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Spatial statistical analysis of the effects of urban form indicators on road-traffic noise exposure of a city in South Korea

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ABSTRACT

The purpose of this study is to present a statistical model which can predict the noise level of road-traffic in urban area. A spatial statistical model which can take into account spatial dependency on geographically neighboring areas is constructed from a noise map of a city in South Korea. A system of 250 m × 250 m grid cells is placed on the city of Cheongju, South Korea, and the noise level and urban form indicators are averaged over each cell. The population-weighted mean of the noise level is subsequently regressed on the average urban form by adopting the spatial autoregressive model (SAR) and the spatial error model (SEM), as well as an ordinary least squares (OLS) model. Direct and indirect impacts are analyzed for a valid interpretation of the spatial statistical models. Factors such as GSI, FSI, traffic volume, traffic speed, road area density, and the fraction of industrial area turn out to have significant impacts on the noise level.

1. Introduction

The noise from high-density road-traffic networks in metropolitan area tends to spread more widely over the city including residential areas where people commute every day than the noise of other transportation including railways and aircraft. Therefore more people could be exposed to a high level of the road-traffic noise, more specifically, at night, which could cause sleep disturbance [1–4].

The continuous expansion of the metropolitan areas causes road networks to expand as well. Moreover, the steadily increasing commuting distances aggravate the noise problem [5]. Consequently, there is a need to establish a sustainable management plan for urban road-traffic noise [6]. Noise maps of cities, including cities in the European Union (EU) [7,8], were generated to facilitate systematic management of the road-traffic noise. The noise maps aid city planners and policy makers in understanding the status of the noise, including the location of hot spots and the specific noise level of a specific noise source to which the population is exposed. In addition, any changes in the traffic and land-use plan are taken into consideration to predict their influence on the status of the noise [9]. In this way, the costs and effects of a single or a combination of noise-reduction measures, e.g., barriers or absorptive pavement, are estimated more efficiently in the process of decision making.

Although a noise map is an efficient tool for administrators in designing noise-reduction measures and estimating their effects and costs, its use is limited to an already existing city for which a noise map has been drafted. Therefore when no noise map is available for an existing city or only minimal information such as population, road density and ground space index is given, any statistical relationship between the fundamental urban form indicators and the road-traffic noise would be useful to the administrators.

Wang and Kang [10] selected Greater Manchester in the United Kingdom (UK) and Wuhan in China from which to sample a number of typical urban areas to generate noise maps. Correlations between noise distribution and urban characteristics relating to urban density, such as road and building coverage ratio, were analyzed. The results indicated that urban morphology had significant effects on the traffic noise. Salomons and Berghauser Pont [11] presented statistical correlations between the façade noise level, the traffic volume, and urban densities, such as population density, road network density, vehicle kilometers per square kilometer per 24 h, ground space index, and floor space index. The urban form factors were averaged over grid cells of 250 m × 250 m for

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the total urban areas of Rotterdam and Amsterdam. It was found that the average sound level decreased with increasing population density, ground space index, and floor space index, but increased with increasing road network density and vehicle kilometers per square kilometer per 24 h. Silva et al. [12] studied traffic noise as a function of the compactness ratio, porosity index, and complexity perimeter index by simulating modeled urban forms. Hao and Kang [13] studied whether and how mesoscale urban morphology of low-density built-up areas influenced the spatial noise level attenuation of overflying aircraft. Six urban morphological parameters were selected and developed. These were Building Plan Area Fraction, Complete Aspect Ratio, Building Surface Area to Plan Area Ratio, Building Frontal Area Index, Height to Width Ratio, and Horizontal Distance of First-Row Building to Flight Path. Twenty sites, each measuring 250 m × 250 m, were sampled. It was found that the influence of the urban morphological parameters on the noise attenuation was greater in the open areas than it was on the façade. Another finding was that the spatial noise attenuation of overflying aircraft was mainly correlated to the Building Frontal Area Index and the Horizontal Distance of First-Row Building to Flight Path.

The purpose of our study is to present a statistical model which can predict the noise level of road-traffic in an urban area. A statistical model is constructed by applying spatial analysis, taking into account the interactions or heterogeneity among geographically neighboring areas, such as spatial spillover effect [14]. In particular, the spatial statistical methodology can account for simultaneous spatial dependence [14] of various urban form indicators on road-traffic noise, which ordinary regression or correlation models do not. The results are presented in the quantitative models of the relationship and the numerical values of impacts of urban form indicators on the noise level. Chun and Guldmann [15] used spatial statistical models to statistically model the relationship between the urban heat island and urban characteristics, such as solar radiation, open spaces, vegetation, rooftops of buildings, and water. Although the urban form indicators used by these authors are different from those used in our study, their results and methodology show the possibility of application to urban design and land-use policies such as greening scenarios.

The city of Cheongju, South Korea, is chosen for our first study and the relevant urban form indicators are averaged over 250 m × 250 m grid cells for the total urban area of the city. The regressions between the representative noise level and the selected urban form indicators are studied by spatial statistical models. In addition, the result by the ordinary least squares (OLS) model is presented together for comparison with the spatial statistical models. An impact analysis for a valid interpretation of the spatial statistical model is also conducted.

2. Materials and methods

2.1. Site selection, data sources and data preparation

The city of Cheongju, located in the central part of the Republic of Korea, is selected for this study. As of 2013, the total population of Cheongju was 679,301 and the number of registered vehicles was 265,545. The total length of roads was 940.2 km and the total city area for this study was 153.44 km^2. Noise maps, generated for an estimation of the number of people exposed to the noise [16], are re-compiled for the analysis. Based on data and results of the reference paper [16], the façade noise levels are calculated at receiver points placed at the exposed facades of each floor of residential buildings. The index of the calculated facade noise level is the A-weighted equivalent noise level for nighttime, $L_{Aeq,night}$. We only focus on the road-traffic as a noise source for noise mapping. RLS90 [17] built in SoundPLAN® [18] is adopted as road-traffic noise prediction model. The RLS90 model is one of the road-traffic noise prediction models recommended by the Korean Ministry of Environment for generating 3D noise mapping in Korea. It takes about a day to generate façade noise map of the entire area of Cheongju by using blade server system with 8 CPUs (2.5 GHz) and 88 threads.

As shown in Fig. 1, the study area is covered by 2660 square cells of 250 m × 250 m. The temporal background for this study is only the nighttime (22:00–06:00) because the majority of the people stay in the own residential buildings in that time. In addition, the nighttime road-traffic noise causes adverse health impact such as annoyance and sleep disturbance on the residents. Since the present study focuses on residents exposed to noise during nighttime, only the cells where residential buildings exist are considered. The cells containing residential buildings are 1201 and only these cells are included for further analysis. The façade noise levels of the residential buildings are utilized to estimate the representative noise levels of the selected cells.

GIS data for the topography and roads were provided by the Chungcheongbuk-do Provincial Government in 2007. GIS data for the buildings, which contain building footprint, the number of floors and building-use classification, were provided by the Cheongju City Government in 2009. The height of a building was estimated by the product of the number of floors and 2.8 m per a floor. The traffic volume data in a road segment were collected from the National Police Agency of Cheongju in 2009, whereas traffic speed and the percentage of heavy vehicles (gross-vehicle-weight more than 2.8 ton) in a road segment were extracted from noise-impact assessment reports and the transportation master plan of the Cheongju City Government with the assumption of no large difference between designed data and measured data. The population data were acquired from the community census statistics of the Korean National Statistical Office and the Cheongju City Government. The population data were allocated to the gross area of residential building, and the allocated population of the building was reallocated to a façade for a floor of the building. GIS data for the 16 detailed land-use classification from Cheongju City Government in 2007 were classified into 4 groups (residential, commercial, industrial and green area) based upon Enforcement Decree of the National Land Planning and Utilization Act [19]. Table 1 presents summary of input data of Cheongju used in this research.

2.2. Definitions of representative values of the urban form indicators of a grid cell

Some urban form indicators, such as traffic volume, speed, type of passing vehicle, and area and height of a building affect road-traffic noise directly or acoustically. Other urban form indicators, such as the residential population and the land-use affect road-traffic noise indirectly. Deciding which urban form indicators contribute directly or indirectly to the extent of the road-traffic noise is not trivial at all. Therefore, as will be explained in the following section, the indicators of urban form to be included in the models are based on the results of statistical significance tests. The representative values of these indicators in a cell have to be estimated for spatial statistical analysis, and the cell-based urban form indicators are defined appropriately for the purposes of the study.

The representative noise level of a cell could be defined as the maximum or any mean value [11] of façade noise levels in the cell area. However, for this study, a mean value, weighted by the number of the residential population in the cell, is chosen. Therefore, the representative noise level of a cell, L_{cell} is defined as follows:

$$L_{cell} \equiv \frac{\sum_k \sum_j \sum_i p_{ijk} L_{ijk}}{\sum_k \sum_j \sum_i p_{ijk}} \quad (\mathrm{dB(A)}) \tag{1}$$