Geographical Studies on the Distance Parameter of Spatial Interaction Model : A Review Article

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I. Introduction

In the real world, there exist various kinds of flows such as person, commodity and information flows. Transportation geographers lay emphasis upon the spatial patterns of these flows as an aspect of "spatial organization" on the earth's surface (Taaffe and Gauthier, 1973). As one of their approaches to these patterns, they attempt to express them into mathematical models, i. e. spatial interaction models, because they can often discriminate certain kinds of regularity in these patterns. Their spatial interaction models, therefore, can be characterized as following two means from the geographical viewpoint. One is to describe the generality in the spatial patterns of various kinds of flows in various regions. The other is to derive the uniqueness of the spatial pattern of a certain kinds of flows in a certain region.

The purpose of this paper is to clarify the recent progress and subjects of geographical studies on the distance parameter, which is a constituent in any spatial interaction models. For attaining this purpose, an attempt is made, firstly, to give a general outline of spatial interaction models and, secondly, to review the recent studies of the distance parameter by classifying them into theoretical and empirical ones.

II. Spatial interaction models

Many researchers have attempted to construct spatial interaction models to describe the spatial patterns of flows, i. e. spatial interactions[1]. As a result, there exist various types of spatial interaction models such as gravity model which has the oldest origin (Ravenstein, 1885, 1889), intervening opportunity model (Stouffer, 1940), static electro-field model (Howe, 1962), multiple regression models (Olsson, 1965 ; Greenwood, 1971) and entropy maximizing model (Wilson, 1970). Some researchers, furthermore, review the development in these spatial interaction models (Kohsaka, 1979 ; Nijkamp, 1979 ; Senior, 1979 ; Suzuki, 1973).

Wilson (1971, 1974) asserts that these spatial interaction models together constitute a "family of models" because all of them are constructed implicitly by the following function as a fundamental framework :

$$T_{ij}=KW_iW_j\,f(d_{ij}), \qquad (1)$$

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where T_{ij} is a measure of spatial interaction between zones i and j, W_i and W_j are measures of "mass terms" associated with zones i and j, respectively, and f is some function of d_{ij} which is a measure of distance between zones i and j. K is a constant of proportionality, which is often called "balancing factor". The mass terms can each be one of two kinds: either some measure of total volume of spatial interaction out of a zone or into a zone, or some kind of an attraction factor. In the latter case, the mass terms can be measured by population size, commodity output, volume of retail sales or something in zones (Haggett *et al.*, 1977).

The distance function f is composed of, at least, a distance parameter β as well as the distance d_{ij}. Many types of distance function are proposed, and most of them are put into a list by Taylor (1971, 1975)[2]. Among these types, the most popular ones are as follows:

$$f(d_{ij})=d_{ij}^{-\beta}, \qquad (2)$$

and

$$f(d_{ij})=\exp(-\beta\, d_{ij}). \qquad (3)$$

In the most cases, gravity model includes the Pareto type of the distance function which is defined as Eqn. 2. On the other hand, entropy maximizing model always has the exponential type as Eqn. 3.

Although there are various types of spatial interaction models, each of them is constructed implicitly by the fundamental framework as Eqn. 1, which always includes the distance parameter in the distance function. The distance parameter, therefore, is an indispensable constituent of any spatial interaction models. It was considered that the distance parameter should be a measure of "friction of distance" affecting the flows, i. e. the spatial interactions. This meaning of the distance parameter, however, has been drastically changed as the result of the progress of theoretical studies since the 1970's. This meaning is discussed in the next chapter.

III. Theoretical studies on the distance parameter

Previous studies on the distance parameter can be classified into two types. One is of theoretical studies including simulation analyses based upon hypothetical data of flows. In this type, the theoretical meaning of the distance parameter is mainly argued. The other is of empirical studies where the emphasis is laid upon the variation of the distance parameter estimated by actual data of flows. This chapter is concerned with the former in order to clarify the theoretical meaning of the distance parameter.

As mentioned above, the distance parameter was used as a measure of the friction of distance before the appearance of the theoretical studies. However, since Curry (1972) cast doubt on this traditional meaning because of the spatial autocorrelation problem in the estimation, many researchers have disputed with each other about the theoretical meaning (Cliff *et al.*, 1974, 1975, 1976; Curry *et al.*, 1975; Fotheringham, 1981, 1984; Fotheringham and

Webber, 1980 ; Johnston, 1973, 1975, 1976 ; Sheppard, 1979 ; Sheppard *et al*., 1976). One of the critical assertions of these theoretical studies is that the distance parameter consists of the following three elements.

The first element is called "behavioral component" which indicates the friction of distance. The reason why researchers used the distance parameter to measure the friction of distance before the 1970's, was that they considered this component as the only element dominating the distance parameter. The friction of distance means the factor which decays the volume of flows according to the increase of the distance between given zones if the flows occur between them. In general, the increase of the distance between them results in strengthening the friction of distance, so that the volume of flows dereases.

In the strict sense, the friction of distance, however, does not influence with the same level upon all kinds of flows. The influencing strength of the friction of distance differs in the kind of flows such as person, commodity and information flows. It also differs in the characteristics of flows, even in a certain kind. In the case of person flows, the degree of the strength would be varied by the demographic attributes of moving persons such as age, sex and occupation, the aim to move and using transportation means.

In sum, the kinds and characteristics of flows result in the difference of the friction of distance and thus this brings about the variation of the behavioral component. Furthermore, the socio-economic attributes of zones where various types of flows are producted, effect ultimately the behavioral component of the distance parameter because, as shown in Eqn. 1, spatial interaction model expresses the volume of inter-zonal flows which are producted aggregately by each zone.

The second element is called "configurational component". This component is influenced by the geometric shape of the study area where a spatial interaction model is applied to estimate the distance parameter. In other words, this component reflects the relative locational relationship among unit zones within the study area. Openshaw (1977), therefore, calls it "zone specification component", because the relative locational relationship among unit zones is affected ultimately by the regionalization of these unit zones within the study area.

The third element is called "spatial autocorrelation component". Accompanied with the just described configurational component, this component is often treated as "map pattern component"[3]. The spatial autocorrelation component arises as bias in the estimation of the distance parameter of gravity model by ordinary least squares regression owing to the existence of spatial autocorrelation in the mass terms.

As just discussed, the theoretical studies since the 1970's have clarified that the distance parameter is dominated not only by the behavioral component measuring the friction of distance, but also by both the configurational and spatial autocorrelation components. Therefore, for the purpose of measuring the friction of distance by the distance parameter in consideration of its theoretical meaning, it becomes necessary to separate the effects of the behavioral, configurational and spatial autocorrelation components in the distance parameter, or to extract only the effect of the behavioral component by removing those of the configurational and spatial autocorrelation component from the distance parameter.

Some theoretical researchers suggest the following tentative plans to satisfy this necessity. Johnston (1976) derives the method of the standardization of distance in order to restrain the configurational component from invading the distance parameter at its estimation[4]. Sheppard (1979), however, doubts its statistical effectiveness. Even if this method is very effective, there remains the separation of the other two components, i. e. behavioral and spatial autocorrelation components.

The other tentative methods are the respecification of spatial interaction models, which are attempted by Fotheringham and Webber (1980) and Fotheringham (1983a, 1983b). After assuming that there exists a feedback between the volume of spatial interactions, mass terms and distance in Eqn. 1, Fotheringham and Webber (1980) reformulate them into the simultaneous equation system where the distance parameter can be estimated by indirect least squares or two-stage least squares regression. Fotheringham (1983a, 1983b) formulates a new set of spatial interaction models which are termed competing destinations models.

Although some tentative plans are suggested as just described, there remain many difficult problems on the way of the theoretical studies to achieve the separation of the effects of the behavioral, configurational and spatial autocorrelation components, or the extraction of the effect of the behavioral component by itself which indicates the friction of distance. In order to resolve these difficult problems or to examine the effectiveness of the tentavive plans, it is necessary to promote the empirical approaches as well as the theoretical ones.

IV. Empirical studies on the distance parameter

Existing empirical studies

There also exist empirical studies on the distance parameter in addition to the theoretical studies. In these empirical studies, researchers attempt to analyze the variation of the distance parameter which is estimated by using actual data of flows. Reviewed which of the behavioral, configurational and spatial autocorrelation components these researchers mainly focus their interests upon, their empirical studies can be classified into four types. It can be, therefore, said that each of these four types is characterized by its analytical framework.

In the first type, a researcher stresses the behavioral component because his analytical framework is of the comparison of the parameter between various kinds of flows within a certain study area, i. e. under the fixed level of the effect of the configurational component. There exist five empirical studies which can be classified into this type. The researchers of these studies are listed in Table 1, which also presents the study area and unit zones, the types of flows and the employed spatial interaction model for each study. Table 1 contributes the following discussions.

Among the empirical studies in the first type, Alcaly (1967) compares the distance parameter between the four flows of air, railway, bus and private-car passengers within California, the United States of America. As a result, he affirms that the distance parameter reveals a higher

Table 1. The first type of empirical studies on the distance parameter.

Author	Study area (Unit zones)	Types of flows	Employed spatial interaction model: Name	Employed spatial interaction model: Equation
Alcaly (1967)	California, U. S. A. (Ten cities)	Four types of passenger flows	Gravity models	$T_{ij}=k\ P_i^{\alpha_1}P_j^{\alpha_2}d_{ij}^{-\beta}$ $T_{ij}=k\ (P_iP_j)^{\alpha}\ d_{ij}^{-\beta}$
Black (1972)	U. S. A. (Nine regions)	Twenty-four and eighty types of commodity flows	Modified gravity model	$T_{ij}=O_iD_jd_{ij}^{-\beta}/(\sum_j D_jd_{ij}^{-\beta})$
Black (1973)	U. S. A. (Nine regions)	Eighty types of commodity flows	Modified gravity model	$T_{ij}=O_iD_jd_{ij}^{-\beta}/(\sum_j D_jd_{ij}^{-\beta})$
Fujime (1977)	Kagawa, Japan (Sixty zones)	Four types of person trips	Gravity model	$T_{ij}=k(O_iD_j)^{\alpha}\ d_{ij}^{-\beta}$
Hathaway (1975)	London, U. K.	Twelve, nine, six and eight types of person trips	Entropy maximizing model	$T_{ij}=A_iO_iB_jD_j\ \exp(-\beta d_{ij})$
Kaneko (1973)	Japan (Nine regions)	Nineteen types of commodity flows	Modified gravity model	$T_{ij}=k\ O_iD_jd_{ij}^{-\beta}/\sum_i O_i$

T_{ij}=volume of flows from zone i to zone j,
P_i=population of zone i,
P_j=population of zone j,
O_i=total volume of flows out of zone i,
D_j=total volume of flows into zone j,
$A_i=[\sum_j B_jD_j\exp(-\beta d_{ij})]^{-1}$,
$B_j=[\sum_i A_iO_i\exp(-\beta d_{ij})]^{-1}$,
d_{ij}=distance between zones i and j,
β=distance parameter, and
α, α_1, α_2 and k=the other parameters.

value in the former passenger flows and a lower value in the latter. Both Black (1972, 1973) and Kaneko (1973) estimate the distance parameter by using various kinds of commodity flows, and then point out the difference in the estimated values. Analyzing the person flows within urban areas, Fujime (1977) and Hathaway (1975) assert that the distance parameter differs in the demographic attributes of moving persons such as sex, age and occupation and in the purpose of moving. In sum, the five researchers clarify the difference of the distance parameter between various types of flows. In other words, they demonstrate the effect of the behavioral component upon the distance parameter. Attention, however, must be given to the fact that the distance parameter estimated by them is invaded by the other component, i. e. the spatial autocorrelation component.

In the second type, a researcher estimates the distance parameter by each unit zone within an study area. His emphasis is, therefore, laid upon the comparison of the distance parameter between the unit zones in order to analyze both the behavioral and configurational components besides the spatial autocorrelation component. As shown in Table 2, the analyses by Gould (1975) and Leinbach (1973) are examplified as this second type. They compare the distance parameter between cities in Sweden and West Malaysia, respectively. As a result, they clarify that the distance parameter varies in relation to the relative location of the cities. It can be, therefore, said that they indirectly demonstrate the effect of the configurational component upon the distance parameter.

Besides these two studies, there further exist the empirical studies which can be classified

Table 2. The second type of empirical studies on the distacne parameter.

Author (s)	Study area (Unit zones)	Type of flows	Employed spatial interaction model: Name	Equation
Chisholm and O'Sullivan (1973)	Great Britain, U. K. (Seventy-eight zones)	Freight flows	Gravity model	$T_{ij}=k_iO_iD_jd_{ij}^{-\beta_i}$
Fotheringham (1981)	U. S. A. (100 SMSA's)	Passenger flows	Gravity model	$T_{ij}=k_iP_j^{\alpha_i}d_{ij}^{-\beta_i}$
Gould (1975)	Sweden (101 regions)	Geographic information	Gravity model	$T_{ij}=k_iP_j^{\alpha_i}d_{ij}^{-\beta_i}-1$
Itoh (1982)	Tokyo, Japan (Eighty-seven zones)	Automobile flows	Entropy maximizing model	$T_{ij}=A_iO_iD_j\exp(-\beta_id_{ij})$
Itoh and Nam (1982)	Seoul, Korea (111 zones)	Person trips	Gravity model Entropy maximizing model	$T_{ij}=k_iO_iD_jd_{ij}^{-\beta_i}$ $T_{ij}=A_iO_iD_j\exp(-\beta_i-d_{ij})$
Leinbach (1973)	West Malaysia (Sixteen towns)	Telephone exchanges	Gravity model	$T_{ij}=k_iP_j^{\alpha_i}d_{ij}^{-\beta_i}$
Okuno (1967)	Shizuoka, Japan (Twenty-five zones)	Person trips	Gravity model	$T_{ij}=k_iP_iP_jd_{ij}^{-\beta_i}$
Riddell and Harvey (1972)	Sierra Leone (148 chiefdoms)	Migration	Gravity model	$T_{ij}=k_iP_jd_{ij}^{-\beta_i}$
Southworth (1979)	Greater London, U. K. (Sixty-three and twenty-seven zones)	Person trips	Entropy maximizing model	$T_{ij}=A_iO_iD_j\exp(-\beta_id_{ij})$

T_{ij}=volume of flows from zone i to zone j,
$A_i=[\sum_j D_j\exp(-\beta_id_{ij})]^{-1}$,
P_i=population of zone i,
d_{ij}=distance between zones i and j,
P_j=population of zone j,
β_i=distance parameter specific to zone i, and
O_i=total volume of flows out of zone i,
α_i and k_i =the other parameters specific to zone i.
D_j=total volume of flows into zone j,

into the second type. These are the analyses of the distance parameter in Britain by Chisholm and O'Sullivam (1973), in the United States of America by Fotheringham (1981), in the Tokyo metropolitan area by Itoh (1982), in Seoul by Itoh and Nam (1982), in Shizuoka, Japan by Okuno (1967) and in Sierra Leone by Riddell and Harvey (1972), because these researchers attempt to investigate the regional variation of the distance parameter. Most of these researchers clarify that the distance parameter becomes lower in urban areas or central cities and higher in rural areas or local cities. In particular, Chisholm and O'Sullivan describe this variation as the urban/rural dualism. It can be, therefore, considered that the behavioral component reflecting socio-economic attributes of unit zones, more strongly dominates the distance parameter that the configurational component in these studies.

In the second type of these empirical studies including those by Gould (1975) and Leinbach (1973), gravity model is often employed and then its distance parameter is estimated by ordinary least squares regression. There often remains the problem of the spatial autocorrelation component in this second type. Incidentally, the work by Southworth (1979) can be also characterized as the second type. In this study, the distance parameter is estimated by each unit zone within the greater London area in order to analyze the effect of the zone specification component rather than those of the behavioral and configurational components.

In the third type of the empirical studies, an interest is focused upon the map pattern

Table 3. The third type of empirical studies on the distance parameter.

Author(s)	Study area(s) (Unit zones)	Type(s) of flows	Employed spatial interaction model: Name	Equation
Griffith and Jones (1980)	Twenty-four urban areas, Canada (Census tracts)	Journey to work	Entropy maximizing model	$T_{ij}=A_iO_iB_jD_j\exp(-\beta d_{ij})$
Ishikawa (1981)	Shiga, Japan (Fifty municipalities)	Migration and journey to work	Entropy maximizing model	$T_{ij}=A_iO_iB_jD_j\exp(-\beta d_{ij})$

T_{ij}=volume of flows from zone i to zone j,

O_i=total volume of flows out of zone i,

D_j=total volume of flows into zone j,

$A_i=[\sum_j B_jD_j\exp(-\beta d_{ij})]^{-1}$,

$B_j=[\sum_i A_iO_i\exp(-\beta d_{ij})]^{-1}$,

d_{ij}=distance between zones i and j, and

β=distancce parameter.

component, i. e. both the configurational and spatial autocorrelation components. The studies by Griffith and Jones (1980) and Ishikawa (1981) are included in this third type as shown in Table 3. In these two studies, the distance parameter of gravity model, however, is not estimated by ordinary least squares regression. It is necessary to employ gravity model and then estimate its distance parameter by ordinary least squares regression, if the researchers attempt to analyze the map pattern component by itself[5].

There also remain the empirical studies which were published before the beginning of the theoretical studies and are uncategorized into the above three types. In this study, all of these studies are treated as the fourth type. The studies by Olsson (1965) and Taaffe (1962) can be taken up as the examples of this fourth type. Reviewing the empirical studies before the 1970's including just mentioned studies, Olsson (1966) points out that the distance parameter should be influenced by the levels of the technical and socio-economic developments of the study area, the purpose to move and the magnitudes of the mass terms.

Subjects for empirical studies

As discussed in Chapter III, it is necessary for the empirical studies to separate the effects of the behavioral, configurational and spatial autocorrelation components in the distance parameter for the purpose of developing the achievement of the previous theoretical studies. Especially, it is geographically meaningful to empirically extract the effect of the behavioral component from the distance parameter, because this component not only measures the friction of distance but also reflects the regional socio-economic attributes.

On the other hand, the existence of the spatial autocorrelation component is nothing else but the problem in relation to the estimation of the distance parameter, because the distance parameter is always influenced by the spatial autocorrelation component. If the distance parameter in gravity model can be estimated by generalized least squares regression, it is not invaded by the spatial autocorrelation component. Also the distance parameter in entropy maximizing model is not influenced by the spatial autocorrelation component if it is estimated by procedures except for ordinary least squares regression. It can be, therefore, said that it is geographically meaningless to extract the effect of the spatial autocorrelation component by itself from the distance parameter.

For these reasons, it is necessary for the empirical studies to analyze the distance parameter dominated only by the behavioral and configurational components and then to discuss the following two subjects. The first is to separate the effects of the behavioral and configurational components in the distance parameter and the second is to pursue the regional attributes dominating the separated effect of the behavioral component, i. e. the measure of the friction of distance. From this point of view, the described four types of the empirical studies are evaluated below.

In the first type, two problems occur although the interest is focused mainly upon the behavioral component. One is the deficiency of analyzing the regional socio-economic attributes which may dominate the variation on the behavioral component. The other is that the distance parameter estimated in this type is affected by the spatial autocorrelation component. The latter problem can be easily solved by employing the other estimation procedures of the distance parameter. In the case of this type, only one distance parameter, however, is estimated by each type of flows in a certain region where spatial interaction model is applied. The comparison of the distance parameter, therefore, can not be made between unit zones in an study area but between various types of flows. As a result, it can be said that, in the analytical framework of the first type of the empirical studies, it is methodologically difficult to discuss the above mentioned second subject.

In the second type of the empirical studies, the regional variation of the distance parameter is analyzed. This regional variation is dominated by both the behavioral and configurational components and thus, in the analytical framework of the second type, it is possible to discuss the above mentioned two subjects. This regional variation may be, however, distorted by the other component, i. e. the spatial autocorrelation component. Although Itoh (1982) and Itoh and Nam (1982) analyze the distance parameter which is not invaded by the spatial autocorrelation component, they achieve neither the separation of the effects of the behavioral and configurational components, nor the extraction of the regional socio-economic attributes which may affect the variation of the behavioral component. In sum, in the second type of the empirical studies, any researchers have not solved the above mentioned two subjects although they can place the distance parameter dominated only by both the behavioral and configurational components as the analytical object by their methodological framework.

In the third type, the researchers focus their interests upon the problem of the spatial autocorrelation component by analyzing the map pattern component of the distance parameter. As mentioned above, the existence of the spatial autocorrelation component is nothing else than the technical problem which relates with the estimation procedure of the distance parameter. As a result, this third type of the empirical studies is not concerned with the aforementioned two subjects which are given to the empirical studies in geographical perspective.

In the fourth type of the empirical studies, no researcher has analyzed the relationship between the variations of the distance parameter and the behavioral, configurational or spatial autocorrelation component, because this fourth type was done before the beginning of the theoretical studies of the distance parameter.

V. Concluding remarks

The purpose of this paper is to clarify the recent progress and subjects of geographical studies on the distance parameter of spatial interaction model. The discussions of this paper can be summarized as follows :

The theoretical studies since the 1970's have clarified that the distance parameter is no longer a measure of the friction of distance because it is dominated not only by the behavioral component measuring the friction of distance but also by the configurational and spatial autocorrelation components. As a result, it becomes necessary to keep the variation of the distance parameter from the effect of the configurational and spatial autocorrelation components. In order to resolve this problem, some researchers attempts to suggest the tentative plans such as the deviation of the method of standardization of distance and the reformulation of spatial interaction model, although the real effectiveness of their suggestions remains the object of debate.

The empirical studies can be classified into four types. Among the four, the first type is concerned with the difference in the distance patameter between the various kinds of flows. The second deals with the regional variation in the distance parameter. And the third is devoted to analyze the map pattern component which consists of the configurational and spatial autocorrelation components. The remaining fourth type is of the empirical studies which can not be categorized into the just mentioned three types.

It becomes necessary for the empirical studies to analyze the following two subjects. The first subject, which is almost similar to the aforementioned problem in the theoretical studies, is to empirically extract the effect of the behavioral component from the variation of the distance parameter. The second is to clarify the regional attributes which should affect the separated effect of the behavioral component. Although these two subject are not solved yet at all by any types of the empirical studies, it may be possible to solve them in the analytical framework of the second type where the comparison of the distance parameter is made between unit zones in a study area.

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Notes

1. So-called spatial choice model, or disaggregate model, including logit and probit models can be categorized into spatial interaction model in a broad sense. In this paper, the author, however, refers to only those that

are classified into spatial interaction model in a narrow sense, because the measure of distance or the distance parameter is not always constituent of spatial choice model.

2. Taylor (1971, 1975) systematically categorizes various types of distance functions. He divides all of them into single-log and double-log types and then subdivides the former into square root exponential, exponential and normal types and the latter into Pareto and log-normal types. As a result, various types of distance functions are classified into five.
3. In the case of the distance parameter of gravity model, some researchers do not conceptionally separate the configurational and spatial autocorrelation components but treat them as one component, i. e. the map pattern component. In this paper, the author conceptionally separates the configurational and spatial autocorrelation components, because the latter component is brought about by the estimation procedure and thus seems a latent bias in the implication of the distance parameter.
4. In the case of the distance standardization method, the distance parameter is estimated on the basis of standardized distance d_{ij}^* which is produced from actual distance d_{ij} by using the following function:

$$d_{ij}^* = (d_{ij} + 1.0 - S_i/R_i) \times 100.0,$$

where S_i is the distance from zone i to the nearest zone and R_i is the difference between the distance S_i and the distance from zone i to the farthest zone.
5. In the dispute originated by Curry (1972) and followed by many researchers on *Regional Studies*, the interest is focused upon the interpretation of the distance parameter in gravity model which is estimated by ordinary least squares regression. The author is, therefore, afraid that this third type should be categorized into the spatial autocorrelation study represented by the work of Cliff and Ord (1973) rather than the study on the distance parameter.

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