

Incorporating Accessibility-based Equity into Stochastic Road Network Design Problem: Sensitive Analyses and Policy Implications

Tao FENG
Post Doctoral Researcher
Urban Planning Group
Eindhoven University of Technology
PO Box 513, Vertigo 8.16
5600MB, Eindhoven, The Netherlands.
Fax: +31-40-247-3044
E-mail: ftaocn@hotmail.com

Junyi ZHANG
Associate Professor
Transportation Engineering Laboratory
IDEC, Hiroshima University
1-5-1 Kagamiyama, Higashi-Hiroshima
739-8529, JAPAN.
Fax: +81-82-424-6919
E-mail: zjy@hiroshima-u.ac.jp

Akimasa FUJIWARA
Professor
Transportation Engineering Laboratory
IDEC, Hiroshima University
1-5-1 Kagamiyama, Higashi-Hiroshima
739-8529, JAPAN.
Fax: +81-82-424-6921
E-mail: afujiw@hiroshima-u.ac.jp

Harry J.P. TIMMERMANS
Professor
Urban Planning Group
Eindhoven University of Technology
PO Box 513, Vertigo 8.18
5600MB, Eindhoven, The Netherlands.
Fax: +31-40-247-2274
E-mail: h.j.p.timmermans@tue.nl

Abstract: This paper aims at examining the sensitivity of an accessibility-based equity measure in the context of the stochastic road network design problem. An equity optimization model system based on the bi-level programming approach is proposed, where the upper level problem addresses equity optimization under road investment constraint and the lower level deals with a user equilibrium model reflecting route choice behavior with varied link capacity improvements. An accessibility-based equity measure is defined in terms of the Gini coefficient. To illustrate the applicability of the model, an empirical study using data collected in Dalian City, China is carried out. Results demonstrate that the accessibility-based equity measure can be applied to measure distributional differences in zonal accessibility. Comparative results also implicate that policy makers may need to trade-off the levels of zonal accessibility and the accessibility distribution.

Key Words: *Transportation equity, Road network design, Accessibility distribution*

1. INTRODUCTION

Equity basically refers to fairness or justice of the distribution of impacts. In transportation, emphasizing the equity means that the public sector is required to provide equal opportunities to different groups of people to use transportation networks. Equity deserves much discussion in the context of accessibility and environmental pollution for different social groups (Zhang *et al.*, 2005; Connors *et al.*, 2005). In the United States, several executive policies and related guidance concerning equity have been put forward. Transportation practitioners are advised to avoid disproportionate adverse impacts on minority and low-income groups and to mitigate such impacts when possible (Torres, 2008).

Recently, the concept of equity studies is usually discussed in terms of changes of policy impacts, such as tax, road pricing, network improvement, etc. A variety of indicators, including travel time, per mile/kilometer, per dollar paid, etc., have been adopted in different research contexts. The difference in scales of those indicators is hard to compare and a measure applied in one field may lose its generality in another. Moreover, the comparison between affected and unaffected areas is unlikely to render robust or meaningful results (Feitelson, 2002). Therefore, it seems necessary to develop an alternative indicator which can be applied to represent the equity differences in various situations.

In economics, equity generally focuses on poverty and social welfare. The measures adopted are a class of formal indicators reflecting distributional differences in income, welfare, etc for different people. Measures such as the Gini coefficient, Theil index, etc., can potentially be used in transportation. To be the best of our knowledge, only few studies (Zhang *et al.*, 2005; Connors, *et al.*, 2005; Santos *et al.*, 2008; Feng *et al.*, 2009) have applied such measures in transportation modeling. However, little is known about the sensitivity of these equity measures, especially in actual contexts.

Therefore, this paper examines the sensitivity of such equity measures in real network modeling. Equity is defined at the level of zonal accessibility distributed through the whole urban area. A bi-level modeling framework is developed with equity optimization as the system objective in the upper level, while the lower level consists of a user equilibrium (UE) model reflecting users' route choice. The model system is constructed based on the policy assumption of the stochastic road network design (SRND) problem where several road segments are randomly selected to determine the best/optimized link improvement scenario, without losing the equity optimization objective. To examine the sensitivity of the equity indicator and the applicability of the model proposed here, an empirical study which adopts the real network data of Dalian city, China is carried out. Moreover, comparative analyses on the results of equity and the levels of zonal accessibility for different network improvement scenarios have been conducted.

The remainder of this paper is organized as follows. Section 2 gives a review of the state-of-art of transportation equity studies and a concrete illustration of the meaning of accessibility-based equity proposed in this paper. After that, the equity optimization model system for the stochastic road network design problem is developed using a bi-level programming approach in Section 3. Section 4 presents the empirical study. Results obtained from model implementation and sensitivity analyses are shown in Section 5. This study is summarized and concluded in Section 6.

2. TRANSPORTATION EQUITY: A LITERATURE REVIEW

Existing studies on transportation equity not only address the definition issue but also measurement approaches. Litman (2007) represented a comprehensive review and discussed different equity issues discussed in transportation research. Equity has been studied with regard to impacts, such as demographics, income class, geographic location, mode, vehicle type, industry, and trip type and value. Researchers may apply several of these indicators, but in that case different indicators may have conflicting outcomes. Decision makers then have to trade-off these results.

In equity related publications, there appears a special interest in the topic of environmental equity which addresses the distribution of exposure to negative environmental externalities by road traffic (Feitelson, 2002). Forkenbrock and Schweitzer (1999), and Chakraborty *et al.* (1999) applied a geographic information system (GIS) to blend U.S. Census data with the results from emission and dispersion models of vehicle-generated pollutants, and from noise propagation models. Air pollution and noise contours were overlaid upon data representing race and income levels to discern whether the disproportionate effects would occur. Torres (2008) developed an alternative approach to measure and compare environmental equity on all members of a given minority group. The impacts and benefits are expressed as accessibility to opportunities, such as jobs, for a given range of travel time. The congestion level of the roadway network is also considered as a measure of equity impact.

In transportation network modeling, equity is generally treated as an impact of change of transportation services provided to various groups. The impact of travel time or travel cost by imposing policies such as network improvement or road pricing have been discussed in the literature. Meng and Yang (2002) talked about equity gained from the benefits of road network design (RND). A model incorporating equity as a constraint was proposed for the continuous network design problem. Results demonstrate that in network design, the benefits of a capacity improvement in some selected links could lead to an increase in travel costs for other O-D pairs. Further, Yang and Zhang (2002) observed that for the congestion pricing problem there were significant differences in the benefits between some O-D pairs. Keeping the similar concept of equity, Lee *et al.* (2006) proposed a model representing an equity-based land-use transportation problem which is intended to examine the benefit distribution among the network users and the resulting equity associated with the land-use development problem in terms of the change of equilibrium in O-D travel cost.

The equity issues discussed above emphasize the impact on network users or travelers of various policies where decreasing changes in indicators such as travel time, environmental pollution, travel distance, and travel cost, are treated as a positive move towards the objective of equity. Such a measuring concept is sensitively affected by external policy factors and is hard to generalize. Although there are various indicators available focusing on different social and spatial aspects, none of them are eligible to interpret the distributional variations in costs-benefits across the whole urban area.

Several recent studies have attempted to introduce formal indicators such as Gini coefficient, Theil index, etc widely applied in economics to measure transportation equity,. Those indicators are normally used to represent the level of differences in social income or welfare in countries or cities. Similar to that concept, transportation equity can also incorporate these types of indicators to evaluate policy effectiveness, such as accessibility, travel time, travel distance and level of service, etc. One of the advantages of these indicators is their capability to represent distributional differences of transportation resources and services. Connors *et al.* (2005) talked about equity measures in network design. A Theil index was introduced into the stochastic road network design problem where the equity indicator was represented by the utility of different users from different user class.

Zhang *et al.* (2005) conducted a comparative analysis of transport accessibility in developing cities from the perspective of social inequity. The inequity levels of nine developing cities were comparatively calculated using five formal equity indicators. Different performances of these measurements and their applicability have been comparatively analyzed based on the

data from JICA (Japan International Cooperation Agency). Recently, Santos *et al.* (2008) presented an optimization model with the objective function incorporating equity measures for the stochastic road network design problem. The model is built in the context of national road network planning. The optimization objectives are integrated by three indicators which reflect different equity perspectives: the accessibility to low-accessibility (regional) centers, the dispersion of accessibilities across all the centers defined using the Gini index and the dispersion of accessibilities across all regional centers and across the centers within the same region measured in terms of a Theil index. Since accessibility, calculated using zonal population and inter-zonal travel costs, has been recognized as an important evaluation indicator (Tsou, *et al.*, 2005), the equity defined in this study refers to accessibility-based equity.

Recently, Feng *et al.* (2009) conducted a study on different equity measures in the context of the continuous road network design (CRND) problem. Six types of indicators, including the Gini coefficient, Theil index, mean log deviation, relative mean deviation, coefficient of variation, and the Atkinson index, were comparatively evaluated based on artificial data, Sioux Falls network. One interesting conclusion is that the six equity measures result in similar variation patterns of accessibility and average inter-zonal travel times on one hand, but different efficiencies of road investment on the other. As a consequence, keeping the equity objective, the Gini coefficient and the relative mean deviation result in the least and the most road investment, respectively.

This paper makes several contributions to this literature. First, we try to define an equity indicator based on zonal accessibility and evaluate the sensitivity in a real application. Second, we deal with the stochastic road network design problem because it is known that road capacity improvement affects network performances (e.g., travel time), and consequently induces equity variation in the range of the whole road network. Third, an equity optimization model based on the bi-level programming approach is proposed, which is different from existing studies where only one-level optimization was conducted. Such a modeling approach allows treating equity as the system objective and deals with the interactive mechanism between planners and followers in different levels by variation in link capacity improvement.

3. MODELING FRAMEWORK

The level of equity can be affected by various factors involving different policies such as network design, road pricing, and land use planning. Since our focus is on equity optimization considering the effect of the stochastic road network design problem, a model system which can represent the interaction between equity estimation and network performance flexibility is necessary. In this paper, we propose a modeling framework and define an accessibility-based equity indicator by using the Gini coefficient.

3.1 Optimizing accessibility-based equity

In order to make road investment most equitable in terms of accessibility, an additional approach is proposed in the context of the SRND problem. It is basically an equity optimization model built upon the bi-level programming approach. The accessibility-based equity indicator (i.e., minimization of inequity in this study) is taken as the objective function at the in upper level problem, while a traditional user equilibrium model is used to deal with

travel demand in responses to network performance at the lower level. The structure of the model is shown below.

Upper level problem:

$$\text{Min: } Z(A_k(y_i | i \in I_1) | k \in N) \quad (1)$$

$$\text{s.t. } y_i = \omega_i \cdot y_0, \quad i \in I_1, I_2 \quad (2)$$

$$A_k(y_i | i \in I_1) = \sum_{j \neq k} [P_j / T_{kj}(y_i | i \in I_1)^\theta], \quad \forall k, j \in N \quad (3)$$

$$\omega_i = 1 \text{ or } 0, \quad i \in I_1, I_2 \quad (4)$$

Lower level problem:

$$\text{Min: } \sum_i \int_0^{v_i} t_i(x) dx \quad (5)$$

$$\text{s.t. } v_i = \sum_r f_r \delta_{ir}, \quad i \in (I_1, I_2), r \in R \quad (6)$$

$$q_{rs} = \sum_k f_{rs}^k, \quad k \in N \quad (7)$$

$$f_r \geq 0, \quad r \in R \quad (8)$$

where k and j indicate zone id (total number is N), i refers to link id, and r means path consisting of links. There are two types of links, i.e., with and without capacity improvement, where the former set is I_1 and the latter is I_2 . y_i is traffic capacity improvement on link i and y_0 is the related capacity improvement. ω_i is a dummy variable indicating the links with improvement ($\omega_i=1$) and without improvement ($\omega_i=0$). Z is the equity measure defined in terms of zonal accessibilities A_k . P_j is the population in zone j ; T_{kj} is the average inter-zonal travel time from k to j . θ is inter-zonal travel impedance parameter. C_i is traffic capacity on link i and v_i indicates traffic volume. t_i is travel time on link i and $t_i(0)$ is travel time under free travel speed. f_r is traffic flow on path r (R is the set of paths), q_{rs} is the travel demand between r and s , and δ_{ir} is the link-path incidence (equal to 1 if i is included in path r ; 0, otherwise).

The decision variable in the upper level problem is network improvement (y_i) on selected links, which inherently affects users' travel behavior in the lower level problem. In this sense, y_i is used to connect the bi-level problem where its value equals either the concrete level of capacity improvement on link i or zero without any improvement, see Equation (4). The mechanism of traffic assignment in the lower level is based on the traditional Frank-Wolfe algorithm where users choose the route with the shortest travel time. The link performance functions of SRND are shown in Equation (9) and (10),

$$t_i(v_i, y_i) = t_i(0) \cdot [1 + \alpha(v_i / (C_i + y_i))^\beta], \quad \forall i \in I_1 \quad (9)$$

$$t_i(v_i) = t_i(0) \cdot [1 + \alpha(v_i / C_i)^\beta], \quad \forall i \in I_2 \quad (10)$$

where α and β are impedance parameters.

The equity measure we proposed here is mathematically expressed as a function of the difference in zonal accessibility, shown in Equation (1). To calculate accessibility, we treat equity as the function of zonal population P_j and inter-zonal travel time, T_{ij} , see Equation (3). Note that inter-zonal travel time is calculated on the basis of the traffic assignment procedure at the lower level, which acts upon the variation in equity at the upper level. The two levels interact with each other and the calculation process is iterated until the optimum is reached.

The nature of the bi-level model structure for equity optimization reflects the feedback mechanism between planners in the upper level and trip makers in the lower level who have different concerns about equity and time costs, respectively. In the upper level, planners determine the optimum network improvement by taking into account the accessibility distribution in the most equitable level, while the resulting network improvement consequently leads to the variation in the link flow distribution in the lower level. The improved network capacity will affect the zonal accessibilities and equity in the upper level. The optimal solution for road network improvement is actually the equilibrium result obtained from the interaction between the two-level decision makers.

3.2 Equity measure

Equity can be measured in various ways, such as quality of services for different groups (Litman, 2007), benefit distribution from road improvement (Meng and Yang, 2002), and the degradation of urban quality of life for environmental equity (Forkenbrock and Schweitzer, 1999; Torres, 2008). Since exploring the most appropriate measure of equity is beyond the scope of this paper, we deal with equity only from the viewpoint of accessibility. Use of the accessibility (here, at the zone level) has its rationality, considering that it is one of the most important indicators for transport policy-making (Tsou, *et al.*, 2005).

Although several equity indicators have been formulated, in this study we use the Gini coefficient because it was the most efficient of six indicators to improve network performance (Feng *et al.*, 2009). The functional form of the Gini coefficient incorporating zonal accessibility can be expressed as:

$$Z = \frac{1}{2N^2\bar{A}} \sum_{j \in N} \sum_{k \in N} |A_j - A_k| \quad (11)$$

where \bar{A} is the average accessibility.

The values of the coefficient are between 0 and 1. A low Gini coefficient indicates a more equal accessibility distribution, while a higher Gini coefficient indicates a more unequal distribution. The value of 0 corresponds to perfect equity (each zone has the same level of accessibility) and 1 corresponds to perfect inequity (where one zone has the total accessibility, while other zones have zero level of accessibility). The concept of accessibility-based equity means the dispersion of accessibilities across zones should be fair. The most ideal state is considered to be that all zonal accessibility values are perfectly equal, meaning that people in different zones can access their destinations with the same travel cost (or time). Because zones may differ in for example population, policy makers could put different distributional emphasis on zones. This is the concept of relative equity, under which the accessibility in the

various zones are not the same. In contrast, equity considering equal accessibility is named absolute equity. This study only deals with absolute equity.

3.3 Algorithm

There are many algorithms that have been proposed in the past for bi-level programming simulation. However, because of the inherent non-convex form of the objective function makes it difficult to find the optimum solution, only some of the algorithms are valid, especially in real applications. One of the qualifying algorithms for solving bi-level programming problems are genetic algorithms (GA). The effectiveness of GA has been verified and confirmed in many studies addressing bi-level problems in transportation (Leblanc, 1975; Yin, 2000; Lee, *et al.*, 2006; Feng, *et al.*, 2008). The GA approach provides an efficient search of the global solution space. One of the important steps in applying GA algorithms is to specify the form of fitness function. Here, the complexity of the upper level objective does not significantly increase the difficulty of the problem as its fitness is evaluated through a simple functional evaluation.

Here, the lower level problem is realized by conventional optimization techniques (Frank-Wolfe algorithm), and the results together with upper optimization problem are left to GA. The optimal result of decision variable (y_i) is randomly searched among potential solutions and only the solution that makes the fitness value change along the direction of optimizing the objective function is reproduced in the next generation. Detailed implementation steps of GA are shown below:

Step 0: Initialization of decision variables, here the link capacity improvements

Code decision variable y to finite strings (y_1, y_2, \dots, y_i), and determine the fitness function;

Step 1: Population initialization

Randomly select chromosomes in the initial population, set $m = 1$;

Step 2: Fitness function calculation

Solve the lower level problem and calculate fitness function for chromosomes.

Step 3: Selection

Reproduce the population $y(m)$ according to the fitness value.

Step 4: Crossover

Carry out the crossover operation through a random choice with probability p_{cro} ;

Step 5: Mutation

Carry out the mutation operation through a random choice with probability p_{mut} . This yields a new population, $y(m+1)$;

Step 6: Stop criterion

If $m =$ maximum number of generations, the individual sample with the highest fitness is adopted as the optimal solution. Otherwise, set $m = m + 1$ and return to Step 2.

4. EMPIRICAL STUDY

This study is based on the data about the urban area of Dalian city, China. Dalian is located in the northeastern part of China and a mountainous city with car and bus as major travel modes. There are almost no motorcycles and few bicycles in use, and more than 70 percent of daily trips are served by public modes such as bus, light rail and tram. As one of the cities in China, with fast economy development, Dalian requires a major expansion of its road network. The number of private cars is increasing year by year with the annual growth rate of almost 20

percent (DMBS, 2005), which consequently results in the traffic problems, including congestion and environmental pollution.

The topological network data was obtained in 2001 and already compiled into the GIS database, shown in Figure 1. The road network, which is simplified for the sake of model calibration, includes 33 zones, 895 links and 544 nodes. The central area which has a dense road network shown by gray line covers a few zones such as 24, 25, 26 and 31. The region located in zone 5 and the northern neighbor is becoming the secondary shopping center.

It is assumed that there are in total seven road segments that could be improved. All these segments are primary roads, as shown in Figure 1. Any capacity changes may affect the distribution of network flows. Note that each of the segments consists of a few links, which are all improved simultaneously. Here the values bracketed in the legend indicate the number of links overlapping with the colored line. It is assumed that only three road segments are improved in each time. This assumption could be reasonable because road investment generally involves limited financial budgets, and the verification of costs-benefits normally follows a step-by-stpe procedure in the decision making process.

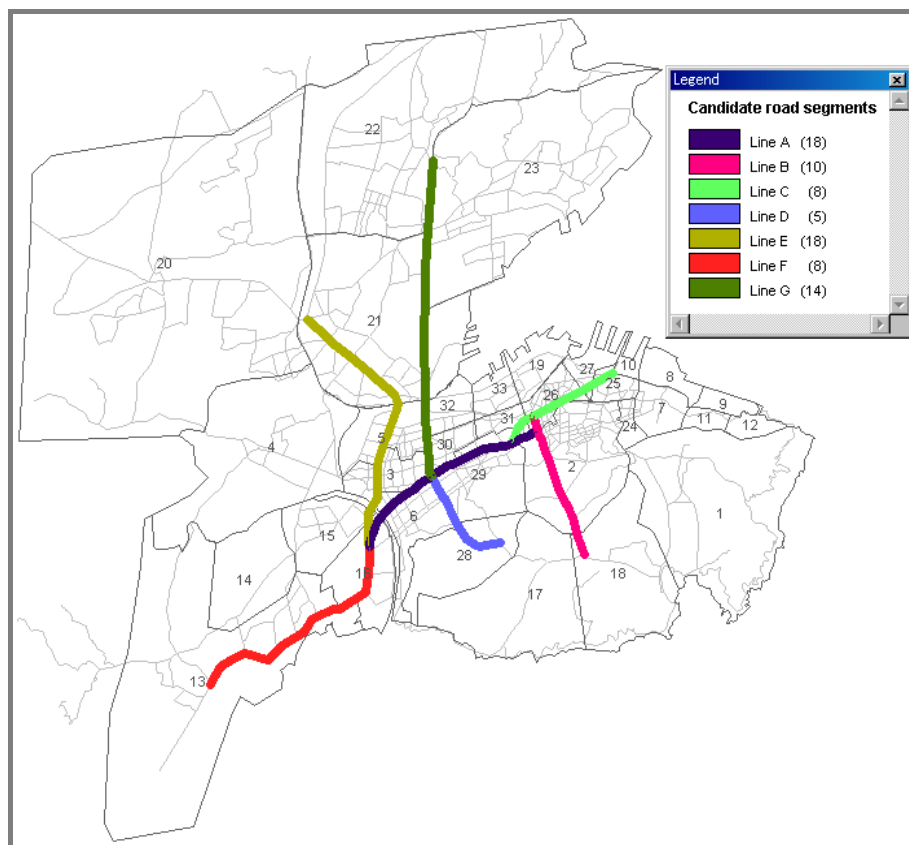


Figure 1 Candidate road segments for SRND in Dalian road network

The link impedance function for traffic assignment is defined using the traditional Bureau of Public Roads (BPR) function, setting α and β to 0.15 and 4, respectively. In addition, the extent of link capacity improvement is fixed as 900pcu/h. Here, the link capacities with improvements are mathematically increased with 900pcu/h, without considering the operational issue to add a new lane or expand the width of current lanes.

5. RESULT ANALYSES

Although GA commonly runs by randomly selecting solutions based on the fitness function, it is also possible to represent each potential solution by additional non-random regulations when the searching space is easily countable. Because it is assumed that only three road segments deserve capacity improvement in each iteration, totally thirty-five RND scenarios are optional, as shown in Table 1. Here, values of 1 and 0 are used to point out the links with and without improvement, respectively. For comparison, two extreme RND cases, with full improvement (meaning that seven road segments are all improved, S_t) and without any link improvement (S_0), are additionally simulated. Results are shown in Table 1.

Table 1 Results of Gini coefficient and average accessibility

Scenarios of RND	Candidate road segments							Gini coefficient	Average accessibility
	A	B	C	D	E	F	G		
S ₁	1	1	1	0	0	0	0	0.194081	213028.3
S ₂	1	1	0	1	0	0	0	0.194086	213053.2
S ₃	1	1	0	0	1	0	0	0.194159	213100.3
S ₄	1	1	0	0	0	1	0	0.192621	213534.2
S ₅	1	1	0	0	0	0	1	0.194964	214072.7
S ₆	1	0	1	1	0	0	0	0.194478	213285.1
S ₇	1	0	1	0	1	0	0	0.194552	213333.5
S ₈	1	0	1	0	0	1	0	0.193033	213777.5
S ₉	1	0	1	0	0	0	1	0.195351	214306
S ₁₀	1	0	0	1	1	0	0	0.194555	213357.1
S ₁₁	1	0	0	1	0	1	0	0.193036	213802.5
S ₁₂	1	0	0	1	0	0	1	0.195355	214329.8
S ₁₃	1	0	0	0	1	1	0	0.193111	213854.7
S ₁₄	1	0	0	0	1	0	1	0.195428	214368.4
S ₁₅	1	0	0	0	0	1	1	0.193962	214872.6
S ₁₆	0	1	1	1	0	0	0	0.193682	212464.8
S ₁₇	0	1	1	0	1	0	0	0.193749	212513.3
S ₁₈	0	1	1	0	0	1	0	0.192299	212950.3
S ₁₉	0	1	1	0	0	0	1	0.19454	213413.1
S ₂₀	0	1	0	1	1	0	0	0.193755	212538.8
S ₂₁	0	1	0	1	0	1	0	0.192305	212975.8
S ₂₂	0	1	0	1	0	0	1	0.194548	213438.7
S ₂₃	0	1	0	0	1	1	0	0.192359	213033
S ₂₄	0	1	0	0	1	0	1	0.194598	213475
S ₂₅	0	1	0	0	0	1	1	0.19319	213916.3
S ₂₆	0	0	1	1	1	0	0	0.194141	212766.3
S ₂₇	0	0	1	1	0	1	0	0.192683	213203.9
S ₂₈	0	0	1	1	0	0	1	0.194922	213666.7
S ₂₉	0	0	1	0	1	1	0	0.192737	213261.1
S ₃₀	0	0	1	0	1	0	1	0.194973	213703
S ₃₁	0	0	1	0	0	1	1	0.193563	214144.6
S ₃₂	0	0	0	1	1	1	0	0.192743	213286.6
S ₃₃	0	0	0	1	1	0	1	0.194981	213728.6
S ₃₄	0	0	0	1	0	1	1	0.193568	214170.3
S ₃₅	0	0	0	0	1	1	1	0.193611	214215
Without improvement (S_0)	0	0	0	0	0	0	0	0.194058	212660.3

Full Improvement (S_t)	1	1	1	1	1	1	1	0.193645	214737.4
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Note: S_t and S_0 indicate the scenario with full improvement and without any improvement, respectively.

It reveals that different RND scenarios result in different levels of equity. The value ranges from 0.192299 (S_{18}) to 0.195428 (S_{14}), and the average is 0.193876. The values vary since the third digit after the decimal point. This phenomenon differs from common knowledge about the Gini value in social sciences where values lower than 0.2 may empirically be considered as fair. Nevertheless, it would be hard to judge whether the system is equitable or not only in terms of the value without empirical threshold verification. However, one can identify the most equitable state by comparing the Gini values: the smaller the value, the more equitable the accessibility across zones.

Results suggest that scenario S_{18} generates most equity (Gini coefficient equals 0.1923). In this scenario, improved links are located on road segment B, C and F. In contrast, scenario S_{14} leads to least equity (Gini value is 0.1954). Figure 2 ranks all results.

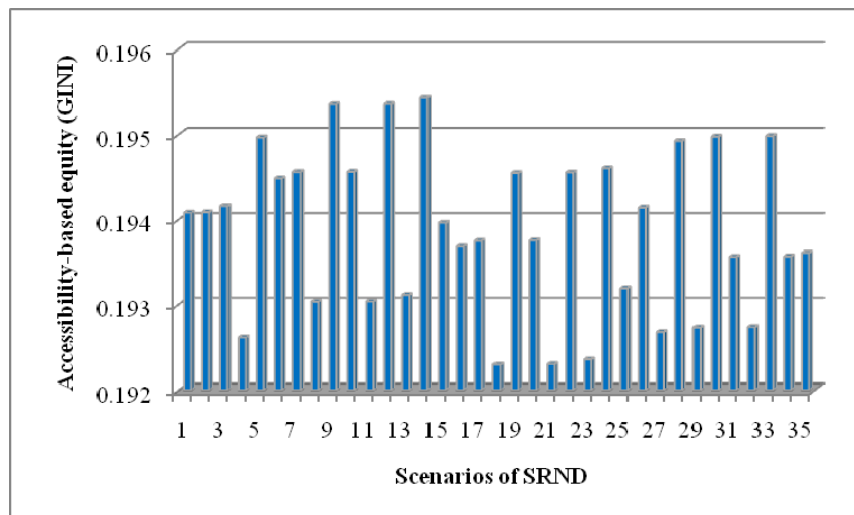


Figure 2 Gini coefficients of different SRND scenarios

Although S_{18} and S_{14} are specified to be the extreme cases, results indicate that the difference in equity values between the top three scenarios (S_9 , S_{12} and S_{14}) and between the bottom three scenarios (S_{18} , S_{21} and S_{23}) are small. Furthermore, S_{18} , S_{21} and S_{23} all put the link improvements on road B and F. The only difference in link selection is the choice among road C, D and E. On the other hand, S_9 , S_{12} and S_{14} all improve Lines A and G and make variations among road C, D and E respectively. These comparative results imply that improvements in road B and F are most beneficial to the equal distribution of zonal accessibility, i.e., equity objective.

The results of the average zonal accessibility in different zones are shown in Figure 3. Here, given the unchangeable, zonal population, a higher level of zonal accessibility means a shorter average inter-zonal travel time, and vice versa. It is shown that the highest accessibility level is obtained for S_{15} , which means that under this scenario the average inter-zonal travel time is the shortest. The lowest average accessibility occurs under S_{16} .

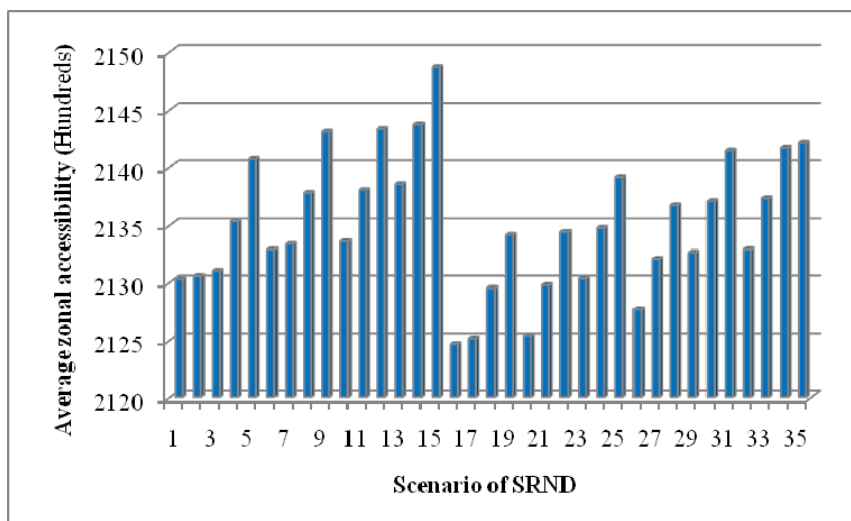


Figure 3 Zonal accessibilities of different SRND scenarios

In addition, simulations of different scenarios with full improvement (S_t) and without any improvement (S_0) on each of the seven road segments were also implemented. Results for zonal accessibility for both scenarios have the same variation patterns, as shown in Figure 3. However, the zonal accessibilities for S_t are all higher than that for S_0 . S_t has a higher level of average accessibility (214737) and a more equitable accessibility distribution than S_0 . Such a significant improvement on network performance benefits greatly from the scenario of network design on all road segments. This is also the same when comparing S_0 to other RND scenarios, where most of the zonal accessibilities are higher than S_0 .

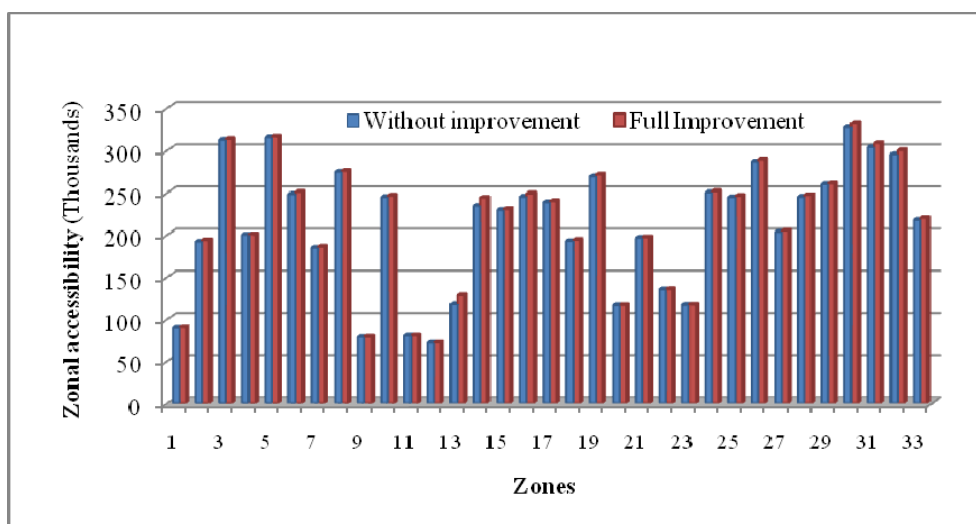


Figure 3 Results of zonal accessibility with full improvement and without improvement

However, it is evident that the zonal accessibility from S_t is nearly but not the highest among all RND scenarios. The corresponding Gini coefficient is also not the lowest. This means that improving more road segments could be helpful in increasing zonal or average accessibility, but may not result in the most equitable accessibility distribution. This could be understood in that systems with different levels of zonal accessibility have similar levels of distributional variations. In this case, policies concerned with improvements in all zones would not

substantially affect equity. Incremental improvement of special zones with a low accessibility may on the other hand lead to a significant change in equity value.

The Gini coefficient calculated from all scenarios range from 0.1923 to 0.1954 where the gap is only 0.0021. Even small changes in equity value might be induced by quite different policies of network design. This conclusion can be also verified if we comparatively analyze results of equity and accessibility. Of all RND scenarios S_{18} get the lowest equity value, but an average zonal accessibility. However, S_{15} , although not the most equitable accessibility distribution, has the highest accessibility which implies the lowest inter-zonal travel time. A similar case also exists in the comparison between S_0 and other scenarios. It can be seen that most of scenarios involve increased accessibility, but different levels of equity. Therefore, this brings about the issue which factor is more important in network design. Policy makers need to trade-off between increasing accessibility levels and balancing the distribution of zonal accessibility. In this sense, a multi-objective choice environment would be important.

6. CONCLUSION

Road network design problem inherently involves multiple planning objectives. In the process of transportation planning, issues that policy makers commonly address involve not only economical and environmental problems, but also social and spatial equity to reduce spatial variations. Since there are different definitions of equity and various measurement approaches, it seems necessary to further discuss the concept of equity and develop a measurement approach which can be generalized. Although several formal equity indicators are available for evaluating equity of income or social welfare, studies in measuring transportation equity on their performance sensitivity based on actual data are absent.

Therefore, this study proposed a model by incorporating the Gini coefficient into the stochastic road network design problem and examined the sensitivity of model performance. Equity is calculated in terms of zonal accessibility, which is formulated as a function of zonal population and average inter-zonal travel time. A bi-level programming approach is used to assess the interaction between accessibility-based equity and network performance flexibility induced by road network design policies. Here, the lower level problem is specified as the user equilibrium (UE) model where link capacities are varied by imposing network improvement scenarios. The upper level model addresses equity optimization with the constraint that potential road segments are randomly selected to be improved.

The results using the Dalian road network data demonstrated that the Gini coefficient can be used to measure accessibility-based equity. It is also verified that the equity value is sensitive to the extent of network improvement investment. Different road network design (RND) scenarios can lead to different levels of zonal accessibility and equity among which the most equitable accessibility distribution can be computed by using the bi-level modeling framework. Further analyses also implicate that the most equitable scenario may not be the best one to improve zonal accessibility, and vice versa. This conclusion suggests that policy makers, when dealing with the problem of increasing zonal accessibility, should not ignore the spatially distributional differences in zonal accessibility.

The concept of representing equity in terms of equal accessibility is certainly of importance in actually circumstances. People who make a location choice for residence or work in long term

always take into account the complex zonal environment where accessibility is one of the most important determinant factors. However, due to the impact of policies on people's location choice behavior, governors or planners are ordinarily required to take into account not only inter-zonal variations of zonal accessibility, but intra-zonal accessibilities to different functional facilities or buildings as well. In this sense, the Gini coefficient can be eligible to measure such spatial difference in travel time or distance for different groups.

It should be noted that the population defined here is the total zonal population. However, the approach can be easily extended to include different groups or minorities. As a consequence, the accessibility equation needs to be adjusted accordingly. From the viewpoint of decision making, it becomes important to explore the weighted importance of the multiple objectives in the context of road network design. It seems also worthy to extend the proposed modeling framework to deal with the design problem of multi-modal networks. Since different cities usually have different configurations of transportation networks, comparative studies across cities (developing and/or developed cities) may be needed in the future to figure out more general ways to deal with transportation equity issues.

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