Journal of Transport Geography 39 (2014) 156–164

Contents lists available at ScienceDirect

Journal of Transport Geography

journal homepage: www.elsevier.com/locate/jtrangeo

Incorporating spatial equity into interurban road network design

Mostafa Mollanejad, Lei Zhang *

Department of Civil and Environmental Engineering, University of Maryland, 1173 Glenn Martin Hall, College Park, MD 20742, United States

ARTICLE INFO

Keywords:
Spatial equity
Accessibility
Transportation network design
Interurban

ABSTRACT

Methods for the road network design problem, typically, are based on optimization of the network efficiency measures (e.g. network-wide travel time) under a predefined budget. In these approaches, equity issues are not taken into account and, consequently, most of the road improvements are planned next to large cities. Thus, disparities between large and small cities increase, which does not conform to sustainable development objectives. In this paper, to overcome concerns associated with traditional methods, equity is incorporated into the interurban road network design problem. To this end, accessibility concepts are employed. However, unlike previous studies, instead of maximizing the total accessibility, a new definition is proposed for inaccessibility, and total inaccessibility is minimized throughout the network. Using this new definition not only is more compatible with the equity issue, but also helps to eliminate the nonlinearity of the problem. Average travel time to neighboring opportunities is utilized to propose this definition for inaccessibility, which captures the reality more effectively. With the aim of this definition, equity is incorporated into the road network design problem implicitly. This is another improvement over previous methods, where a new term in the objective function or a new constraint is added to include the equity. The proposed model is formulated as a mixed integer linear programming (MILP) problem, where the objective is to minimize the aggregate inaccessibility over all the population centers in the network. To illustrate the application of the model, the Northwest region of the United States is used as the case study. The respective exact solution of the example is found using a commercial solver (CPLEX). This new solution is also compared with the solutions from the traditional methods.

1. Introduction

Over the past forty years, a considerable amount of research has been conducted on road network design models (Yang and Bell, 1998). Among these models, interurban road network designs often focus on minimizing the total travel costs or maximizing the aggregate accessibility over the entire network. In both cases, construction of new roads and/or improvement of existing roads center on large population centers. This happens because improvements to links with higher traffic volumes have more positive effects on the aforementioned objective functions. Presumably, one of the consequences of such an approach is an increase in transportation and economic disparities between large and small cities, which does not conform to the sustainable development principles like advancing equity, providing transportation choice, and increasing job and business opportunities. These disparities may include income, employment opportunities, housing, education, access to health services, etc. Therefore, transport network designers should consider both the efficiency of network improvements and their equity in the decision-making process.

In different studies, the selection of road transportation investments is conducted based on different objectives, such as providing higher levels of mobility, safety, reliability, and/or maintaining high environmental standards. Moreover, road infrastructure investments are seen by the public and by many decision makers as an effective tool to promote economic development. At a higher level, enhancing accessibility is the ultimate goal of most transportation projects that encompass other objectives such as economic development. The focus of this paper, therefore, is on optimizing network accessibility.

Proposing a definition for inaccessibility that is consistent with real experiences is the first goal of this paper. We aim to use this definition to incorporate equity into the road network design process. Many factors affect accessibility, including mobility, the characteristics of transport modes, transportation system connectivity, mobility substitutes, and land-use patterns. This paper defines inaccessibility in term of people's overall difficulty in reaching neighboring opportunities. By this definition, for each population center, inaccessibility can be evaluated considering the weighted average travel time between that center and all other

* Corresponding author. Tel.: +1 301 405 2881; fax: +1 301 405 2585.
E-mail addresses: mostafa@umd.edu (M. Mollanejad), lei@umd.edu (L. Zhang).

http://dx.doi.org/10.1016/j.jtrangeo.2014.06.023
0966-6923/

population centers that are located in a predefined neighborhood (the exact definition of neighborhood is provided in the next section). The weight of each neighboring center is determined by the level of opportunities in that center. For example, this weight can be determined with regard to the size of each center (employment, population, etc.). Another issue is the definition of the neighborhood. Travelers usually use the interurban road network just for short-distance and medium-distance trips. Therefore, one center can be considered as a neighbor of another center, if the Euclidean distance between them is less than a predetermined value, which, in this study, is called the Neighborhood Radius. In this definition, due to applying the Euclidean (straight-line) instead of network distance (measured along a street), the neighborhood includes both present and potential network opportunities.

In the case of considering accessibility for equity concerns, the equity objective can be the maximization of accessibility for low-accessibility centers (i.e., the 20% centers with lower accessibility), or the dispersion of accessibility values across centers using a Gini coefficient or Theil index (Santos et al., 2008). When each of these measures is applied, the optimum solution generally contains the projects that increase the accessibility of centers with lower accessibility. But equity is a complex concept. It can be defined in various ways and assessed through different measures, which make it harder to choose one that is most appropriate. Accordingly, the literature on equity measures is vast, and the main conclusion is that equity cannot be fully described by a single measure (Sen, 1997). Thus, it would be more reasonable if, instead of dealing with the equity separately, a new method is presented to consider it implicitly in the optimization of network efficiency problems, like maximization of aggregate accessibility. In this way, equity is not quantified by any single measure. Instead, different components of the optimization problem (e.g., objective function) are designed to be consistent with equity principles.

The objective in this study is to minimize total inaccessibility over all the centers in the transport network. To consider equity implicitly, objective function is defined without regard to the population of centers, and inaccessibility of all the centers has the same weight in this function. The rationale behind this approach is that all people should have a reasonable ability to reach all the opportunities in their neighborhood. In this case, there is no difference whether they live in a big city or in a small town. Therefore, reducing the inaccessibility of a big center has the same meaning to us as reducing the inaccessibility of a small one. In this research, the problem is modeled as a mixed integer linear program (MILP) to select the optimal set of projects among the candidates (construction and improvement). In this optimization model, as mentioned before, the objective function is to minimize the total inaccessibility over all the centers, bearing in mind that there are several constraints like budgets, etc. It should also be noted that the preceding definition of inaccessibility helps to contextualize equity in this approach more effectively, and is key to overcoming the nonlinearity of the road network problem.

The paper is organized as follows. In the next section, the relevant literature is reviewed briefly. Next, the definition of inaccessibility is discussed in detail, followed by a description of the optimization model formulation that considers equity impacts in the road network design. After that, the results obtained for a large real network are presented. Finally, we provide some concluding remarks and directions for future research.

2. Literature review

In the transportation field, until the end of the 1990s, equity issues were mostly limited to an evaluation of the economic impacts of transportation policies. Gutiérrez and Urbano (1996) and Gutiérrez et al. (1996) were among the first to address the other dimensions. They evaluated the impact of European road and high-speed train networks on the spatial distribution of accessibility. These studies pay particular attention to the equity effects of new infrastructure. The ultimate goal is to reduce the dependency of the spatial distribution of accessibility on the geographical location of centers. Instead, the type of available infrastructure should play a more substantial role in providing accessibility. To this end, centers with initial locational disadvantages should benefit most from the investments. Meng and Yang (2002) demonstrated that, in the continuous network design problem, the benefits of a capacity enhancement in some selected links can lead to an increase in travel costs for some O–D pairs. After this study, the debate over equity issues in transportation network design became more intense. Yang and Zhang (2002) also observed that, for the congestion pricing problem, there are significant differences between the benefits of some O–D pairs. Thus, they proposed the consideration of spatial equity in the road pricing problem. Other examples of dealing with equity in road pricing can be found in McMullen et al. (2010) and Robitaille et al. (2011).

Following these studies, other researchers proposed the inclusion of equity concerns in network design problems. Antunes et al. (2003) present a new accessibility maximization approach to interurban road network design based on a nonlinear combinatorial optimization model. This model aims to determine the maximum-accessibility solution, while guaranteeing a given level of equity for the distribution of accessibility gains across the centers (cities or regions). For this purpose, the objective function of the model expresses the weighted accessibility for a given percentage of centers, where accessibility gains are smaller. Feng and Wu (2003) discuss the improvement and expansion of highway network systems considering the equity of accessibility for cities. Accessibility is measured by the travel cost from the city to the regional center. Based on the idea of horizontal equity, all the main cities in the same region should have the same accessibility. Also, based on the idea of vertical equity, the accessibility of cities in different regions is supposed to be as reasonably fair as possible. To do this, a multi-objective model with three different objective functions is proposed. The first objective function optimizes accessibility for all cities, while the other two optimize horizontal and vertical equities. This optimal solution of the problem is estimated by fuzzy programming for a highway system in Taiwan (Feng and Wu, 2003).

Chen and Yang (2004) include spatial equity as a constraint in the link capacity improvement problem to ensure the worse-off of any network users is less than a pre-defined threshold value. According to this constraint, for each O–D pair, the ratio of the travel cost after capacity enhancement to the travel cost before capacity enhancement should be less than a predetermined value (fairness ratio). In a more recent study, Szeto and Lo (2006) consider the inter-generation equity in the time-step network design problem. They formulate a network design problem, where the optimal infrastructure improvement timetable, the associated financial arrangement, and tolling scheme over the planning horizon are planned together. In this approach, inter-generation equity is contained in the model with the help of a constraint that at least assures a minimum degree of equity can be maintained. Connors et al. (2005) presented another example on how equity can be represented with constraints in the network design problem.

A new variation of the user equilibrium discrete network design problem is proposed by Duthie and Waller (2008) for achieving equity amongst population groups. They divide population into protected (i.e., minority or low-income) and unprotected groups and try to avoid disproportionate adverse impacts on minority and low-income groups. In our study, eight potential objective functions are developed and discussed, which focus on maximizing