Effect Equilibrium Approach in Calculating the Economic Range of a Freeway Industrial Zone

Xin Miao*[,1], Bao Xi*[,2] and Xi-qiao Zhang**
* National Center of Technology, Policy and Management
School of Management
Harbin Institute of Technology
Harbin, 150001
China
[1] tel: +86 451 8640 2927
fax: +86 451 8640 2960
e-mail: miaoxin@yahoo.cn
[2] tel: +86 451 8640 2927
fax: +86 451 8640 2960
e-mail: xib@hit.edu.cn

** School of Transportation Science and Engineering
Harbin Institute of Technology
Harbin, 150090
China
tel: +86 451 86400119
fax: +86 451 86402260
e-mail: zhangxiqiao@126.com

EJTIR, **8**, no. 1 (2008), pp. 31-44

Received: November 2006
Accepted: September 2007

This research aims to develop a valid method to examine the relationship between transportation infrastructure and economic growth through the measurement of the economic boundary of a freeway industrial zone in developing countries. By comparing the similarities of a freeway industrial zone with an electromagnetic field, the Boit-Schwander law in electromagnetism is applied to create an electromagnetic model, which can calculate the attractive effect caused by a freeway on its influential area. When the attractive effect is equal to the traffic impedance, the economic range of the industrial zone can be determined by the effective equilibrium approach. An empirical analysis of the Ha-Shuang freeway demonstrates this approach is valid and practical.

Keywords: Freeway, Economic range, Industrial zone, Electromagnetic model, Effective equilibrium

1. Introduction

Since the 1990s, freeways have developed rapidly in Mainland China accompanied by freeway industrial zones along them. A *freeway industrial zone* is a long and narrow area along a freeway, which stimulates regional social and economic developments in terms of a mass of industrial parks, business networks and clustered towns, thus forming a belt-shape or corridor-liked industrial zone. In developed countries, where a high quality, well-connected transport infrastructure network exists, further investment in that infrastructure will not alone result in economic growth (Banister and Berechman, 2001). On the contrary, a freeway industrial zone represents itself as an emergent matter in a developing country such as China.
Most studies, which have examined the relationship between investment on transportation infrastructure and economic development, typically focused their resources on measuring development through employment and income gains or productivity growth, and so on (Jara-Díaz, 1986; Horst and Moore, 2003). Using this approach, various types of Land-Use/Transportation Interaction (LUTI) models have been developed (Mackett, 1979; Paulley and Webster, 1991; Hunt, 1993 and 1994; Wilson, 1998; Devereux et al., 2004; Schoemakers and Hoorn, 2004). The LUTI models can be classified as illustrated in figure 1. These models have advantages in predicting behaviours in urban systems. In other words, these models mainly focus on studying relations between transportation and interests/activities of different people or organisations.

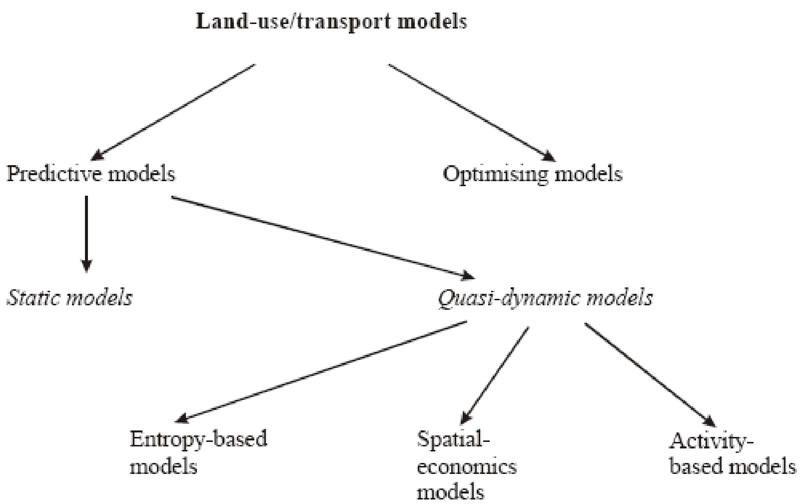

Figure 1. Classification of LUTI Models
Source: Department of Transport. (2005) *Land-Use / Transport Interaction Models*, TAG Unit 3.1.3, London

The employment of location modules in any LUTI model is based on the assumption that economic development is influenced by accessibility, highway proximity, distance to the central business district (CBD) or other related measures. In general, the accessibility measures apply a form of distance decay function and thereby account for a (gradual) range of impact of highway networks. While comparing with other distance decay or gravity-based measurements, this paper borrows the electromagnetic theory to discover the physical significance of the Economic Range Model.
For transportation research, bounding the range is a necessary precondition of techno-

economic appraisal for freeway infrastructure projects. Clarifying the bounding range can help researchers recognise the interaction among cities in the industrial zones and further enable a rational allocation of infrastructures (Botham, 1980).
In another aspect, studying the range of economic regions is an important topic for economic geography scholars (Helliwell, 1996 and 1997; Eaton and Kortum, 2002). Urban economic literature provides a wide range of methods, which take into account transport conditions (Graham, 2003), such as clustering analysis, economic centre method, and terrain division analysis (Greenhut, 1995; Crang, 2000). Through the analysis of land characteristics, in terms of administrative boundary, the above methods usually involve subjective judgement to obtain the bounding range (Okabe et al., 1994). In addition, these methods are not vivid and give insufficient consideration for special transportation conditions.
The economic range of a freeway industrial zone is a geographic region with not only natural but also economic significance. Some transportation researchers have proposed a few evaluative approaches, but most treat the problem in a subjective manner (Wu, 1997; Dong, 1998). Until now, no reliable method for range calculation has been devised. In reference to the electromagnetic theory, a tentative quantitative approach is proposed in this paper for calculating and forecasting the freeway industrial zone’s economic range.

2. A Comparison between an Industrial Zone and an Electromagnetic Field

Ordinarily, some transportation theory can be traced back to the physical realm. For example, traffic flow theory demonstrates similarity with hydrokinetics. In 1955, British scholars Lighthill and Whitham found analogies between traffic flow and liquid (Lighthill and Whitham, 1955). Through studies of traffic flow on long congested roads, they developed a traffic kinetic waves theory, which utilises basic theory in hydrodynamics to imitate the continuous equation of liquid motion with traffic flow. The similarities between traffic flow and liquid are shown in table 1.

Table 1. Similarities between traffic flow and liquid

Physical characteristics	Hydrodynamics system	Traffic flow system
continuum	one-way incompressible liquid	one-way incompressible traffic flow
discrete elements	molecules	vehicles
variable	mass (*M*)	traffic follow density (*K*)
	velocity (*V*)	traffic flow velocity (*U*)
	pressure (*P*)	traffic volume (*Q*)
momentum	*MV*	*KU*
state equation	*P=CMT*	*Q=KU*
continuous equation	$\frac{\partial M}{\partial t}+\frac{\partial (MV)}{\partial x}=0$	$\frac{\partial k}{\partial t}+\frac{\partial (KU)}{\partial x}=0$
kinetic equation	$\frac{dv}{dt}+\frac{c^2}{M}-\frac{\partial M}{\partial x}=0$	$\frac{du}{\partial t}+k(\frac{du}{dk})^2\frac{\partial k}{\partial x}=0$

Another example is the gravity model for traffic distribution in transportation planning (Murchland, 1996). Gravity models are popular trip distribution procedures. They rely on historical origin destination (OD) information for calibration. Gravity models incorporate the idea that trip patterns develop due to the activity of the origin, the relative attractiveness of the destination, and the difficulty of completing the trip. This idea is similar to the Newtonian Law of Gravity extended by Einstein. The basic assumptions of the gravity model for traffic distribution are as follows: the traffic distribution from traffic zone *i* to traffic zone *j* is directly proportional to the product of traffic generation in traffic zone *i* and traffic attraction in traffic zone *j*, and at the same time is inversely proportional to traffic impedance between *i* and *j*. The basic form of the gravity model for traffic distribution is shown by formula (1).

$$X_{ij} = K \frac{T_i^{\alpha} U_j^{\beta}}{t_{ij}^{r}} \tag{1}$$

X_{ij}	traffic distribution from traffic zone *i* to traffic zone *j*
T_i	traffic produced in traffic zone *i*
U_j	traffic attraction in traffic zone *j*
t_{ij}	parameter of traffic impedance between *i* and *j*
K, α, β, γ	pending parameters

In this paper, using comparative analysis, the electromagnetic theory of physics is used to study the transportation problems. According to electromagnetic theory, the flow of electric current can produce a magnetic field in the surrounding space. The mutual interaction of the electric field and the magnetic field produces an electromagnetic field, which is considered as having its own existence in space, apart from the electric charges or current with which it may be related.

By analogy, the freeway can be simplified as a charged straight faradic lead and the industrial zone along it can be seen as an electromagnetic field. Therefore, the passing traffic volume, which is, in this paper, termed the economic value unit, is equal to the electric charges that pass though the straight lead. Accordingly, all the productive factors in the industrial zone bear an analogy to the testing charges in the electromagnetic field. The above analogies are shown in table 2.

Table 2. Analogy between an industrial zone and an electromagnetic field

Electromagnetic field	**Straight lead**	**Electric charge**	**Testing charges**
Industrial zone	Straight freeway	Economic value unit	Productive factors

3. Range Calculation Based on Effect Equilibrium

3.1 Basic assumptions

1. Continuity of economic effect provided by the freeway.

Divide a freeway into infinite sections and assume the economic effect of each section to its surrounding influencing area varies continuously. Since it is obvious that the economic effect in the passageway is greater than the basic section of the freeway, it is necessary to distribute the passageway's effect to the whole freeway to satisfy the assumption of continuity.

2. Linearity of the freeway.
The actual freeway is simplified as a beeline to make the calculation simple and convenient.
3. Identity of area influenced by transportation.
The area influenced by transportation is assumed as an ideal plain. The productive factors vary uniformly in the zone.

3.2 The electromagnetic model

$$F_q = \int_0^L dF_p = \int_0^L k \frac{I(x_p) \cdot q(x_q, y_q)}{(x_q - x_p)^2 + (y_q - 0)^q} dx_p \quad (2)$$

$$F_p = k \frac{I(x_p) \cdot q(x_q, y_q)}{r^2} \quad (3)$$

$$r = \sqrt{(x_q - x_p)^2 + (y_q - 0)^2} \quad (4)$$

$(x_p, 0)$	a random spot on the freeway, denoted as p
(x_q, y_q)	a random spot in the industrial zone, denoted as q
$I(x_p)$	the function of economic value unit at spot p
$q(x_q, y_q)$	the function of productive factors at spot q
r	the distance between spot p and q
k	the coefficient for adjustment
F_p	the attractive effect that spot p exerts on spot q
F_q	the attractive effect that the whole freeway exerts on spot q

Since formula (3) is very similar to the Boit-Schwander law of electromagnetism, as shown in formula (5), the model raised in this paper is nominated as an electromagnetic model. Figure 2 illustrates the attractive effect function of a freeway.

$$dF = \frac{Idl \cdot \sin\theta \cdot q}{R^2} \quad (5)$$

Idl	the electric current unit
q	the testing charge
R	the distance from one electric current unit to the testing charge
θ	the angle between the connecting line, which lies between Idl and q, and the electric current unit

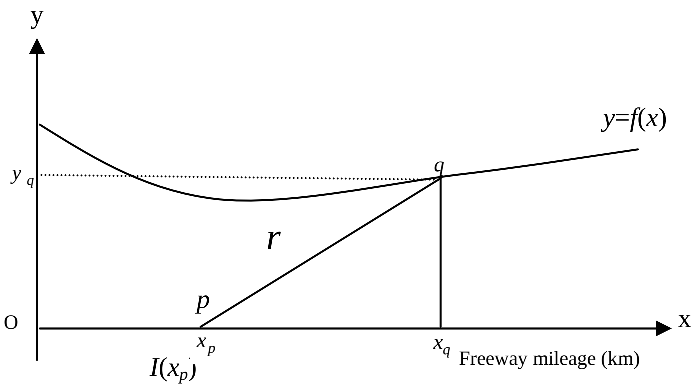

Figure 2. The attractive effect function of a freeway

Figure 2 is only an illustration used to demonstrate the intuitive physical meaning of Formula 5. Usually, a freeway between two cities can be simplified as the abscissa axis, and the origin of the freeway can be seen as the origin of the abscissa axis. For a random spot q near the freeway, we can use coordinates (x_q, y_q) to denote its location relative to the origin. Therefore, the abscissa x_q of spot q is on the freeway.

In order to determine the boundary function of a freeway industrial zone, two forces need to be calculated: the attractive effect, F_q, which the entire freeway exerts on spot q, and the traffic impedance effect, F_q', which is the impedance between location q and the freeway. The boundary function can be obtained from Formula (6). When F_q is greater than F_q', spot q lies within the industrial zone; otherwise, q lies outside this zone.

$$F_q - F_q' = 0 \tag{6}$$

4. Calculation of Relevant Functions and Parameters

4.1 $I(x)$, the function of economic value unit

A freeway with traffic volume will bring economic benefit to the surrounding industrial zone. In this paper, the economic value unit is measured by statistical indexes, such as the turnover of freight or ridership, traffic volume or combined indexes, which can express a freeway's capability.

The operation of a freeway accelerates the economic development along its route and leads to certain regional advantages in forming 'poles'. These 'poles' accumulate productive factors, for example, talented labor, capital, logistics, information, technology, and so on. These poles expand following the freeway's path and diffuse transversely, which indicates that $I(x)$, the function of economic value unit, varies by location relative to the freeway.

4.2 $q(x, y)$, the function of productive factors

The indexes related to productive factors, in terms of natural resources, human resources, transportation conditions, and so on, should meet the operable requirements in calculation, and the distribution function of productive factors needs to be determined based on the distribution of the above indexes.

4.2.1 Preliminary index system for evaluation

The indexes can be selected according to two main aspects of economy and transportation. Based on the research of 'social indexes' conducted by the Sociological Department of Chinese Social Sciences Academy, economic indexes generally include ten indexes in terms of social structure and human qualification. In this paper, the indexes of transportation are chosen and include density of road network, turnover of freight and ridership, and so on.

4.2.2 Indexes filtration

The first level indexes can be obtained using the Analytic Hierarchy Process (AHP) (Tudela et al. 2006), while the sub-indexes can be obtained through the Principal Components Analysis (PCA) (Nagendra and Khare, 2003; Tao and Lin, 2005).

4.2.3 Non-dimensional disposal

Since the metrical indexes vary greatly, it is necessary to employ a non-dimensional disposal to examine the consistency of the statistical dimension. The Fixed Base Conversion Method (Yuan, 1995) can be adopted for non-dimensional disposal, and its formula is shown as follows:

$$Z_i = \frac{X_i}{X_{i1}} \times 100 \tag{7}$$

X_i the statistical value of index i at the present location or time
X_{i1} the statistical value of index i at the reference location or time
Z_i the relative value of index i

4.2.4 Distribution function calculation

According to the distribution of the selected non-dimensional economic index, $q(x, y)$ is determined by the approach of piecewise function and parabola fitting. $q(x, y)$ is denoted as $y = f(x)$ in the orthogonal coordinates system.

4.3 k, the coefficient for adjustment

Following the abovementioned non-dimensional disposal, the resultant boundary of the industrial zone is a physical value that is measured in kilometres. Next, a coefficient for adjustment is introduced to make the results approximate the real-life situation. The value of

k can be determined by the testing algorithms. First, the value of k can be experientially assumed. Second, the range of the industrial zone in partial typical sections is calculated by the above approach and compared with the municipal statistics. Finally, the value of k is regulated to minimise the difference between the theoretical calculation and the empirical results.

4.4 F_q', the function of traffic impedance

Traffic impedance indicates the conditions that affect road users when deciding whether to use a freeway. It is determined by the principle of minimum total transportation cost, which is the product of a vehicle's unit operational expense multiplied by the distance from a given locus to the freeway using the shortest highway route.

5. Empirical Analysis

Using the data of the Ha-Shuang Freeway, which runs from the City of Harbin to the City of Shuangcheng, Heilongjiang Province, China, the empirical analysis is offered to demonstrate the application of the electromagnetic model.
The Ha-Shuang Freeway is one of China's critical highways. The section bordered by the freeway's start point to milestone $K25+900$ is an encircled highway of the Harbin city. Therefore, milestone $K25+900$ is taken as the origin for the purpose of our analysis. Milestone $K98+630$ is denoted as the destination for our analysis, since there are several on-/off-ramps for Shuangcheng.

5.1 Determining the economic value unit

Traffic volume is regarded as an economic value unit. Table 3 presents the forecasting results of traffic volume in the Feasibility Study Report of Ha-Shuang Freeway Project. As there is only one on-/off-ramp at the starting point and two at the destination, (the rest of the freeway is a basic section and has no entrances or exits), $I(x)$ is assumed as a constant and equals to the traffic volume in each year being studied.

Table 3. The forecasting data of an economic value unit

Year	2010	2015	2020
Economic value unit	15,915	22,685	32,334

Unit: medium-sized trucks/day

5.2 The function of productive factors

Three indexes selected from ten indexes using the PCA and AHP are disposed in a non-dimensional way (Fixed Base Conversion Approach). The disposal results are shown in table 4.

Table 4. The value of metrical indexes for productive factors after non-dimensional disposal

Year	Non-dimensional index	Harbin City	Shuangcheng City
2010	Population	25.27	2.10
	GDP	32.25	2.86
	Gross output value of industry and agriculture	37.53	2.68
	Average	30.68	2.55
2015	Population	25.20	2.11
	GDP	33.01	3.13
	Gross output value of industry and agriculture	38.41	2.94
	Average	32.21	2.72
2020	Population	25.15	2.11
	GDP	33.79	3.36
	Gross output value of industry and agriculture	39.31	3.08
	Average	32.75	2.85

Set up an orthogonal coordinates system and take milestone $K25+900$ as the starting point, the freeway to Shuangcheng direction as the abscissa axis and the average value of the non-dimensional indexes as the ordinate axis. Use piecewise function and parabola fitting to fit the curve of the index value and get the function of productive factors in each year being studied:

$$q_{2010}\left(x\right)=0.0217x^2-2.7232x+87.815 \quad (8)$$

$$q_{2015}\left(x\right)=0.0233x^2-2.7854x+89.547 \quad (9)$$

$$q_{2020}\left(x\right)=0.0228x^2-2.8416x+91.208 \quad (10)$$

5.3 k, the coefficient for adjustment

By referring to relevant empirical data and the range of some industrial zones along freeways in China, k is determined to be 4.9645×10^{-4}, based on testing algorithms.

5.4 Range calculation of the industrial zone along Ha-Shuang freeway

According to the above functions and parameters, the attractive effect in each characteristic year is calculated through Formula (2). The calculation results are as follows:

$$F_{2010}=15915k\cdot\int_{25.9}^{98.63}\frac{0.0217x^2-2.7232x+87.815}{x^2-2x_qx+(x_q{}^2+y_q{}^2)}dx \quad (11)$$

$$F_{2015}=22685k\cdot\int_{25.9}^{98.63}\frac{0.0233x^2-2.7854x+89.547}{x^2-2x_qx+(x_q{}^2+y_q{}^2)}dx \quad (12)$$

$$F_{2020}=32334k\cdot\int_{25.9}^{98.63}\frac{0.0228x^2-2.8416x+91.208}{x^2-2x_qx+(x_q{}^2+y_q{}^2)}dx \quad (13)$$

According to the relevant data, the minimum operational cost of a vehicle is 1.31. If the shortest route from a given point to the freeway is denoted as y_q, the traffic impedance function F' will be 1.31 y_q.

The boundary function of the economic industrial zone in each year being studied can be obtained by using Formula (6). The discrete data of the calculated results are shown in table 5 and the fitting curve for each function is presented in figure 3.

Table 5. The unilateral range of industrial zone in each characteristic spot along Ha-Shuang freeway (km)

Mileage of freeway	25	35	45	55	65	75	85	95
Range in 2010	12.09	13.08	12.02	10.45	10.31	11.79	12.94	12.19
Range in 2015	14.08	15.14	14.26	12.86	12.79	14.17	15.15	14.29
Range in 2020	16.39	17.54	16.89	15.76	15.78	16.97	17.73	16.77

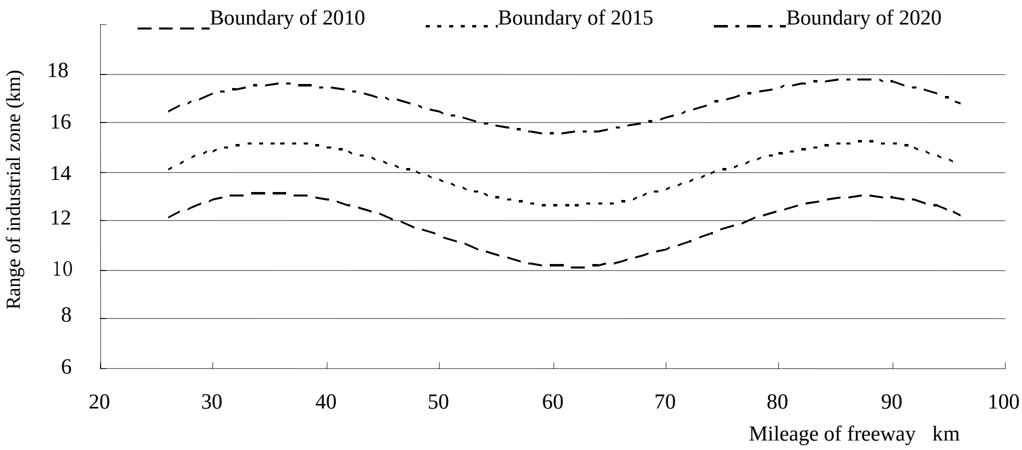

Figure 3. The boundary function of the industrial zone along Ha-Shuang freeway (unilateral)

5.5 Results analysis

Table 5 and figure 3 present only unilateral data and unilateral bounding of the economic range of the freeway industrial zone. Based on the basic assumptions in this paper, in order to get the complete economic range of the industrial zone, it is necessary to fill the axisymmetric part along the abscissa.

Furthermore, due to continuous variation of the distribution of productive factors, the function of productive factors in each year being studied is depicted by parabola fitting. In figure 3, each boundary function is obtained through the interaction of productive factors and economic value units, and is difficult to depict using a rigorous curve. However, some might prefer to average questionable data points in a sample, rather than distort the curve to fit them. This preference might support the fitting of the boundary function with a wave-like shape.

In this paper, the economic value unit $I(x)$ is assumed to be a constant, and the boundary function is determined accordingly by the density and location of productive factors. Such a representation would accord with a subjective image of an industrial zone's economic range, with relatively dense productive factors in a centralised area. Since the curve fitting the productive factors is nearly axisymmetric, the boundary function may exhibit some symmetry, as shown in figure 3.

The force exerted by the freeway on the productive factors also varies with location relative to the freeway. The distance is a quadratic function and the comprehensive function of productive factors blending in with the distance makes the boundary more curved than the previous anticipation. Figure 3 represents the function as a symmetrical wave.

In figure 3, with the yearly increase in traffic volume, the attractive effect of the freeway would gradually increase, thus resulting in the expansion of the freeway industrial zone; therefore, the effect equilibrium boundary will project outwards from the freeway. As shown in table 5, the average unilateral economic range of the industrial zone of the Ha-Shuang freeway in 2010 is approximately 12 kilometres, and the average unilateral range expands at a rate of about 2 kilometres per five years.

6. Conclusions

This research provides a new insight for calculating economic range, and contributes to land-use/transport interaction research and economic geography studies. This paper introduces an electromagnetic model to calculate the economic range of freeway industrial zone. Transportation phenomena may help us understand and verify physical laws, and further help people discover new transportation laws. Through an empirical analysis of the Ha-Shuang freeway, this approach was demonstrated to be practical.

However, the interaction between the transportation infrastructure system and the regional economic system is very complex. This paper is only a preliminary study and the basic assumptions in this paper are faily ideal. Further research is needed in order to release the basic assumptions and extend the scope of the research. For example, this paper assumes that the economic value unit associated with the freeway is a constant and equals to the traffic volume in each year being studied. In fact, the freeway’s on/off ramps are its most influential sections, and it is important to develop proper functions to distribute the economic value units of passageways throughout the entire freeway. Another case in point is that different functions of productive factors need to be developed based on particular situations; the parabola function used in this paper is only offered for reference. In addition, this paper only examined a section of a freeway. One with more than two on-/off-ramps needs to be further studied in order to enhance the generalisation.

In addition, the Geographic Information System (GIS) application is a very useful tool for visualising economic boundaries around freeways. GIS has unique capabilities of managing and manipulating spatially referenced data and presenting them in an easily understood graphical format, which provides instant visual indications by calling up maps with relevant information shown graphically through the use of different colours, thicknesses or types of hatching. The presented approach in this paper can be further tested with the assistance of the GIS application in providing a vivid figure of the boundary shape.

Acknowledgements

This work is supported by National Center of Technology, Policy and Management at Harbin Institute of Technology, and by the Program for New Century Excellent Talents in University. The authors would like to thank the anonymous referees, Dr. Caspar Chorus and other editorial board members for their constructive comments, which helped improve the paper's presentation.

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