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Basic Concepts And Future Directions Of Road Network Reliability Analysis

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The stability of road networks has become an increasingly important issue in recent times, since the value of time has increased considerably and unexpected delay can results in substantial loss to road users. Road network reliability has now become an important performance measure for evaluating road networks, especially when considering changes in OD traffic demand and link flow capacity over time.

This paper outlines the basic concepts, remaining problems and future directions of road network reliability analysis. There are two common definitions of road network reliability, namely, connectivity reliability and travel time reliability. As well, reliability analysis is generally undertaken in both normal and abnormal situations. In order to analyse the reliability of a road network, the reliability of the links within the network must be first determined. A method for estimating the reliability of links within road networks is also suggested in this paper.

Background

The value of time has increased in recent years due to increased economic activity and improvements in the quality of life. Travel time stability has therefore become an important issue in transport. Consequently, alternative routes to destinations should be provided even if some sections of the road network are disrupted due to accidents or disasters. Since road networks are dynamic systems the variability of supply and demand of traffic networks should be considered when assessing the performance of road networks.

Road networks are now required to have high degree reliability to ensure drivers smooth travel under normal traffic flow fluctuations and to avoid serious unexpected delays for disruptions within the network.

There are currently 3 main areas of research in road network reliability analysis. The first area involves developing a modelling framework that is capable of investigating the reliability of road networks. This is necessary since the characteristics of road networks are

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different from those in systems engineering. The second area involves the establishment of a traffic management system that is able to provide users with a high level of road network performance.

This could be achieved by using a hardware approach such as constructing new infrastructure or by software approach such as traffic regulation and control/guidance. The third area involves the development of new evaluation procedures for optimising the planning, construction and management of road networks that incorporate road network reliability

Road network analysis is generally based on mean values, using static traffic assignment techniques, such as travel time, travel distance or level of congestion. In traffic assignment, traffic demand between origin and destinations is generally assumed as constant, although actual traffic demand changes from time to time.

It is difficult to determine the flow performance of a link using static traffic assignment. Suppose that we have two types of road, one is a road with high capacity and the other with low capacity, and assume that both the roads are not congested as a result of static traffic assignment. In this case, however, if OD traffic demand changes over time, the probability of congestion would be much higher for the low capacity road than for the high capacity road. In addition, capacity will vary from time to time due to traffic accidents, illegal parking or maintenance work etc.

It is therefore difficult to evaluate the robustness or the performance of road networks using only the mean value of traffic flow. It appears that a probability measure is much more appropriate for evaluating the reliability of road networks. For example, the probability of smooth travel without congestion, the probability of a stated travel time to arrive at a destination and the probability of time duration of unexpected delay on travel could be used as evaluation measures to assess the performance of road networks.

Road users in the 21st century will desire a more stable transport system where they can be confident of arriving at their destination on schedule. As stated above, road network reliability analysis will play an important role in the planning, design and management of road networks in the future.

Definitions and Aspects of Road Network Reliability

There are two kinds of definitions of road network reliability, connectivity reliability and travel time reliability (Bell and Iida, 1997). Connectivity (or terminal) reliability is defined as a probability that there exists at least one path without disruption or heavy delay to a given destination within a given time period. For example, if some road links were degraded due to an accident or disaster, any pair of nodes in the road network should be connected by at least one path without congestion. If the connectivity reliability between an OD pair is 0.6, then a trip from an origin can reach its destination without encountering congestion 6 times out of 10. Travel time (or performance) reliability is defined as the probability that traffic can reach a given destination within a stated time. For example, if the travel time reliability to arrive at a destination in 30 minutes is 0.5, this means that drivers will arrive at the destination within 30 minutes 1 time out of 2.

There is another important aspect for road network reliability analysis relating to the type of situation on the network. Here, both abnormal and normal situations must be distinguished. In abnormal situations, events such as serious disasters, huge accidents, large-scale maintenance work can effect reliability. In these cases, some components of road network system will fail. Normal situations are due to usual variations in traffic demand and road capacity. There remain many research subjects still to be studied in these areas, for example, network flow characteristics in emergency.

Features of Road Network Reliability

Reliability analysis for road networks differs from common system reliability analysis. Firstly, road networks should be treated as multi-commodity flow and not as single commodity flow just like electric or water flows, because each trip has its own origin and destination nodes. Secondly, path choice behaviour must be considered in road network reliability analysis. In communication networks, for example, shifting from a shorter path to a much longer path poses no problem, whereas in road networks, trip-makers are assumed to prefer less costly paths. Thirdly, there are many uncertainty factors in road network reliability analysis, such as simplified network representation, treatment of trips outside the study area and the non-uniqueness of link reliability definitions. Finally, the level of accuracy required in road network reliability analysis is not as high as commonly encountered in systems engineering applications.

Connectivity Reliability

Let us show first the basic concept of connectivity reliability (Mine and Kawai, 1982). The state of link a is represented by the 0-1 variable. For example, if link a is not congested, the state variable is 1, and if link a were disrupted or congested, then the state variable is zero.

$$x_a = \begin{cases} 1 & \text{if link } a \text{ works} \\ 0 & \text{otherwise} \end{cases} \tag{1}$$

The condition of the system is represented by structure function $\phi(\mathbf{x})$, where $\mathbf{x}$ is the state vector of link variable. If the system functions, then the structure function is equal to 1, and if the system fails, then the structure function is zero.

$$\phi(x) = \begin{cases} 1 & \text{if the system functions} \\ 0 & \text{if the system fails} \end{cases} \tag{2}$$

Link reliability is represented by an expected value of the link state variable. As well, the system reliability is shown by a probability that the system works, namely by an expected value of the system structure function $\phi(\mathbf{x})$.

$$r_a = E\{x_a\} \tag{3}$$

$$R = E\{\phi(\mathbf{x})\} \tag{4}$$

If the system consists of a series system as in Fig.1, the structure function is the product of link state variables. This means that, if any one of the links failed, then the system would fail. Accordingly, the structure function for series system can be represented by a path. For example,

$$\phi(\mathbf{x}) = \prod_a x_a = x_1 \times x_2 \tag{5}$$

Figure 1. Series System

If the system consists of a parallel system as in Fig.2, the structure function is shown by a cut set as shown below, meaning that, if both links failed, then the system would fail. Namely if any one of the links failed, the system would work. For example,

$$\phi(\mathbf{x}) = \coprod_a x_a = 1-(1-x_1)(1-x_2) \tag{6}$$

This measure of the system's reliability can be obtained respectively by the expected value of the system structure function expressed by paths or cut sets. But the state variable of any link

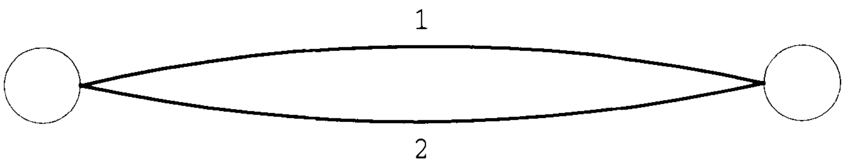

Figure 2. Parallel System

appears more than once in the expressions of the structure functions for a complicated road network system. In order to correct the errors due to this overlapping of state variable, Boolean algebra should be used (Inoue, 1976). In addition, to obtain the exact value of the system's reliability, the system structure function consisting of all paths or all cut sets must be identified. This may however require a tremendous amount of calculation using Boolean algebra, since the computation time and the memory requirement both increase exponentially with the number of links. Although this may not pose any problem in communication networks, some paths are unrealistic in transportation networks. As for cut sets, it is more practical to handle cross sections corresponding to screen lines or cordon lines. Thus, for road networks, it is desirable to develop an efficient heuristic for the estimation of reliability.

Method to Determine Link Reliability

In order to determine the reliability of a road network system, the reliability of the links in the network must be first determined. The link reliability value is the expected value of a random binary variable for the link state, namely, 0 or 1, depending on whether the link functions or not. The link reliability values can be determined from observed link flow data by traffic counters or detectors. In general, however, traffic counters or detectors are installed only on a limited number of links in the network. It is therefore necessary to estimate link reliability values on unobserved links from the observed link flows. For this estimation, the Time-Dependent Path Flow Estimator by Bell and Iida (1997), or the Dynamic Estimation Model for OD and Path Flows by Iida et al. (1998) can be applied.

From historical observed link flow data, a probability density function of link flow can be obtained. Since the link reliability is an expected value of the link's state for smooth flow, it can be determined by a probability that traffic volume is less than the link's capacity as shown in Fig.3. With this definition of link reliability, the connectivity reliability of the road network shows a probability that there exists at least one path to the destination without congestion. When the link reliability is defined by a probability of disruption or failure, the connectivity reliability of road network indicates a probability that any one of paths connecting to the destination is available at worst. This corresponds to the case of the abnormal situation.

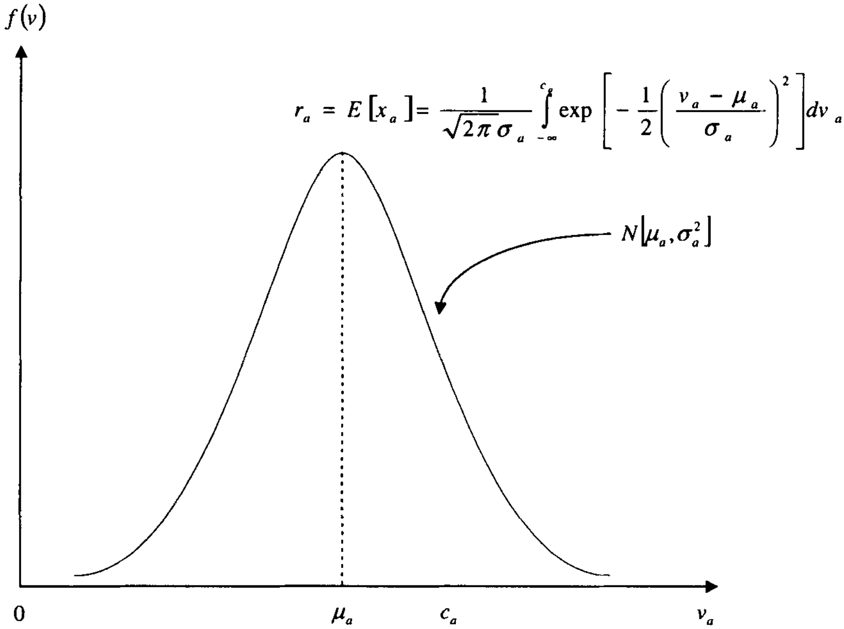

Figure 3. Link Reliability

The probability of a certain degree of road facility damage due to a disaster could be estimated by using earthquake engineering or disaster prevention engineering techniques. Likewise, it may be possible to determine link reliability, or the probability of a degree of reduction in link flow capacity in the case of a disaster. For incidents, maintenance or other events, it would be possible to use historical data in determining link reliability, namely, a probability of link availability. Since link reliability is affected not only by the degradation of link capacity but also by changes in the network flow behaviour in abnormal situations, a network flow simulation approach would be effective. However, past research on flow variation in abnormal situations is scarce, and so further work is required in this area.

Travel Time Reliability

Travel time reliability is the probability that a trip will arrive at its destination within a given period. Travel time reliability is a measure of the stability of travel time, and therefore is affected by fluctuations in traffic flow. Let us suppose here that an observed distribution of link flows is subject to a normal distribution. It has been found that a summation of normal distributions forms a normal distribution, provided the distributions are statistically independent. In general, the relation can be represented using the following equation.

$$T \approx N\left(\sum_{a \in P(s)} \mu_a, \sum_{a \in P(s)} \sigma_a^2 \right) \tag{7}$$

where, T is travel time along route $P(s)$, μ_a mean value of travel time on link a, and σ_a^2 variance of travel time on link a. Namely, the mean travel time along a route is given by the summation of mean values of links. Similarly, the variance of travel time along a route is shown by the summation of variances on links. By normalisation of the travel time in terms of probability variable, the probability that travel time on a certain path is less than some threshold value t may be found using the integral of the unit normal distribution from minus infinity to the normalised threshold value of travel time.

$$\Pr\{T \leq t\} = \Phi\left(\left(t - \sum_{a \in P(s)} \mu_a \right) \Bigg/ \sqrt{\sum_{a \in P(s)} \sigma_a^2} \right) \tag{8}$$

Like this, travel time reliability may be determined for individual paths unlike connectivity reliability between OD pairs (For example, Asakura and Kashiwadani, 1991).

Future Research Works

The remaining problems with the road network reliability analysis are as follows (Bell et al. 1997).

(1) As for road network reliability analysis, connectivity reliability is defined only for each OD pairs, and travel time reliability only for individual paths. It is therefore necessary to construct a definition of reliability for the entire road network system.

(2) Mutual relationships or dependencies among links are overlooked in reliability analysis. When a link becomes congested or fails, the adjacent links are also affected by this congestion or failure. Thus it is desirable to take into account this correlation.

(3) Traffic flows are generally ignored in finding the connectivity reliability. Since paths and cut sets with heavy flows are important from the standpoint of traffic management, flow should be considered in future studies.

(4) Travel time reliability is different from connectivity reliability in concept. Past studies are scarce and lack theoretical profundity. It is expected that future study would construct new concepts of travel time reliability between OD pairs.

(5) Methods for road network reliability in abnormal situations are required to be developed. In abnormal situations, the flow variation differs greatly from those prevailing normally. However insufficient knowledge currently exists about flow variation in abnormal situations. Simulation may provide a useful technique for this investigating this area.

Future Directions for Practical Applications of Network Reliability

It is important to develop and extend the field of transportation network reliability analysis for practical use. Firstly, network reliability concepts could be used as a new evaluation measure for designing road networks, which is different from the existing measures, such as mean travel time or degree of congestion. Since network reliability is represented by a probability value between 0 and 1, meaning a normalised degree of robustness or stability of network performance, it is possible to compare reliability values among several cities with different levels of service. Secondly, the network reliability concept could be applied in planning new roads which can satisfy a certain level of redundancy or connectivity, considering cost-benefit relation. In particular, this approach is very useful for designing a road network which can work even in the case of disaster or incident. Thirdly the network reliability concept will play an important role in traffic management systems as well. ITS technology will contribute to the alleviation of traffic congestion, thereby leading to an increase in network performance or credibility. The problem is however how to control trips, using ITS technology, such as traffic information systems, dynamic route guidance systems, and car park reservation systems etc., in order to enhance network reliability.

In relation to traffic management systems, let us show one application of the reliability analysis concept to dynamic route guidance system, in which at present only travel time information is provided users. In this system, however, it is likely that traffic flow will concentrate consecutively into the shortest route suggested by travel time information, thereby causing traffic congestion on the current shortest route shortly. For example, with two parallel routes between an OD pair, it repeats that the shortest route will change into congested one and vice versa alternately due to dynamic route guidance based on only current travel time information. The objectives of dynamic route guidance systems are not only to ensure the shortest travel time to get to the destination but also to reduce unexpected delays on the route. Accordingly, it is required that dynamic route guidance should be conducted so as to reduce congestion in order to improve travel time reliability. For this purpose, the following methods of information supply on routes could be applied:

Method 1 (current travel time) + (probability of encountering congestion)

Method 2 (current travel time) + (probability of travel time more than this)

Method 3 (current travel time) + (mean and deviation of travel time)

The second term in the above methods indicate information on road network reliability, which can be given by historical data on network flow. In short, it would be desirable that risk (or delay) information should be provided to users in addition to travel time in dynamic route guidance system in order to avoid excessive flow concentration onto a particular route, or in order to encourage dispersion of route choice by drivers. Further studies are necessary to determine whether or not the above methods will contribute to the improvement of network system reliability.

Concluding Remarks

Due to the increasing value of time, it will be required that the most appropriate means of transport should be available depending on the current traffic conditions and trip purpose in future transport systems. Road network reliability analysis is aimed at constructing and controlling road networks so as to ensure that users have smooth travel even if some links in the network become congested or fail. Accordingly, road network reliability analysis techniques should be further developed not only from theoretical aspect but also for practical application.

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