Cities 31 (2013) 57–68

Contents lists available at SciVerse ScienceDirect

Cities

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

Spatial–temporal analysis of urban growth and transportation in Jeddah City, Saudi Arabia

Mohammed Aljoufie [a,*], Mark Zuidgeest [b], Mark Brussel [b], Martin van Maarseveen [b]

[a] *Department of Urban and Regional Planning, Faculty of Environmental Design, King Abdulaziz University, Jeddah, Saudi Arabia*
[b] *Department of Urban and Regional Planning and Geo-Information Management, Faculty of Geo-Information Science and Earth Observation (ITC), University of Twente, The Netherlands*

ARTICLE INFO

Article history:
Received 13 May 2011
Received in revised form 6 January 2012
Accepted 25 April 2012
Available online 18 May 2012

Keywords:
Urban growth
Transportation
Spatial–temporal analysis
Indicators
Remote Sensing
GIS

ABSTRACT

During the past decades, the city of Jeddah in Saudi Arabia has witnessed dramatic changes in its urban area, population and transportation. To better understand the relationship between urban growth and transportation, this paper aims to quantify and analyze the spatial–temporal relationship between urban growth and transportation for Jeddah using Remote Sensing (RS) and Geographic Information System (GIS) approaches. In this paper, eight urban growth and transportation indices were developed to analyze the relationship between spatial–temporal urban growth and transportation changes: (1) annual urban spatial expansion index, (2) land use change index, (3) population density index, (4) transportation infrastructure expansion index, (5) road density index, (6) road area density index, (7) urban trips density index, and (8) modal split change index. The results show that in the past four decades (1964–2007), Jeddah has experienced a rapid population growth, a large spatial expansion, rapidly changing land use and expanding transportation infrastructure. As transportation infrastructure expands with population growth, this expansion has not been able to accommodate increases in travel demand. This has led to an increase in urban congestion. The analysis further shows that transportation infrastructure expansion has stimulated Jeddah's urban spatial expansion and residential area growth. The enormous spatial expansion has also caused significant changes in the daily share of travel modes. The developed indicators in the paper bridge the knowledge gap between urban growth and transportation research, as the results of this study provide a rich understanding of the relationship between urban growth and transportation in rapidly growing cities.

Introduction

Transportation plays a crucial role in urban development: transportation systems provide mobility for people and goods and influence patterns of growth and levels of economic activity through land accessibility (Meyer & Miller, 2001). Transportation infrastructure is considered one of the main causes of urban growth (Bhatta, 2010), as different studies reveal relationships between the development of high-speed roads, urban expansion, and growth in population (Brotchie, 1991; Parker, 1995; Priemus, Nijkamp, & Banister, 2001). Fan, Wang, Qiu, and Wang (2009) demonstrate that transportation corridors play an important role in urban expansion. Urban transportation systems are complex networks shaped by various geographical, social, economic, and environmental factors (Wang, Lu, & Peng, 2008). To understand this complexity, it is crucial to study the interactions and effect(s) produced by each of these factors, as they exhibit many patterns within urban growth that reshape urban spatial structures. In other words, urban growth is strongly related to transportation's reciprocal causes and effects, as rapid growth of cities and their populations increase urban traffic (Cervero, 2003; Millot, 2004), traffic congestion, and infrastructure pressure (Allen & Lu, 2003; Bhatta, 2010; Brueckner, 2000). Previous studies have focused only on the causes and effects of the relationship between transportation and urban growth, while there is a lack of research on the spatial–temporal aspects of the relationship. A thorough understanding of the spatial–temporal processes of urban growth and urban dynamics, then, is necessary (Bhatta, 2010; Bhatta, Saraswati, & Bandyopadhyay, 2010; Müller, Steinmeier, & Küchler, 2010) in enhancing and expanding our knowledge of the relationship between urban growth and commuting (Zhao, Lu, & de Roo, 2011).

Spatial indicators are potentially effective measures to quantify and analyse the relationship between spatial–temporal urban growth and transportation. An indicator can be used to monitor and review the conditions of cities, providing benchmarks for the development of urban conditions and policies over space and time (UNCHS, 1995). Few indicators have been developed, however, to

* Corresponding author. Tel.: +966 564 559133 (mobile).
E-mail addresses: aljoufie@itc.nl, mjoufie@hotmail.com (M. Aljoufie).

0264-2751/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.cities.2012.04.008

quantify and analyze spatial–temporal urban growth. Examples of such indicators include *the annual urban expansion index* (Fan et al., 2009; Tian et al., 2005), *the population growth index* (Jat, Garg, & Khare, 2008; UNCHS, 1995; Zhang & Guindon, 2006), *the urban land use/land cover change index* (Xie, Mei, Guangjin, & Xuerong, 2005; Zhang & Guindon, 2006), and *the urban population density change index* (Feng, 2009; Zhang & Guindon, 2006). The *proximity of growth to the transportation infrastructure index* (Fan et al., 2009; Müller et al., 2010; Zhu, Xu, Jiang, Li, & Fan, 2006) is the only index that has been developed and used repeatedly to analyze the spatial–temporal relationship between urban growth and transportation. By and large there is a considerable lack of discussion in the literature on the development of such indicators (Dendoncker, Schmit, & Rounsevell, 2008; Fan et al., 2009). This paper describes the use of Remote Sensing (RS) and Geographical Information Systems (GISs) techniques to quantify the relationship between spatial–temporal urban growth and transportation, and to develop and analyze a new set of indicators.

Jeddah, Saudi Arabia, which has experienced rapid urban growth, spatial expansion and transportation infrastructure expansion over the last 40 years, will be the focus of urban analysis in this paper. Its urban growth has significantly varied over time, giving way to complex urban dynamics. No systematic study is yet available on the spatial–temporal dynamics of urban growth and transportation changes in Jeddah. In light of the many challenges the city faces in its short and medium-term development, such a study is urgently needed.

Methodology

Study area

Jeddah is the second largest city in Saudi Arabia. It is located on the west coast of the Kingdom, at latitude 29.21 North and longitude 39.7 East, in the middle of the Red Sea's eastern shore (Fig. 1).

Jeddah has witnessed a dramatic increase in population primarily due to out-migration from villages and suburbs into the city as individuals search for jobs and better standards of living. The strength of the economy and the growth in population are increasingly straining the city's transportation system. Jeddah is car-dominated, with residents using private automobiles for 93% of their transportation (IBI, 2007). The city faces an increase in accelerated urban expansion, population growth and traffic congestion, and its local government faces many challenges in managing its urban growth, land use and transportation.

Data and image processing

This study utilizes a time series of aerial photos and satellite images to quantify the spatial–temporal urban growth and transportation system situation, from 1964 to 2007. Aerial photo data of 1964, 1970, and 1980 were used for the period before 1981. Spot satellite image data were used for 1993, 2004, and 2007. Moreover, a variety of secondary data were collected to facilitate the analysis of urban growth and transportation. These data include the following: Jeddah master plans for 1963, 1973, 1980, 1987, and 2004; Jeddah transportation studies for 1980, 1995, 2004, and 2007; census data for 1993 and 2005; an urban growth boundary study for 1986; and Jeddah topographic maps for 2000.

Given the inconsistent spatial and temporal resolution of the available Remote Sensing data for this study and the different types of formats, a consistent method for quantifying urban growth and transportation infrastructure changes was critical. A cooperative visual interpretation method (Fig. 2)—a method in which human and computer based (automatic) interpretation is combined (Liu & Chen, 2008)—was adopted to quantify temporal urban land use and transportation infrastructure as the main drivers of urban growth and transportation in Jeddah.

To prepare the base data for analysis, an image-to-image registration strategy was adopted to geo-reference the various images using a polynomial model second-order function in ERDAS IMAGINE. Subsequently, the cooperative visual interpretation method was applied. The process started with an unsupervised image classification to differentiate between urban built-up elements and non-built-up elements using the ISODATA clustering algorithm in ERDAS IMAGINE. This process shows the spatial pattern of urban built-up areas in Jeddah, which facilitates a better understanding of the elements of built-up areas such as buildings, road infrastructure and green areas. In the next step, land use and transportation infrastructure reference data from master plans and transportation study reports were integrated with built-up and non-built-up images using the overlay function in ArcGIS. Ten urban land use classes were specified for extraction: residential, commercial, industrial, institutional, informal settlements, airport, port, roads, vacant lands and green areas. Thereafter, visual interpretation indicators such as pattern, shape and size were extensively used in identifying features from aerial photographs and satellite images based on field knowledge. Consequently, a final interpretation was conducted incorporating all the aforementioned processes in ArcGIS v9.3 using on-screen digitizing, overlay tools and Area Of Interest (AOI) functionality. Accordingly, land use and transportation infrastructure maps for 1964, 1972, 1983, 1993 and 2007 were obtained. Finally, accuracy assessments were performed based on a comparison of the cooperative interpretation outputs with a set of reference data. The average overall accuracy of land use maps produced by this approach was 90%, which exceeds the minimum 85% accuracy of land use data that is mentioned by Anderson, Hardy, Roach, and Witmer (1976), as required for satisfactory land use maps.

Urban growth and transportation indicators

Indicators can be used as an effective tool for quantifying and analyzing the spatial–temporal relationship between urban growth and transportation. Eight indicators were developed in this study to quantify the urban growth and transportation patterns; these indicators are discussed below.

Annual urban spatial expansion index

The urban spatial expansion index is imperative in describing the temporal changes of an urban area, in terms of its annual urban growth rate and annual growth area (Fan et al., 2009; Tian et al., 2005). The annual urban spatial expansion index (AUSEI) has been adopted to discuss the temporal urban spatial growth of Jeddah and is defined as follows:

$$\mathrm{AUSEI}_t = \frac{(U_t - U_{t-1})/U_t}{(N_t - N_{t-1})} \times 100 \qquad (1)$$

where AUSEI_t [%/year] is the annual urban spatial expansion index; U_t and U_{t-1} are the total urban areas of the study area in hectares at time t (current year) and time $t-1$ (former year); and N is the total number of years from time t (current year) to time $t-1$ (former year).

Annual land use change index

Land use change is critical, not only in spatial temporal urban growth and transport analysis but also in different global, regional and urban analysis. It reflects the dynamics of urban areas and is one of the driving forces of urban development (Xie et al., 2005;