial morphology of hot spots. Simply put, actual spatial shapes used to tessellate space. Second, imposed structures can impede statistical inference, masking the underlying causes of clusters. Traditional clustering methods only focus on one dimension at a time. For example, in unsupervised clustering, such as hierarchical clustering, entire columns or rows are grouped together even though most of the time not all the objects in the column (or row) form part of the found cluster (Ribeiro and Chen, 2012). On the other hand, biclustering methods perform clustering in two dimensions simultaneously (Madeira and Oliveira, 2004), which means that only subgroups of attributes and roads are in a given bicluster.

Moreover, approaches to support cluster analysis are generally designed to impose structure on observations/events in order to account for similarity of some sort (Murray et al., 2014). In this work the biclustering technique goes forward, the biclusters are ranked according with the average level of connectivity of the roads that integrate each bicluster based on a multiple regression analysis.

This work seeks to take a step forward by combining different attributes in a single connectivity index, identifying the role played by each attribute by means of biclustering and ranking the biclusters according its connectivity level. The approach proposed in this work allows one to understand, for example, that Bonacich Power plays an important role in network Z structure, which means that network management should take into account the roads identified as the most powerful.

The case study concerns the road network in the municipality of Coimbra, a municipality in the central region of Portugal (Fig. 1).

The case study is a hub of multiple health and education services for the entire region (CCDRC, 2010), meaning that if a certain route is disrupted, it will not only have local and regional consequences, but in some cases effects at the national level.

The remainder of this work is the following: firstly, connectivity patterns are identified based on the biclustering technique; then, the biclusters obtained are ranked based on the connectivity level of the roads that integrate each bicluster. Afterward, the model presented here will be compared to the mean geodesic distance variation. Both methodologies will be applied to a case study and subsequently, advantages and disadvantages will be discussed.

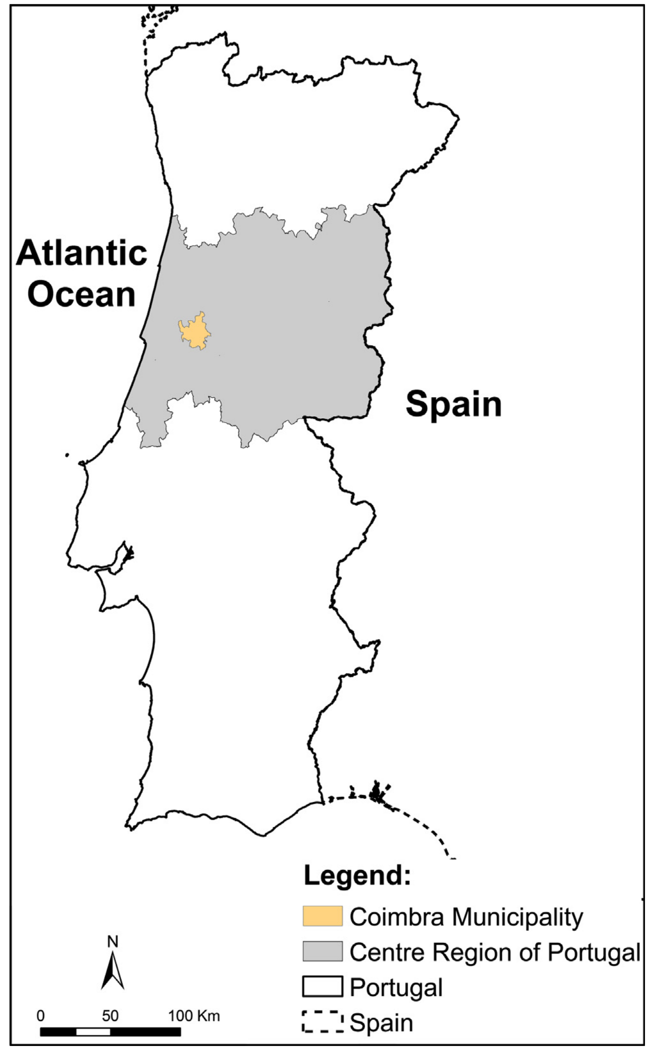

Fig. 1. Case study location.

2. Literature review

Centrality measures have been widely used in the relevant literature to identify the most important roads. However, they seem to lack important properties that would make them more robust tools capable of providing realistic representations of complex systems (Berdica, 2002; Lewis, 2006; Solano, 2010; Murray and Grubesic, 2012).

Jiang and Claramunt (2004) propose a topological analysis where vertices represent named streets and edges represent street intersections. The importance of measures such as street connectivity, average path length and clustering coefficients in the road network structure are discussed in their analysis.

Crucitti et al. (2006) compared five different measures of centrality: degree, closeness, betweenness, straightness and information. This approach was applied to 18 samples, each one of 1 sq. m from different cities. The analysis took into account the influence of centrality measures in the urban structure, and the variables of a planned or self-organized city.

Porta et al. (2006) propose a generalization model called "Intersection Continuity Negotiation", which recognizes the continuity of streets over a plurality of edges. Topological properties in focus were: degree and degree distribution; degree correlations; characteristic path length; clustering coefficient; global and local efficiency and small-world networks. The model was applied to six cases of urban street network with 1-square mile each.

Xie and Levinson (2007) reviewed the existing measures of heterogeneity, connectivity, accessibility and interconnectivity as well as proposing measures of entropy, connection patterns and continuity. These measures were applied to 16 test networks. Some of the proposed measures were later applied by Erath et al. (2009b) to characterize the growth of the Swiss road network between 1950 and 2000.

Levinson (2012) focused on questions of how network scale and connectivity vary with city size. This model predicts that road networks will be more connected, less circuitous, and less tree like according to the degree of greater accessibility a new link creates.

Novak and Sullivan (2014) propose a measure of Critical Closeness Accessibility (CCA) that quantifies the relative importance of each link in a roadway network with respect to its system-wide contribution to emergency accessibility and is based