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Application of gravity model on the Korean urban bus network

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HIGHLIGHTS

- Mobility networks on urban bus operations are constructed for five Korean cities.
- The gravity model successfully estimated the traffic in bus stop and town networks.
- Population and distance work as fitness and cost of intraurban movements.
- The potential traffic is affected by its locational character as well as the population.

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ABSTRACT

Mobility models have been studied to describe the underlying mechanism of human mobility. The mobility patterns in various transportation systems were understood with the gravity model by estimating the traffic as a simple function of population and distance. Compared to most studies on large-scale systems, we focused on the validity and characteristics of gravity model for intraurban mobility. Several variations of gravity model are applied on the urban bus systems of five medium-sized cities in Korea. The gravity model successfully estimates the intraurban traffic without universal exponents for cities. From the change of exponents by predictor types, we figure out the effect by a non-trivial relation between traffic and population in the urban areas.

1. Introduction

An individual moves to where satisfies any need at some cost, and the aggregation of these movements emerges to a collective behavior called mobility or traffic. The fitness and cost landscapes given by the distributions of urbanization and resources generate universal mobility patterns for movers. In that sense, the observed human mobility patterns were interpreted as scaling laws [1–3], and its predictability [4] was discussed. As the practical applications, the real-world problems affected by human mobility have been studied such as disease spreading [5–7], traffic congestion [8] and migration [9].

Mobility models have been studied to understand the underlying mechanism of movement and to predict the future traffic flows. The gravity model is a widely accepted mobility model which predicts the traffic flow between areas with a simple function of traffic and cost similar to the Newton's gravity law [10–12]. It was applied on many types of mobility networks including highway [13], cargo ships [14], commuters [6,15,16] and mobile phone users [17]. Beyond the mobility studies,

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the gravity model was used for various real-world networks such as world trade network [18], collaboration network [19] and mobile phone communication [20].

The gravity model aims to predict some flows by using the external independent parameters, for instance, population [10], economic size [18], communication size [17], amount of citation [19], distance, time and so on. By an empirical basis, residential population and euclidean distance are commonly used as the mass and cost terms in the gravity model for mobility, since population is a primary source of traffic and distance is an immediate cost of movement. The cost function and exponents have also been investigated in relation with the theoretical derivation by entropy maximization [11,21]. Recently, the radiation model was proposed as an alternative to the gravity model [15]. Its modifications [22,23] and comparison with the gravity model [16,17,24,25] have been investigated for better estimation of traffic.

In this study, we applied the gravity model on the intraurban traffic flows in the medium-sized Korean cities. Most studies examined the gravity model for the nationwide or metropolitan scales. Likewise, for Korea, the gravity model was studied for highways [13], intercity buses [26] and long-term migration [27] in the nationwide scale, and for subways [28] and metropolitan buses [29] in the metropolitan areas surrounding Seoul. In contrast with most studies on the large-scale systems, we focused on intraurban mobility. We intensively tested whether the traffic mass, residential population and distance work as fitness and cost of movement for intraurban traffic. We examined their influence by comparing the exponents with the Korean intercity bus case [26]. Due to ambiguity of intraurban boundaries and relatively short moving distances unlike a nationwide or metropolitan area, traffic flows probably have a weaker relation with the gravity model.

A metropolitan city has a polycentric structure composed of several subcenters [30], and the mobility patterns between them have very high complexity by various transportations. To concentrate on the salient features of intraurban mobility, we studied medium-sized Korean cities where one primary public transportation can represent the mobility structure within them. The urban bus operation networks in five Korean cities without a subway system are analyzed with the gravity model. We also focused on the methodology and characteristics of gravity model for the urban scale, rather than comparing it with other mobility models.

The manuscript is constructed as follows: first, the traffic flow matrix is constructed from the urban bus schedule of five Korean cities. Then, we introduce strength distributions and traffic-population relations as basic statistics of the network. Finally, we apply several types of gravity models to the bus networks with bus stop and town resolutions, and compare their estimation performance with R^2 statistics. Most cases are fairly well estimated with the gravity model. The response of traffic to the cost term (distance) is intensively discussed in relation with the intercity bus case.

2. Data and method

Buses and subways are the most popular public transportations in urban areas. The multilayer structure constructed by their combinations complicates the understanding on transportation system. We confined the investigated cities to which without a subway system to reconstruct the urban mobility only with the bus system. Five cities in Korea, Ulsan, Changwon, Cheongju, Jeonju and Pohang, are selected in order of populations. The geographical span of each city is commonly about 50 km along its longer axis.

The urban bus operation data for five Korean cities were collected from three data sources. The bus operation data which contains bus stops on bus lines, and daily operation frequencies of bus lines were obtained from the official Bus Information System (BIS) webpage of each city: Ulsan (its.ulsan.kr), Changwon (changwon.go.kr), Cheongju (dcbis.go.kr), Jeonju (jeonjuits.go.kr) and Pohang (bis.ipohang.org) in 2013. The operation data is given for the weekday schedule. We collected the geographical information from the online map services, NAVER (map.naver.com) and DAUM (map.daum.net). It includes the GPS position and town information of bus stops, and the GPS position of town offices. We defined the town office as the reference position of a town. The population data is collected from the Korean Statistical Information Service (KOSIS, kosis.kr), which is based on the census in 2010. Since the census in Korea is held every 5 years, we used the most recent census data before 2013. The census output areas in Korea are based on 'Dong' which is the administrative unit of area corresponding to a town or a village. The residential population in a Dong is approximately from 1,000 to 100,000 ($17,301 \pm 15,079$). See Table 1.

Unlike interurban buses, urban buses usually have tens of bus stops on their routes similar to railway and subway systems. The whole structure of bus operations can be understood as the aggregation of each bus line operation. As in Fig. 1, each bus line r contains bus stops and daily operation frequency $f(r)$. From the bus operation data, we constructed two types of networks for the bus stop scale and the town scale. In bus stop networks, two nodes, bus stops, are connected by a directed and weighted link when the destination can be reached from the origin by one bus riding. For example, the blue node in Fig. 1 is connected to all bus stops on bus line 1, since a passenger who took the bus line 1 at the blue node can reach all bus stops on line 1 with one riding. If two stops i and j are connected by more than one bus lines, the link weight between them becomes the summation of operation frequencies of the lines ($w_{ij}^{s} = \sum_r f_{ij}(r)$).

We constructed the aggregated town networks based on Dong to match the nodes with population data. When two towns are directly linked by one or more bus lines, they are connected in the town network. Network construction from bus operations to a town network is described in Fig. 1. The bus line 1 with black arrows travels the towns c, b and d in order. Since a passenger who took the bus line 1 at town c can reach towns b and d with one riding, the links are made for c to b and c to d. In that same way, a passenger from town b can move to town d by bus line 1, the link from b to d is created. Like the bus stop network, the link weight w_{ij}^{t} is obtained by the summation of the daily operation frequencies of the bus