EVALUATION OF EXTERNALITIES CAUSED BY ROAD TRANSPORTATION IN A METROPOLITAN AREA

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Abstract: This paper presents a methodology to evaluate the external cost of traffic congestion generated by residents in an urban area, and a trial calculation in Sendai Metropolitan Area. Externalities related to car traffic depend on two factors: transportation system and land uses. This system is able first to distinguish between a generator and a receiver of externalities and then to estimate who generates the externality, how much of it generates, and who receives it. With this model, the relation between land use and generated externality are investigated. Using it, it will be possible to provide useful information for land use and transportation policies.

Key Words: externality, traffic congestion, land use policy, suburbanization

1. INTRODUCTION

It is well known that problems such as traffic congestion, air pollution, or noise pollution caused by car travel are becoming more severe. All are characterized by a situation known as "externality" in the economics context, since the person who causes it does not share the appropriate cost. It is said that externalities distort the market mechanism and also generate deadweight loss. Thus, public interventions such as regulation or tax system should be adopted to internalize the external costs. For instance, TDM schemes such as road pricing are proposed to reduce car travel demand. However those externalities caused by car travel depend on the urban structure i.e., land use pattern, road network configuration and residential location. Therefore, a land use approach such as the introduction of development tax in suburbs is also essential in order to tackle the problems of externalities caused by road transportation.

The objective of the present study is to quantitatively clarify the relationships between urban structure and externalities caused by car travel, and to suggest a desirable urban structure from the viewpoint of external costs. To achieve this, an evaluation system for urban externalities caused by car travel is constructed. The original concept of this system is to distinguish between generators and receivers of externalities. With this system, it is easy to determine who generates the externality, how much it generates, and who receives it. This information is displayed in an externality incidence matrix, in which the rows express the generator of externalities and the columns the receiver. This information is useful to assess externality-internalizing policies. In addition, one more feature is the integration of a Geographical Information System (GIS) to handle various types of spatial data such as land attributes, transportation networks, etc. As a result, it is easier to store, analyze, manage and display all related data visually.

In many cities, urban sprawl to suburbs causes an increase in car traffic volume. The objective of the present study is, therefore, to estimate the amount of the external cost caused by increased traffic that changes when population in the suburban area increases. In this paper only traffic congestion is considered since the amount of time loss caused by congestion is perceived as one of the most serious external effects. As a case study, Sendai metropolitan area of Japan is selected. In the following section, the definition of externality, externalities associated with car traffic and existing countermeasures for congestion externality are discussed. This study's evaluation method for congestion externality is explained in section 3. In section 4, this model is applied to Sendai Metropolitan Area and the external cost by zone is estimated. Finally, we offer some concluding remarks in section 5.

2. CONGESTION EXTERNALITY AND ITS COUNTERMEASURES

2.1 About the Externality

Increasing traffic volume generates many problems such as traffic congestion, environmental pollution, noise and others. These problems can be interpreted as an inefficiency of resource allocation and are called externalities in the economics literature.

Many economists have studied the concept of externality since Marshall introduced it in 1890. However there are several interpretations about the meaning of it, and there is no general consensus on its exact definition. In this study, the following three conditions are regarded as common grounds in previous works on externality. We say that an externality exists when these three conditions are met: (1) Behavior of an actor A (the generator) has an effect on the utility of another actor B (the receiver); (2) To have an effect on the actor B is not the purpose of behavior of an actor A; (3) Actor B cannot control the effect of the actor A. In short, externality exists when actor A does not pay an appropriate cost for his/her effect on other persons.

2.2 Congestion Externality and Land Use

Externalities in an urban area closely depend on land use decisions, such as where to live or where to work. The negative influences of suburbanization or decentralization have been frequently discussed. It is considered that these influences are related to the externalities. The aggravation of the traffic and environmental situation, additional construction costs of infrastructure, and declining of commercial activities in the center are examples of externalities (Suzuki and Miyamoto, 2000). Traffic-related externalities are one of the most serious effects of suburbanization.

Many studies about car traffic-related externalities have been conducted for years in Europe and the USA (e.g. ECMT/OECD, 1994). Similarly, there are numerous studies that evaluate the external cost. Verhoef (1994), for instance, made a typology of external costs of road transport. According to his work, external costs resulting from actual transport activities can be classified in three categories: (1) Intra-sectoral externality, e.g. congestion; (2) Adverse effects on social environments, e.g. noise and accident; (3) Adverse effect on ecological environments, e.g. air pollution. In our study, congestion is selected as the externality caused by road transportation. The reasons for this are,

(1) In most existing studies, congestion is regarded as the largest externality in terms of monetary cost.
(2) It is difficult to specify the external cost that each actor generates because there are many, usually interrelated concerned parties (the generators and the receivers).
(3) It closely depends on land use and road network configuration.

(4) The condition of congestion is expected to worsen, if no intervention is taken.

2.3 Countermeasures to Congestion Externality

(1) Road Pricing

The driver on a congested road is not only slowed down but he also contributes to slow down others. However, when considering costs it is very likely that he takes into account only his own travel cost and disregards that of others. In this case, a difference between social and private cost generates inefficiency, and as a consequence demand for road use is above the optimal level. This difference is just a congestion externality. So, the well-known approach introduced by Pigou (1920) is effective to offset the inefficiency. Imposing a tax on each driver can attain a social optimum. A tax of this kind is known as Pigovian tax, and a road-pricing scheme is an application of it. The concept is very clear and it is said to be the most effective (First-best) method for externality, because the tax is imposed to the cause of the inefficiency. It is difficult to implement this tax, however, because it requires that a public agent have all the information regarding the external cost by each driver, and also to levy the congestion tax on all links. Moreover, the level of congestion is highly variable, and changes by the hour. For the present, this method presents many technical difficulties. Therefore, many economists have proposed various practical second-best approaches. Some of them, such as cordon line pricing, have been put to practical use in some cities.

Road pricing has the effect of controlling traffic demand in the short run. In the long run, it has been shown that it would cause a change of the land use configuration, towards more compact development in general, because of increased trip costs (Arnott, 1979; Kanemoto, 1980; Sullivan, 1983). However, most of these studies are limited to a simplified urban structure and network configuration, one mode trip, one destination, uniform population distribution and so on. Of course, these simplifications give us a number of clear-cut findings. In recent years, the research of second-best pricing is pursued actively (e.g. Verhoef, 2000; May and Milne, 2000). However, there is little empirical research for the establishment of congestion tax in an actual urban area with an irregular road network.

(2) Land Use Policy

More practical measures such as land use regulation or location guidance is adopted for mitigation of traffic congestion. These are also a second-best strategy for congestion externality because first-best pricing is not feasible at the present. The generation of traffic volume depends on the location characteristics in the urban area. If a zone is near a station of railway, automobile mode share will be lower. A person who lives near to his office may commute there on foot or by bicycle.

Land use policy is a practical measure and thought to contribute to relieve traffic congestion. Actually, land use regulations, such as zoning or growth control, are carried out in many countries. But the policy may decrease social welfare depending on the situation. Therefore it is important to investigate the influence and evaluate the external cost. In order to design a land use scheme that takes into account traffic congestion, it would be useful to have information regarding the generated amounts of the externality by zone. This is the subject of the following sections.

2.4 Required Information and Externality Incidence Matrix

In the previous section, congestion externality caused by car traffic and its countermeasures were discussed. There it was argued that, although the imposition of a road charge on each driver for his share of external cost is the first-best method to deal with traffic congestion, it is a method difficult to turn it into practice because of inadequate technology and high operational costs. Therefore, we turn our attention to some second-best strategies, of which a land use approach is thought to be effective. These public interventions can reverse the market failure, but in order to do so, it is important to have all the necessary information and investigate the likely impact of the externality countermeasures. Information such as who generates the externality, how much of it generates, and who receives it, is necessary to control the externality. However, so far we lack the appropriate tools to clarify all these issues. The objective of this study is to propose a tool to obtain a detailed information by location with an evaluation model. Relationships between generator and receiver and quantity of the externalities are expressed in the externality incidence matrix shown in Figure 1, where EC_{ij} denotes external cost and i indicates generator and j recevers. This information is necessary for the design of public policies. In this paper, the information can be linked to the location in the urban area and represented visually with a GIS (Geographical Information System).

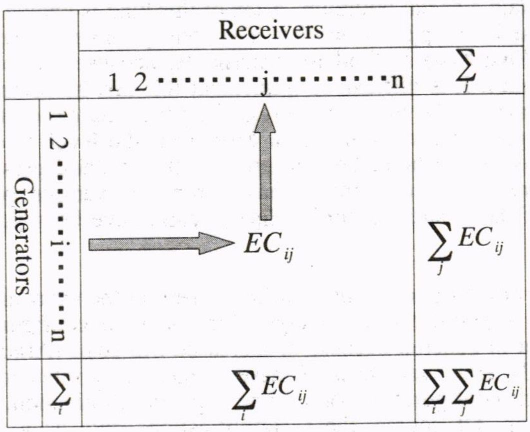

Figure 1. Externality Incidence Matrix

3.METHODOLOGY

In the previous section the information required to set externality countermeasures was mentioned. This study proposes an operational model to evaluate the zonal external cost caused by traffic congestion in the actual city. This model can express the local differences of externality generation by dividing the study area into zones. The structure of the evaluation model for analyzing a zonal congestion externality is described in this section.

3.1 Model Structure

The evaluation model for zonal congestion externality is composed of three parts: a GIS-based land use database, which has land attributes and road network, a traffic model, and a model of evaluation of external cost. These elements are explained as follows;

(1) Database

A GIS is used as a database and output display. The database contains land attributes and the road network. The urban area is divided into zones each of which has one centroid. Road network consists of a set of links and nodes, which includs the centroids of zones. Zonal data contains land uses, area, population, number of employees, etc., and person trip data used by the traffic model.

(2) Traffic Model

The traffic model operates in 3 steps, car trip generation, trip distribution and trip assignment. In the step of car trip generation, trip generation and attraction by automobile can be explained by zonal attributes such as population and share of travelers that select automobile as transportation mode. The difference of modal choice between zones is important for the analysis of transportation and land use. From the viewpoint of traffic congestion, it is desirable that people lives in an area where public transportation is highly developed, trip distance is short and the share of car using is low. In this model, modal split doesn't depend on the travel cost. It is better to consider travel cost explicitly. Trip distribution between zones was estimated with the BPR gravity function. It is denoted as,

$$q_{ij} = \frac{k_{ij} G_i A_j t_{ij}^{-\lambda}}{\sum_j k_{ij} G_i A_j t_{ij}^{-\lambda}} \tag{1}$$

where q_{ij} is trip distribution from i to j, Subscript ij is OD pair ij, G_i expresses the trip generation from i by automobile, A_j expresses the trip attraction to j by automobile, t_{ij} is travel time from i to j, and k and λ are the parameters.

Travel time between each pair of centroids can be calculated by trip assignment. Traffic volume on each link and travel time between all zones can be derived following Wardrop's first principle (1952). Traffic demand estimation package software "JICA STRADA" was used to conduct the calculation.

3.2 Process to Evaluate the Zonal Congestion Externality

In this paper, the external cost of traffic congestion is defined as an increment of travel time for households in the urban area generated by a newcomer who migrates into the target zone k. It is assumed that an increase of population occurs in the target zone alone. The aim of this study is not to investigate how much external cost is generated in the urban area but the spatial difference of the generation of congestion externality and the relation between generator and receiver of it. Average external cost of traffic congestion per capita generated by the new comer in the target zone is named as "Generation of External Cost (GEC)" and external cost of traffic congestion received by drivers living in other zone is called the "Recipient of External Cost (REC)".

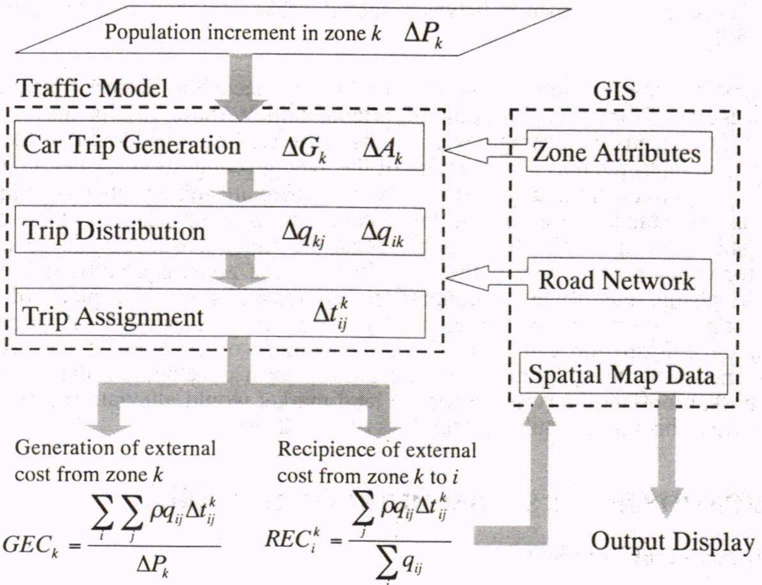

Figure 2 Flow of the Evaluation for the Zonal External Cost

Figure 2 is a flow chart of the process to evaluate congestion externality by zone, where k indicates the target zone. If population in target zone k increases by ΔP_k, trip generation by car from zone k (going destinations) and attraction to zone k (coming home) will increase by ΔG_k and ΔA_k. The increments of trip distribution Δq_{kj} and Δq_{ik} are calculated by ΔG_k and ΔA_k from equation (1). The increase of OD trips by automobile from and to zone k alters the network equilibrium. Traffic volume of newcomers has an effect not only on drivers on the link through which they pass but also drivers on all network links in the urban area. In short, most households in the urban area will suffer external congestion costs by new comers in the target zone, therefore the name of network externality. Average external cost of congestion per capita generated by the new comer in the target zone is expressed as,

$$GEC_k = \sum_i \sum_j \rho q_{ij} \, \Delta t_{ij}^k / \Delta P_k \tag{2}$$

where GEC_k is the average external congestion cost per capita generated by the new comer in the target zone k, Δt_{ij} is a change of travel time for the drivers who trips from zone i to zone j, q_{ij} is trip distribution between zone i and j, ρ is each driver's value of time.

The external cost of traffic congestion per trip received by drivers living in other zones is calculated as:

$$REC_i^k = \sum_j \rho q_{ij} \Delta t_{ij}^k \Big/ \sum_j q_{ij} \tag{3}$$

where $REC_i{}^k$ is the external cost of traffic congestion generated by new comers living in zone k and received by drivers living in zone i. The output can be visually displayed with the help of a GIS.

3.3 Characteristics and Usefulness of the Proposed Model

The model proposed in the study has the following characteristics,

(1) It can deal with a large-scale road network.
(2) It visually displays the generator and receiver of external cost of traffic congestion.
(3) It analyzes the relationships between spatial urban structure and the generation of externality.

These characteristics are useful to provide information needed to discuss traffic congestion countermeasures. From the viewpoint of pricing policy, these results may offer useful material. GEC_k means the average external cost generated by a resident that locates in the zone. It can be interpreted as a benchmark of the average congestion tax per a day imposed on a person who lives in the target zone. However, there are some problems to interpret the outcome as the standard for one of the second-best pricing schemes. First of all, trip characteristics such as destination, mode, departure time, frequency and so on, are not uniform for every person even if they live in the same zone. Secondly, it is technically difficult to charge the drivers a congestion tax according to their place of residence. Therefore this information is not extremely useful for the purpose of pricing policy. However, the information can be used for the purpose of developing land use policies. Zonal external cost information can be the ground for a development charge or land use regulation. Appropriate intervention for the land market would alleviate the market failure by externality. This model could be useful for these reasons.

4. APPLICATION IN THE SENDAI METROPOLITAN AREA

4.1 Study Area and Data Source

In this section, congestion cost is analyzed by the proposed model using real data. We select as a study area, the Sendai Metropolitan Area, in Tohoku region, Japan. Sendai Metropolitan Area is composed of 20 municipalities, with a total population of almost 1.4 millions in an area of about 2200 square km. The shape of the city is monocentric with a subway line running in the north-south direction.

OD traffic volume is obtained from the Person Trip Survey in 1992 and Road Traffic Census in 1994. Land use data is taken from Basic Planning Survey in 1992. The road network used corresponds to 1992 and consists of 1904 links and 1477 nodes. The study area is divided into 168 zones, each one with its corresponding centroid (see figure 3).

4.2 Characteristics of Zones

Figure 3 is a map of the study area divided into 168 zones with the subway (a black line), road networks (white lines) and Sendai station in the center of the area, overlaid. The automobile share in the modal split by zone is expressed in the map. It can be said that the modal share of automobile in the areas near the subway line is generally lower than that in the far areas. The farther from the center of the city the zone is, the higher the modal share of automobile. So, generation of the trip by car in the suburb area will be larger than in the central area even if the number of population in the zone is same.

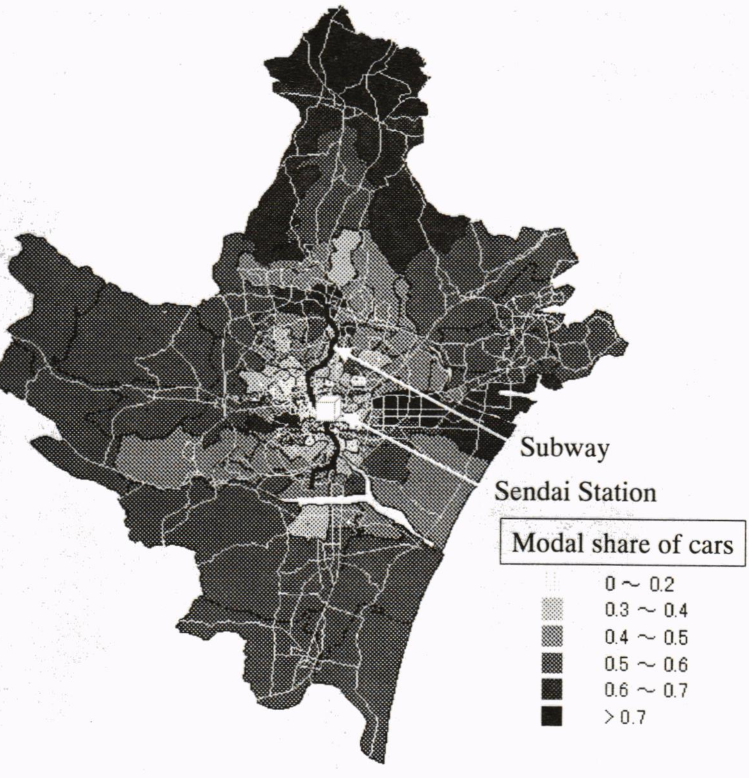

Figure 3. Study Area and the Modal share of cars

4.3 Evaluation of Congestion Externality

An increment of population of 50,000 in the target zone ΔP_k is assumed. Although it may seem large, the figure is not extraordinary for a large-scale residential development. On the other hand, if the increment of population in the target zone ΔP_k is small, calculation for the traffic assignment is likely to become unstable. A value of 54 yen/min per car is adopted as the driver's value of time. 32 zones are selected as target zones for the evaluation of GEC.

Following, two zones from among the above 32 are selected as examples of target zone for the comparative study of GEC and REC. One is named Zone-A, an area adjacent to the subway line and about 5km north from the Sendai station. Modal share of car trips in this area is 0.39. The other is named Zone-B, and is a suburban zone 12 km northeast from Sendai station. Modal share of car trip in this area is 0.55, a high figure explained by the inconvenience to residents of public transportation. The zonal external cost inflicted by these target zones to other area (REC) is shown in Figure 4. The total external congestion cost generated by newcomers to these target zones (TEC) is 29.7 (million yen/all urban area) for Zone-A and 40.8 (million yen/all urban area) for Zone-B. In average, the external cost per capita generated by a newcomer to each target zone GEC is 595 and 816 (yen/a day) for Zone-A and Zone-B, respectively.

Compared with the case of Zone-A, an increase of population in Zone-B has a heavier influence on surrounding areas. There are two reasons for this. One is the higher modal share of car trip in Zone-B. More car trips originate from Zone-B than from Zone-A. The other is related to the road network configuration. Since there are few roads to access the central area form B-zone, an increase of traffic volume from or to B-zone has a direct influence on surrounding zones through congestion of access roads to central area.

These results clearly show who generates the externality, how much of it generates, and who receives it.

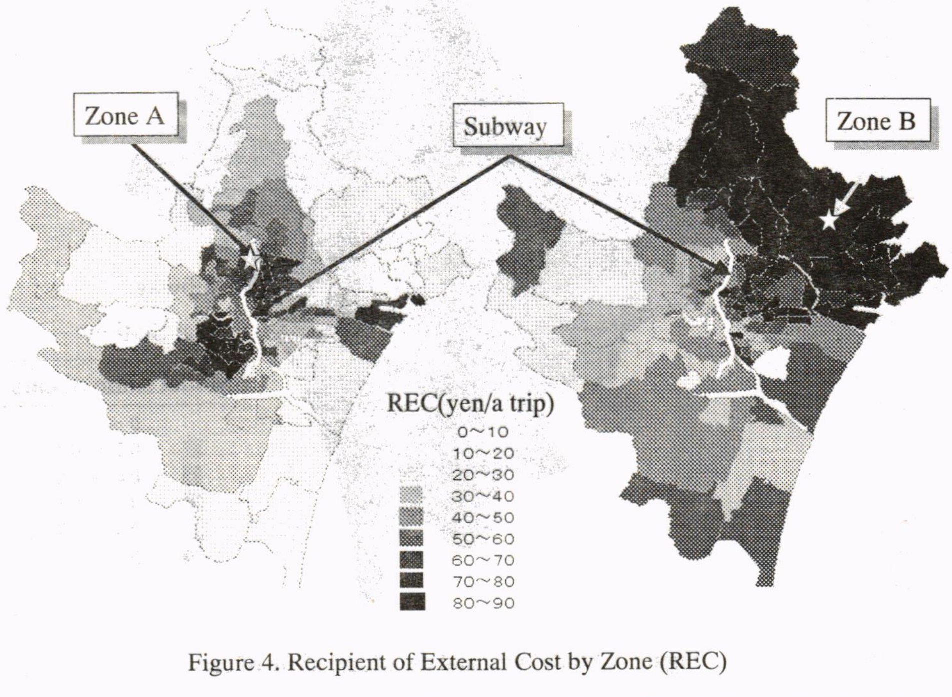

Figure 4. Recipient of External Cost by Zone (REC)

32 zones are selected for the evaluation of GEC, the result of which is shown in Figure 5. It is difficult to interpret this result due to the complexity of the road network and trip characterization. However, a broad trend can be grasped. GEC is higher in zones with a high proportion of car modal share that are located near road links with heavy traffic volume. Generation of externality in the east and west zones is larger than north and south,

perhaps due accessibility to transit service, if we recall that the subway line follows a north-south route. More detailed investigation is necessary to clarify these matters.

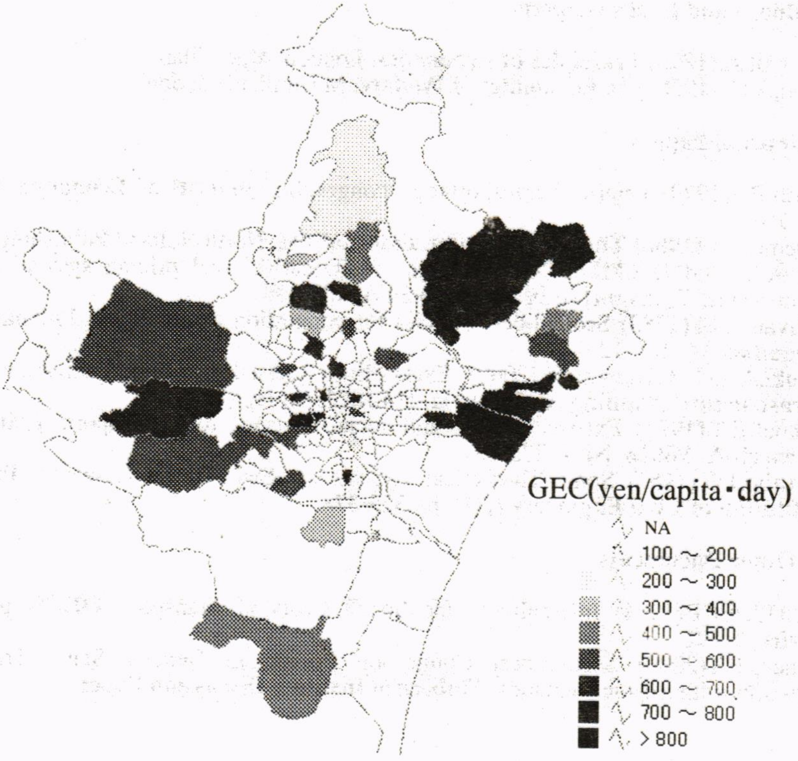

Figure 5. Generation of External Cost from the Target Zones (GEC)

5.CONCLUSIONS

This study proposed an operational methodology to analyze the relation between generators and receivers of congestion externality. It is hoped that the information proposed in this study will be useful to design land use schemes for metropolitan areas. The external cost of traffic congestion generated from each zone was estimated, and a test evaluation of the tool was carried out using Sendai Metropolitan Area as a case study.

In the case study, the following tendencies of GEC and REC are confirmed. Generation of the external cost by zone (GEC) in the suburb zones is generally larger than that in the central zones. In the analysis of the recipient of external cost by zone (REC), it was confirmed that the external cost is borne not only by zones near the origin of the externality, but also by zones far in urban space. This result is a clear expression of the indirect and network character of the externality.

In the future, it is planned to extend the scope of this study to include externalities other than traffic congestion.

ACKNOWLEDGEMENT

The authors are grateful to Mr. Y. Nishiyama, Mr. K. Hoshi of IBS (Institute of Behavioral Sciences) and Dr. A. Yoshida of Tohoku University of Art & Design for supplying data for analysis, and for their useful advice.

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