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Differences in network reliability improvement by several importance indices

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Abstract

For constructing a highly reliable highway network under a disaster environment, this paper presents a comparative study of the importance indices and proposes an approximate method for improving highway network reliability. Three indices are compared. Two of them are conventional indices of reliability importance (*RI*) and criticality importance (*CI*), and the other is the improved criticality importance (*CIW*) index recently proposed by Wakabayashi (2004). First, the significance of reliability importance is discussed. Second, their definitions, merits, and demerits are explained. Third, several cost functions for improving link reliability are introduced. Fourth, *RI* and *CIW* are compared for a small-sized network and differences in improved link reliability are discussed. Fifth, an approximate method is proposed using partial minimal path sets. Lastly, after calculation experiments, the advantages of the *CIW* index and the effectiveness of the proposed approximate method are demonstrated.

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Keywords: Highway network reliability, Importance index, Probability importance, Partial minimal path set, Cost-benefit analysis

1. Introduction

Under the threat of a potential disaster such as the 2011 Japan earthquake, constructing and sustaining a highly reliable highway network for national resilience is an urgent necessity. However, improving all the links at once is

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difficult because of budget constraints. Therefore, identifying key links to improve network reliability is important; this process is called the *importance analysis*. Importance analysis of a highway network mainly entails two concerns: (1) the development of an effective importance index and (2) the reduction of the amount of calculations. Therefore, this study verifies the relevance of an index proposed by the authors and develops an efficient method for approximate calculations. To resolve these two concerns, this study presents both a comparative analysis of importance indices for actual use and an efficient method for approximate calculations.

The remainder of this paper is structured as follows:

Section 2 reviews the reliability analysis of a highway network and the study of importance analysis. Section 2 also highlights the characteristics of and problems with importance indices that have been previously proposed. Section 3 provides a definition of connectivity reliability and introduces the conventional and newly proposed importance indices. Section 4 presents three cost-reliability functions. Section 5 compares terminal-reliability improvement using two importance indices, *i.e*. *CIW* and *RI* with cost-benefit functions for a network with nine nodes and twelve links. Section 6 uses examples to show an approximate calculation method that chooses partial minimal path sets to reduce calculations. Section 7 presents concluding remarks for the problem discussed in Section 2.

2. Reliability and Importance Indices of a Highway Network

Connectivity, travel-time, and capacity reliabilities (Nicholson *et al*., 2003) have been proposed as methods to measure the reliability of a highway network. Our study focuses on the improvement of connectivity reliability and importance indices. Reliability means that "systems are in a condition to be able to accomplish a predetermined function during a prescribed period of service" (Barlow and Proschan, 1965); it is defined as an expression of probability.

The CPU-time and memory size required for reliability analysis increases exponentially as the size of the highway network increases. This is called a non-deterministic polynomial-time hard (NP-hard) problem (US NRC, 1983). For solving this problem, efficient and practical reliability analysis has been proposed by Wakabayashi and Iida (1992). However, efficient and practical importance analysis remains unsolved.

The purpose of the importance index is to effectively improve the reliability of the system. Probability importance (Birnbaum, 1969) and criticality importance (*CI*) (Henley and Kumamoto, 1981) are previously proposed and discussed later. Importance indices can be interpreted as the degree to which a component contributes to the reliability of the system when the reliability of the component is improved. Moreover, in this study, the importance of the connectivity reliability of the highway network is defined as the degree to which a component contributes to the reliability between nodes when link reliability is improved.

Next, we explain the problem of importance indices of a highway network as they are currently used.

(1) It is more difficult to improve a more reliable link than to improve a less reliable link. This is called diminishing marginal utility. Birnbaum's importance index, *i.e.*, Reliability Importance (*RI*), does not reflect this fact.
(2) In a parallel network, use of the *RI* and *CI* results in only the more reliable links being improved, and the less reliable links will remain unimproved.
(3) The importance index does not always result in an economical highway network improvement. A cost-benefit perspective should also be considered.
(4) Importance analysis also is an NP-hard problem. An efficient and approximate method for practical use is required for actual highway networks.

An improved criticality importance (*CIW*) index has recently been proposed to solve the problems (1) and (2) (Wakabayashi, 2004). However, till date, the results of applying this index to a network are not calculated and evaluated enough, and the index is not yet compared with the *RI* index; this paper attempts this analysis and comparison.

For problem (3), only a few comparisons have been made to determine what difference in the terminal reliability exists when the network is improved using a conventional importance index. We can form the following hypotheses: if we set the cost-reliability function that expresses an expense and relations of the link reliability (the higher link