Transport Policy 49 (2016) 105–113

Contents lists available at ScienceDirect

Transport Policy

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

Optimal sustainable road plans using multi-objective optimization approach

Jin-Hyuk Chung [a], Yun Kyung Bae [b], Jinhee Kim [c,*]

[a] Department of Urban Planning and Engineering, Yonsei University, 134 Shinchon-Dong, Seodaemun-Gu Seoul 120–749, Republic of Korea
[b] Korea Research Institute for Human Settlement, Infrastructure Research Division, 254 Simin-daero, Dongan-gu, Anyang-si, Gyeonggi-do 431–712, Republic of Korea
[c] Eindhoven University of Technology, Department of Urban Science and Systems, Urban Planning Group, PO Box 513, Eindhoven 5600MB, The Netherlands

ARTICLE INFO

Article history:
Received 20 March 2015
Received in revised form
3 March 2016
Accepted 25 April 2016
Available online 4 May 2016

ABSTRACT

To construct a sustainable road network, the three dimensions of sustainability—economic efficiency, environmental impact, and social equity—should be significantly and simultaneously taken into account at the planning stage. Because these dimensions have trade-off relationships among them, we developed a multi-objective optimization model for planning optimal road capacity improvement. Three indicators, each measuring one dimension of sustainability, were used as the objectives in the proposed model. The total travel cost, which combines the monetized value of travel time and operating costs, was adopted as the economic indicator. The total emissions cost and the GINI coefficient based on zonal accessibility were adopted as the environmental and equity indicators, respectively. We performed an experimental test with three model scenarios to compare the single- and multi-objective approaches and different objective functions. We obtained Pareto optimal solutions using the elitist non-dominated sorting genetic algorithm. The results show that the proposed model, which is based on the multi-objective approach and considers all three dimensions of sustainability, is more suitable than other options for designing a sustainable road network. In addition, we suggest that the frequency rate of a link within Pareto solutions can be used to prioritize capacity improvement for maximum road network sustainability.

1. Introduction

Recently, sustainability has attracted considerable attention among decision makers and transportation planners as a primary goal of transportation planning. Transport activities and constructing transportation infrastructure have significant and broad effects on economic growth, social progress, and environmental damage. Numerous studies underline that those three dimensions must be significantly and simultaneously considered in planning and evaluation to enhance the sustainability of transportation systems (Litman and Burwell, 2006; Hall, 2006; Samberg et al., 2011; Ramani et al., 2011; Szeto et al., 2015). The dimensions often overlap one another and require trade-offs among them. For example, to achieve economic growth, travel costs should be reduced, even though low costs induce more transportation demand and use of resources for constructing and operating transportation systems. Accordingly, transportation-related decisions can have significantly negative influences on environmental and ecological systems by consuming many natural resources such as fuel, energy, land, and minerals and by producing more emissions such as greenhouse gases (Button and Rothengatter, 1993). Furthermore, although minimization of travel costs plays a crucial role in increasing the accessibility of places, it does not guarantee fairness in the spatial distribution of that accessibility (Feng et al., 2009, 2010). Accessibility, one measure of transportation social equity, provides opportunities for economic activities, educational services, and other social relationships. Therefore, spatially uneven accessibility means that some people find it more difficult to get such opportunities than other people. That disparity causes economic and social inequalities, which then hinder economic efficiency. Consequently, all three dimensions and the trade-off relationships among them must be considered when constructing sustainable transportation systems.

Planning an optimal road capacity improvement project is one of the most popular road network design problems (RNDPs). RNDPs involve finding the best way to expand or construct links to achieve specific objectives. Traditionally, the objective of RNDPs was to minimize the total network travel cost at the equilibrium status of an assigned network. Several studies used construction costs with the total network travel cost for the objective. Yang and Bell (1998) comprehensively reviewed traditional RNDP research.

* Corresponding author.
E-mail addresses: jinchung@yonsei.ac.kr (J.-H. Chung), ykbae@krihs.re.kr (Y.K. Bae), j.kim@bwk.tue.nl (J. Kim).

http://dx.doi.org/10.1016/j.tranpol.2016.04.011
0967-070X/

In early studies, most researchers were interested only in minimizing travel-time costs when they designed and planned improvements for road networks. In other words, they focused on only one dimension of sustainable transportation, economic efficiency. Fortunately, recent research tends to take the other dimensions of sustainable transportation into account. Feng et al. (2009) used various measures of spatial accessibility as the objective of an RNDP to consider social inequality. However, in order to achieve the sustainability in a road network, the minimization of travel cost and the minimization of environmental damage also need to be taken into consideration simultaneously. Sharma and Mathew (2011) and Szeto et al. (2014) researched minimizing travel costs and negative environmental effects as the objectives of an RNDP. While the former study considered the negative environmental effects caused by emission, the later study considered them caused by both emission and noise. Although these studies recognized the importance of sustainability in RNDPs and thus incorporated the dimension of environmental damage into their objective functions, the dimension of social equity has been ignored. On the other hand, Szeto et al. (2015) deal with the three dimensions of sustainability when designing optimal road capacity and toll price using a time-dependent land use transport interaction model. In their model, they employed various sustainability indicators as the objectives of the RNDP, including total vehicle emissions, the change in consumer surplus, the variance of discounted landowner profit and the variance of discounted generalized user cost. Among them, the variance of discounted landowner profit was proposed to measure land-owner inequity, which is to be minimized to achieve the equality of landowner profit over time. By doing so, a particular facet of social equity could be incorporated. In terms of designing road networks, however, the inequity in accessibility should be also importantly considered because the accessibility is highly relevant to the opportunity to meet people's basic needs. To achieve sustainable road networks, it is essential to consider all three dimensions in the planning stage, but to the best of our knowledge, little research on sustainable RNDPs has considered more than two dimensions of the sustainability at a time.

Simultaneously considering all three dimensions as objectives requires a multi-objective optimization model, which can take one of two approaches. One approach is to convert multiple objectives into a single objective by adding them with a user-specified weighting factor for each objective. This approach enables a multi-objective problem to be treated and solved as a single-objective problem. Early studies with regard to RNDPs applied this approach and solved their multi-objective problems using existing single-objective optimization techniques (Meng and Yang, 2002; Yang and Wang, 2002; Szeto and Lo, 2005, 2006, 2008; Ukkusuri et al., 2007). But that approach has some limitations. It cannot find certain Pareto optimal solutions, which means that "*none of the solutions can be said to be better than others with respect to all objectives*" (Deb, 2001). If the objectives are of equal importance and have trade-off relationships, the optimal solution set is likely to include multiple Pareto optimal solutions. Moreover, deciding the user-specified weighting factor is a highly subjective procedure, and different runs of the model are required to obtain a solution set for different weighting factors (Sharma et al., 2009). Accordingly, this approach is inefficient and inappropriate when considering the trade-off relationships among the dimensions of sustainability. The other approach searches a non-dominated solution set in the feasible region of a certain problem. This approach finds multiple solutions for a Pareto optimal solution set; therefore, decision makers can choose from among the solutions obtained using higher-level information such as decision makers' preferences about the objectives. Deb (2001) argued that this Pareto optimal solution approach is "*more methodical, more practical, and less subjective*." Recently, several researchers incorporated this approach into RNDPs (Sharma and Mathew, 2011; Sharma et al., 2009; Chen and Subprasom, 2007; Unnikrishnan et al., 2009; Chen et al., 2010; Sohn, 2011). Those studies solved their multi-objective problems using various genetic algorithms (GAs), which mimic nature's evolutionary principles to find an optimal solution. Because GAs use a population of solutions, it is possible to capture multiple solutions in a single simulation run. This trait of GAs can be used in a Pareto optimal solution approach. Details of the GA used in this study are described in the third section.

The objective of this study is to develop a multi-objective optimization model for RNDPs by considering the trade-off relationships among the three dimensions of sustainability. It is the primary contribution of this study that all three dimensions were simultaneously taken into consideration in road network planning by developing a Pareto multi-objective optimization model. In addition, we suggest more elaborate indicators for measuring each dimension of road network sustainability. We used the total travel cost to measure economic efficiency. In general, travel cost considers only the monetized value of travel time; however, we also considered the user's operating costs, which are important to road users because fuel and maintenance costs are substantial. We used the speed-dependent emissions model to measure the environmental effects of road network usage. Although Sharma and Mathew (2011) studied an RNDP using a speed-dependent emissions model, they omitted fatal emissions such as carbon dioxide and particulate matter. Such emissions have a critical effect on climate change and ecological systems. To consider those emissions, we used the national emissions model of Korea, which was developed by conducting enormous exploratory studies. To measure the road-network's social equity, we adopted the GINI coefficient, which represents a degree of spatial dispersion of a certain value. Various studies have used it to determine the spatial equity level of accessibility (Chen and Subprasom, 2007; Feng et al., 2009; Feng et al., 2010).

This paper is organized as follows. The next section presents the mathematical formulation and detailed description of the proposed multi-objective RNDP model with indicators for measuring the three dimensions of sustainability. The third section describes the details of the genetic algorithm used to solve the proposed multi-objective problem. In the fourth section, we address the results from experimental tests of the proposed model. Finally, the last section contains concluding remarks.

2. Model formulation

In general, an RNDP is formulated as a bi-level optimization problem to reflect the different objectives of planners and network users. The planners' optimization problem is the upper level problem (ULP), and the users' problem is the lower level problem (LLP). In the ULP of our model, as described in the previous section, we use three indicators as objectives of the planner's problem, defined as the maximization of road network sustainability. Therefore, our ULP consists of three models, one for each indicator.

2.1. Economic indicator: Total travel cost

Total travel cost was chosen as the economic indicator with the goal of reducing travel costs by improving the road network and thereby enhancing the economic efficiency of the network. The total travel cost function comprised the total link travel time and the total link operating cost and can be expressed as: