HIGHWAY NETWORK RESTORATION AFTER DISASTERS

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ABSTRACT

In the second half of 2011, Thailand has recently faced with the most devastating flood of her modern history. More than 3,330 national highways are damaged by this flood. Some roads are heavily destroyed while others are partially damaged and emergency relieves cannot access to the flooded areas. Highway restoration is an urgent responsibility of road authorities. This study presents the sequential highway network restoration decision model where highways are restored one by one in sequence. To determine an optimal restoration sequence, the model is formulated as a dynamic program where the primary objective is to sequentially restore roadways to minimize the travel demand loss for the disconnected network. Once the network is connected, the secondary objective is to sequentially restore roadways to minimize the network travel time where traffic assignment onto the network is based on User Equilibrium concept. A sample network is examined to investigate the solution characteristics. It is found that the proposed algorithm can provide good practical solutions to the sequential highway network recovery problems.

BACKGROUND

In the second half of 2011, Thailand has confronted with one of the devastating floods of her modern history. The area affected by this flood is approximately more than 350,000 squared kilometers and the death toll is more than 700 and still rising at the of writing this paper. This does not exclude Bangkok, the capital city of Thailand, where business and government offices are located. The total economic loss is estimated more than 1.40 trillion baths (43 billion US dollars). Some people in flooded areas are evacuated but others still desire to stay in their neighborhoods to look after their properties. Emergency relieves are to a great extent needed for those people. Highways, which were normally used for transport, are mostly destroyed from the flood and emergency relieves cannot promptly access to the flooded areas. More than 3,330 national highways are damaged by this flood. Furthermore, food and medicine distribution in the central part of the country has by large been disrupted. As a consequence, highway restoration is an urgent responsibility of road authorities. The decision to sequentially restore highways is very important because not all damaged highways can be recovered at the same time due to the limited budget. In fact, an amount of available budgets or resources is not known at the time of emergency and a highway is restored one by one. This problem is therefore a sequential highway restoration decision process, which is a focal point of this study.

Literature search is conducted to identify relevant literature on sequential highway network restoration problems but none has been found. Most existing research is discussing network reliability and vulnerability. The relevant studies are briefly discussed here. Wakabayashi and Iida (1992) developed a graph theory approach for assessing the reliability between a pair of nodes in a transportation network using partial minimum path and cut sets. This involves excluding all paths that are circuitous and are not perceived as feasible alternatives by users. Yee et al. (1994) studied how the 1994 Los Angeles earthquake, which closed highways, affected road user costs. They found that the cost road user delay corresponding with Interstate Highway 10 was almost US $1 million per day, even after detour, car-pool lanes, and rail and bus service improvements was established. Nicholson and Du (1994) mentioned various methods for improving network reliability including, 1) improving component reliability such as replacing or strengthening bridges, 2) improving the network configuration such as constructing new links, 3) having stand-by components, which are activated after degradation of the original component such as Bailey bridges, emergency air-ferry services, 4) monitoring critical components to detect degradation and advise users of alternatives, 5) undertaking regular preventive maintenance, and 6) identifying priorities for repairing degraded components to minimize the socio-economic impacts. Nicholson and Du (1997) suggested unreliability can be considered to come from two distinctly different sources; flow variations and capacity variations. The main focus of transportation network reliability research has been upon reducing the impact link capacity variation because there are authorities that are responsible for managing transport networks and are expected to minimize the frequency of such events. Du and Nicholson (1997) proposed measuring reliability using the probability that the reduction in flow does not exceed a specified threshold. They defined network reliability in terms of the reliabilities of the sub-networks connecting individual OD pairs. When a link is degraded, the cost of travel between one or more OD pairs may be affected. Bell and Schmocker (2002) defined encountered reliability to be the probability of not encountering a link degradation on the path with least (expected) costs.

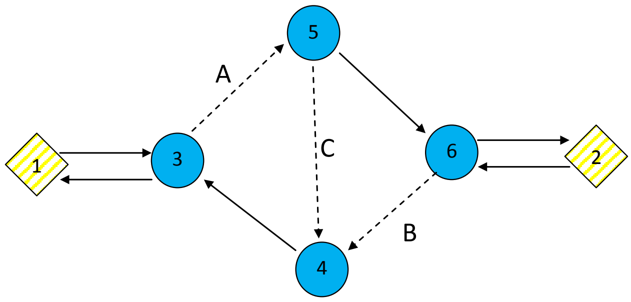
In summary, to the extent of our knowledge, the sequential highway network restoration problem from disastrous events, which is the focal point of this study, is a new area of research in transportation network analysis. Therefore, the objectives of this study are:

- To develop a sequential highway network restoration decision model after disastrous damage,
- To develop a heuristic solution method for practical-sized problems, and
- To test the proposed model with a sample network.

In the remainder of the paper, the model development is presented where an optimization formulation is proposed using dynamic programming followed by the solution method based on the so-called Particle Swarm Optimization (PSO) technique. Next, a case study as well as a sensitivity analysis of the sample network are examined to investigate an accuracy of the proposed method. The paper is then closing with conclusions and recommendations.

METHODOLOGY

Some roadways are heavily destroyed and others are partially destroyed from flood. These result in a condition that some trips of origin-destination pairs cannot be made and other origin-destination pairs have to take detours instead of direct routes. There are two types of disutility involved. First, there is a demand loss from trips that cannot be made due to a disconnected network. Second, the trips that have to take indirect routes will produce higher travel times when compared to a normal road condition, which is called a travel time increase. The demand loss is considered by far more important than the travel time increase because it means that some parts of the network are being cut off. The primary objective is to sequentially restore roadways to minimize the demand loss. Once the network is connected, the secondary objective is to sequentially restore roadways to minimize the network travel time. Since the budget is not known at the time of emergency, the road authorities will have to restore highways sequentially one by one according to both objectives in their respective orders. For an illustrative purpose, let us consider a sample network shown in Figure 1. There are three links destroyed from flood, links A, B, and C. To recover the network to its normal condition, link A would be selected first to be restored followed by links B and C, respectively because link A must carry 500 veh/day for OD pair 1 - 2. If it were disconnected, this demand would be left unsatisfied. Link B must carry 200 veh/day for OD pair 2 - 1. If it were disconnected, this demand would be left unsatisfied. For link C, it is on an alternative route for OD pair 1 – 2. Therefore, the optimal decision to sequentially restore this highway network should be [A B C] in their respective order.



O/D Demand (veh/day)	1	2
1	-	500
2	200	-

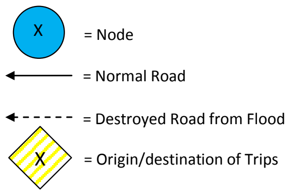
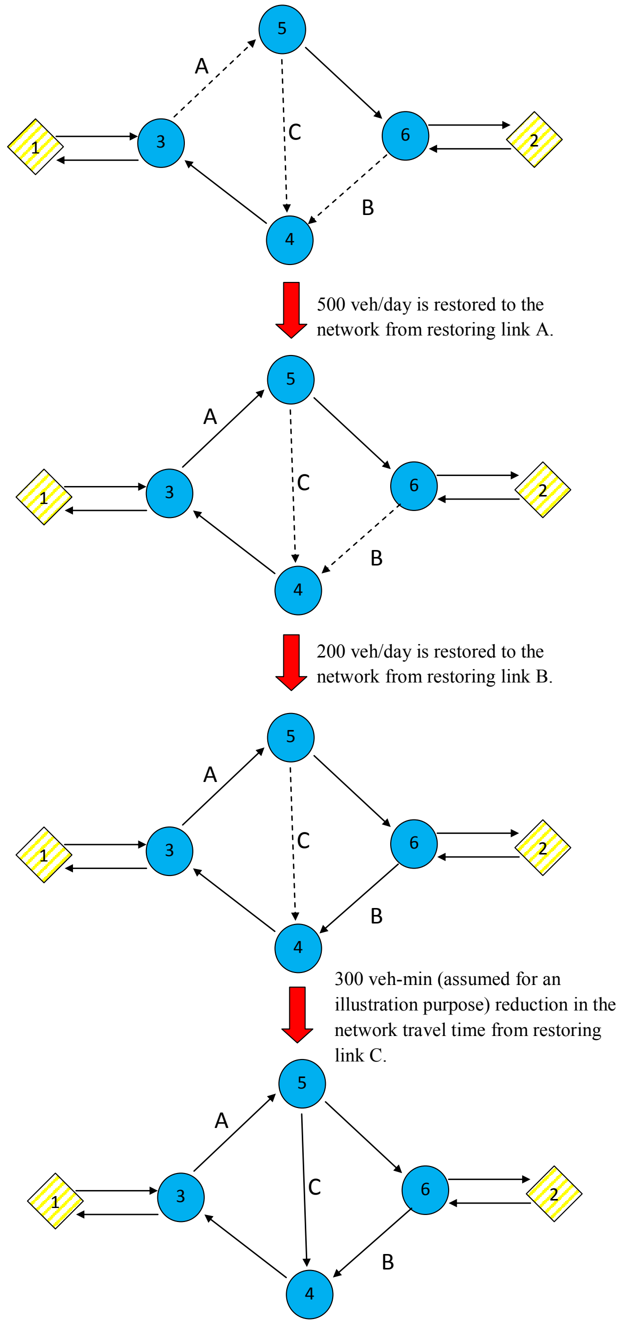


Figure 1 – A Sample Network

In general, for a network with N destroyed links, the solution space is a combination of the permutation of integer numbers from 1 to N corresponding to each link in sequence to be restored. An objective ***vector*** of the proposed formulation is more interesting than the solution space. It is a ***vector*** whose elements are either a number of ***reconnected*** OD demand for the disconnected network or a reduction in the network travel time for the connected network as shown in Figure 2. The disconnected network is considered more important than the connected case; hence, for the calculation purpose, the reconnected OD demand is multiplied with a big positive number. From figure 3, one feasible solution for a restoration sequence is x_A = [A B C] with the corresponding objective vector f_A = [500M 200M 300] where M is a big positive number. If another feasible solution for a restoration sequence is considered x_B = [B A C] with the corresponding objective vector f_B = [200M 500M 300], f_A is better than f_B because 500M is greater than 200M. In other words, two objective vectors are ***lexicographically*** compared.



Feasible solution = [A B C] with an objective vector = [500M 200M 300].
where M is a big positive number.

Figure 2 – Feasible Solution and Objective Vector

In order to calculate the objective vector, we check whether the network is disconnected for any OD pair and calculate the network travel time. There are two cases involved. In the first case, the disconnected network, the reconnected OD demand is calculated as a result of the link restoration. In the second case, the connected network, the network travel time reduction is calculated as a result of the link restoration. Traffic is assigned onto the network based on User Equilibrium (UE) notion, which is a condition when no traveler can improve his travel time by unilaterally changing routes. For each OD pair, at User Equilibrium, the travel time on all used path is equal, and also less than or equal to the travel time that would be experienced by a single vehicle on any used path. For further details of traffic assignment, see Sheffi (1985). Because of the sequential decision nature, the highway network restoration problem can be formulated as a dynamic program as follows:

$$f_t(j,S) = \text{lexmax}_k\{f_{t-1}(k,S-\{k\}) \oplus \Delta_{S-\{k\},j}\};\ t = 1, 2, 3,\ldots, \text{N (no. of links)};\ j = 1, 2, 3,\ldots, \text{N}$$

$$\text{Boundary condition: } f_1(j,\emptyset) = \Delta_{\emptyset,j}$$

$$\text{Answer: } \text{lexmax}_{j=1,2,\ldots,N}\{f_{N-1}(j,N-\{j\}) \oplus \Delta_{N-\{j\},j}\} \tag{1}$$

Where lexmax = Lexicographic maximization

$f_t(j,S)$ = Objective ***vector*** of the restoration sequence with the set of t-1 intermediate links S (the stage variable t indicates the number of links in S plus one) where j is the most-recent link to be restored.

$$\Delta_{S-\{j\},j} = \begin{cases} \text{Number of reconnected OD demand from restoring link j} \\ \quad \text{if the network in set } S-\{j\} \text{ is disconnected.} \\ \text{Network travel time reduction from restoring link j} \\ \quad \text{if the network in set } S-\{j\} \text{ is connected.} \end{cases}$$

$\oplus$ = Appending operator (e.g. [A] $\oplus$ b = [A b], b is appended to the vector [A].)

The proposed dynamic program can be solved by backward induction to provide an exact solution for any network. Please refer to Held and Karp (1962), and Dreyfuse and Law (1977) on an overview of dynamic programs in sequencing problems. However; the practical limit on size of the problem can be solved by the above procedure is due to storage space and a number of function evaluation. At stage *t*, $f_t(j,S)$ must be evaluated for $N \cdot \binom{N-1}{t-1}$ different *j* and *S* pairs where N is the total number of destroyed links in the network. Each such evaluation requires *t*-1 operations to calculate $\Delta_{S-\{j\},j}$, each of which requires either traffic assignment or network connectivity-check computation. Therefore, for all stages the following number of traffic assignment or network connectivity-check computation is required:

$$\begin{aligned} &= N + \sum_{t=2}^{N-1}(t-1) \cdot N \cdot \binom{N-1}{t-1} + N \\ &= 2N + N(N-1)\sum_{t=2}^{N-1}\binom{N-2}{t-2} \\ &= 2N + N(N-1)\{2^{N-2} - N + 2\} \end{aligned} \tag{2}$$

For an illustration purpose, let us consider the required traffic assignment or network connectivity-check computation for different problem sizes as shown in Table 1.

Table 1: Computation efforts of the proposed dynamic program (DP)

No. of Destroyed Links	No. of Traffic Assignment Computation or Network connectivity-check for the DP
5	110
10	22,340
20	99,607,920
40	428,809,534,773,440
80	1,910,102,794,991,110,000,000,000,000
100	3,137,435,235,564,870,000,000,000,000,000,000

Since the computation cost of traffic assignment and network connectivity check is high, the proposed dynamic program is limited to small-sized network problems. In this study, we develop a heuristic algorithm, based on particle swarm optimization, to bypass an extensive computation burden of the dynamic program.

APPLICATION AND CASE STUDY

In this section, an application of the proposed method to the sequential highway network restoration problems is illustrated with a sample network. The network consists of 32 links, ten of which are destroyed from flood as shown in Figure 3, with the traffic demand. Link travel times are represented by the Bureau of Public Roads (BPR) function as expressed below.

$$t_k(x_k) = t_k^0\left(1 + \alpha \left[\frac{x_k}{CAP_k}\right]^{\beta}\right) \tag{3}$$

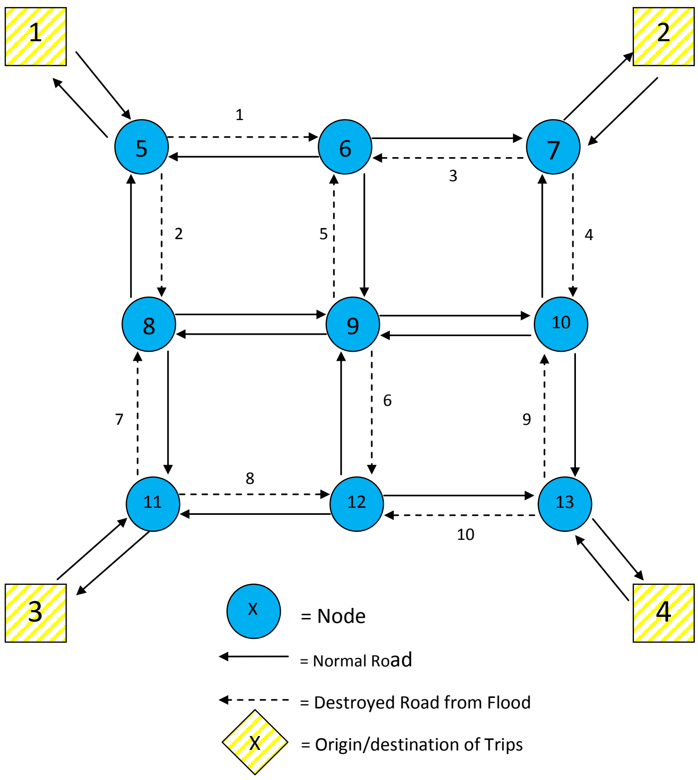
Where $t_k(x_k)$ = travel time on link k given its flow x_k

t_k^0 = free-flow travel time on link k

x_k = traffic flow on link k

CAP_k = traffic-carrying capacity on link k

α, β = BPR parameters with typical values α = 0.15 and β = 4



(a) A Case Study Network

O\D	1	2	3	4	Total
1	-	100	150	50	300
2	75	-	200	40	315
3	90	150	-	50	290
4	175	25	10	-	210
Total	340	275	360	140	1115

(b) Traffic Demand for the Case Study

Figure 3 – A Case Study Network with Traffic Demand

Upon the application of the PSO technique using the number of particles 10 and the number of PSO iterations 100, the solution is obtained as follows: x_{opt} = [3; 1; 7; 9; 2; 10; 4; 6; 8; 5] and the objective vector is f_{opt} = [315M; 300M; 290M; 210M; 11611.56; 3328.45; 2999.88; 1702.07; 1601.25; 0]. This solution shows an anticipated result because links are restored according to their relative importance. Link 3 is the first in sequence to be restored because it carries the highest OD demand loss followed by links 1, 7, and 9, respectively. After that, the network is already connected. Restoring link 2 will reduce the network travel time by 11611.56 veh-min. Links 10, 4, 6, and 8 are restored in sequence to further reduce the network travel time whereas link 5 is the last to be restored since it provides no further network travel time reduction.

CONCLUSIONS

In this study, the sequential highway network restoration problem after disasters is considered. This problem is new in transportation network analysis as previous studies only discuss reliability or vulnerability of network. The decision model is formulated as a dynamic program. The network is considered in two cases: 1) the disconnected network where some trips cannot be made for some OD pairs, and 2) the connected network where all trips can be made for all OD pairs but some of them might have to take indirect routes. Therefore, the primary objective is to sequentially restore roadways to lexicographically minimize the travel demand loss. Once the network is connected, the secondary objective is to sequentially restore roadways to lexicographically minimize the network travel time where traffic assignment onto the network is based on User Equilibrium concept. Due to the computation burden of the dynamic program, the heuristic solution method using particle swarm optimization (PSO) technique is presented for practical size problems. A sample network problem is examined to investigate the solution characteristics with a sensitivity analysis. It is found that the proposed algorithm can provide good practical solutions to the sequential highway network recovery problems. Currently, this algorithm is incorporated to the Thailand highway maintenance management system.

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