Combinatorial reconfiguration problem based on MFD for evacuation management under disasters

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1 INTRODUCTION

In disaster situations, unique trip patterns distinct from normal traffic emerge, necessitating network-wide traffic control to avoid heavy congestion. Previous research has proposed control methods such as perimeter control (Geroliminis *et al.*, 2012) and reversed lanes (Kim *et al.*, 2008) to alleviate daily and evacuation congestion. To achieve such real-time controls, models that predict evacuation demands fast, and algorithms that determine control sequences are necessary.

Extensive research has been conducted on predicting evacuation demands and traffic conditions during disasters and optimizing traffic control accordingly. However, the computational costs of predicting traffic conditions in large-scale networks pose challenges to real-time predictive control. Furthermore, the transition from normal to disaster network configurations has been insufficiently addressed in previous research. Extensive network modifications for control are undesirable in disasters whose risks are gradually escalating; instead, it is preferable to incrementally expand the control areas as risks increase. This gradual change must be managed without causing congestion or network disruptions, necessitating complex decisions.

In response to these challenges, this study proposes a zone-based traffic assignment model using Macroscopic Fundamental Diagrams (MFD) (Geroliminis & Daganzo, 2008) and the Recursive Logit model (Oyama & Hato, 2017) that predicts dynamic traffic congestion during a disaster. Additionally, we employ an algorithmic technique of combinatorial reconfiguration to

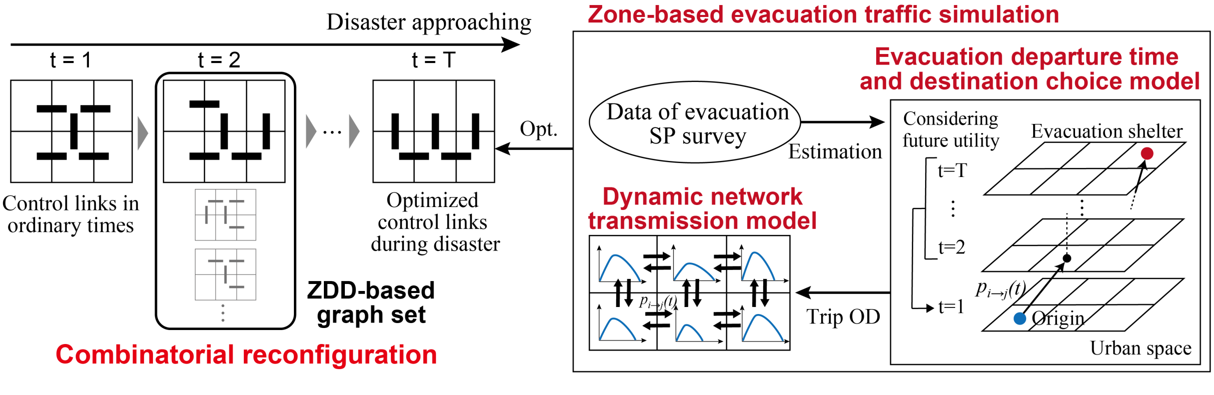

Figure 1 – *Framework of this study*

determine optimal control switching sequences. Figure 1 shows the framework of our study. Firstly, the evacuation behavior, including departure time and destination choices, is modeled using the Recursive Logit model. This demand is assigned on a network that is approximated by zones using MFD, enabling fast, wide-area traffic prediction. Using this model, we determine the optimal road capacity configuration during a disaster. Next, an algorithm for combinatorial reconfiguration (Ito *et al.*, 2011) is used to switch from traffic control in ordinary times to control during disasters. Combinatorial reconfiguration is a field of theoretical computer science that analyzes changes over state spaces. The approach is distinctive for considering the intermediate state and constraints during the transition from the initial state to optimal solutions. The configuration of discrete control variables exists in exponentially large numbers, making it challenging to enumerate all possible transitions of control variables over time. In the field of combinatorial reconfiguration, an algorithm has been developed that uses a data structure of Zero-suppressed Decision Diagrams (Minato, 2001) to efficiently preserve and retrieve the data. We apply the algorithm to determine the optimal transition from normal to disaster-time traffic control.

2 FRAMEWORK OF THE PROPOSED MODEL

2.1 Dynamic network transmission model with Recursive Logit model

A dynamic evacuation departure time and destination choice model is modeled to predict pre-disaster evacuation behaviors. The model is formulated as a route choice on the time-expanded network, using the discounted Recursive Logit model (Oyama & Hato, 2017). Consider evacuees at state s_t, a combination of zone and time, moving to the next state $s_{t+1} \in A(s_t)$. $A(s_t)$ is the set of next states from s_t. We assume that evacuees choose the next state to maximize the sum of the instantaneous utility $u(s_{t+1} \mid s_t) = v(s_{t+1} \mid s_t) + \mu\epsilon(s_{t+1})$ and the expected maximum utility $V^d(s_{t+1})$. $v(s_{t+1} \mid s_t)$ and $\epsilon(s_{t+1})$ is the deterministic term of the utility and random term following the i.i.d. Gumbel distribution with a scale parameter μ, respectively. $V^d(s_t)$ is formulated by the Bellman equation with discount factor β,

$$V^d(s_t) = E\left[\max_{s_{t+1}\in A(s_t)} \{v(s_{t+1} \mid s_t) + \beta V^d(s_{t+1}) + \mu\epsilon(s_{t+1})\}\right]. \tag{1}$$

By the assumption of the random term, Equation (1) is reformulated in the form of log-sum, and the transition probability from s_t to s_{t+1} is calculated as follows:

$$p(s_{t+1} \mid s_t) = \frac{\exp\left(\frac{1}{\mu}(v(s_{t+1} \mid s_t) + \beta V^d(s_{t+1}))\right)}{\sum_{s'_{t+1}\in A(s_t)} \exp\left(\frac{1}{\mu}(v(s'_{t+1} \mid s_t) + \beta V^d(s'_{t+1}))\right)}. \tag{2}$$

Next, evacuation trips calculated with Equation (2) are assigned on the zone-based network. The number of vehicles demanding to evacuate from zone i to j at time t is defined as $n^{VOD}_{i\to j} = p(s_{t+1} \mid s_t) \cdot n_i(t)$, where $s_t = (i,t)$ and $s_{t+1} = (j, t+1)$. $n_i(t)$ is the number of vehicles in zone i at time t. We calculate the inter-zone traffic flow with demand $n^{VOD}_{i\to j}$, the zone capacity defined by the MFD of the receiver zone, and the capacity of boundary links. The other assignment procedures for the network transmission model follow Kim *et al.* (2018).

This assignment model for inside-zone traffic congestion is used to obtain the optimal combination of control links. We consider road capacity enhancement as a means of traffic control by changing the signal phase or inflow of vehicles. We perform the assignment model for all the combinations of control links and obtain the one that minimizes the total waiting steps.

2.2 Combinatorial reconfiguration

The transition from control links in ordinary times to those during disasters is described as a reconfiguration problem. The zones' connectivity is represented by a graph $G = (V, E)$, where the vertex set V represents the zones, and the edge set E represents the boundary links between zones. The reconfiguration problem involves finding a sequence of transitions that meet specific constraints and rules, from a control link combination in ordinary times $S \subseteq E$ to an optimal evacuation control link combination $T \subseteq E$. A transition sequence is $I_0 = S, I_1, \ldots, I_{l-1}, I_l = T$, where each I_i is a set of edges that meets the constraints. The edge constraints considered are: (1) any node can reach an evacuation zone by following control links, and (2) each zone is connected to at least one control link. Since replacing several control links, i.e., changing signal phase or direction of lanes at one time, is practically difficult, two transition rules are considered: (1) add one link and remove another, and (2) add or remove a link.

Due to the vast number of possible link combinations, it is difficult to search all solutions exhaustively. Therefore, we use Zero-suppressed binary Decision Diagrams (ZDD) to efficiently preserve and compute the solution sets. ZDD is a data structure that compactly compresses and maintains a family of sets. For a universal set $E = \{e_1, e_2, ..., e_n\}$, a binary tree would need 2^n terminal nodes to represent whether each link is included in the sets. On the other hand, ZDD reduces the nodes in the tree by sharing nodes, thus maintaining large sets efficiently. It also allows for efficient operations on compressed sets, such as union and intersection.

Starting from an initial solution set $Z_0\{S\}$ containing only S, we calculate the intersection of transitionable solution sets and constraint-meeting solution sets, thereby constructing the feasible sets in the form of ZDD. This breadth-first search can determine the shortest transition sequence by tracing back from the target state T. The fast set operations of ZDD enable more efficient searching than simple breadth-first search. There may be multiple feasible transitions when seeking back from the target solution. Therefore, weights are assigned to the control links in normal times, and the transition is made to maximize the sum of the link weights. This implies selecting control links that involve minimal modifications from those in ordinary times.

3 CASE STUDY

3.1 Parameter estimation

The case study is conducted in Koto City, Tokyo, Japan. We divided the city into 2 [km] grids, and each grid corresponds to one zone in the dynamic network transmission model. The explanatory variables of the evacuation behavior model are, for destination choice, flood depth of destination, residence in inundation areas (binary), and staying in residence (binary), and for departure time choice, subjective probability of disaster and distance to destinations. We estimated the parameters using a Stated Preference survey on a flood disaster. The MFDs are approximated as triangular shapes whose parameters are estimated using microscopic simulations.

3.2 Optimal link configuration and reconfiguration process

Figure 2 presents the optimal configuration of control links (bottom left) and the transition of control links from the initial state (top left). The optimal configuration of control links consists of links that run east-west through the flooded area and those connecting the flooded and non-flooded zones. According to the evacuation destination choice model, evacuees are likely to select non-flooded zones 7 and 8 as their destinations, hence the choice of control links that facilitate flow to these areas by expanding their capacity. Next, the transition from the initial state to the optimal state during a disaster involves a gradual reconfiguration of control links, with minimal changes to the existing normal control links. Throughout the transition, the connection between the shelter zone, zone 7, and the flooded zones is maintained, which means the transition meets the constraints. Finally, the 'total wait' at the top of each figure represents the total waiting steps within the simulation if the corresponding control links persist until the terminal time. As the disaster approaches, the total waiting steps decrease, indicating that modifications to the control links are effectively reducing congestion caused by evacuation traffic.

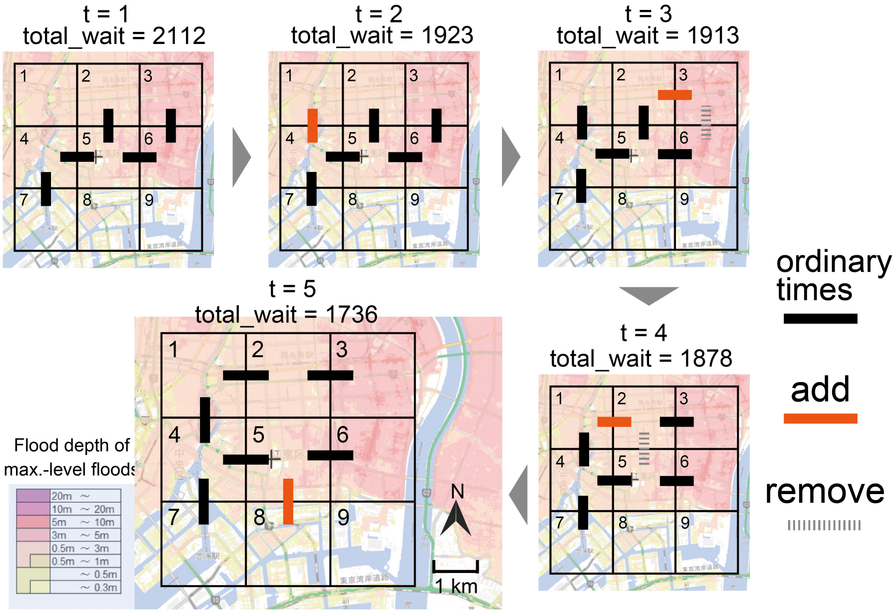

Figure 2 – *Results of reconfiguration problem*

4 CONCLUSION

In this study, we developed a dynamic evacuation behavior model using the Recursive Logit model to predict and evaluate dynamic traffic flow during disasters. Additionally, we integrated a zone-based traffic assignment model employing MFD. Using this model, we determined the configuration of inter-zone control links to minimize congestion during evacuations. To facilitate a smooth transition from regular traffic control, we introduced a combinatorial reconfiguration problem and successfully devised a rapid computational solution using Zero-suppressed binary Decision Diagrams for exhaustive enumeration. Future research will focus on applying this method to larger networks and comparing it with microscopic simulation-based methods in terms of computational cost and optimality.

References

Geroliminis, Nikolas, & Daganzo, Carlos F. 2008. Existence of urban-scale macroscopic fundamental diagrams: Some experimental findings. *Transportation Research Part B: Methodological*, **42**(9), 759–770.

Geroliminis, Nikolas, Haddad, Jack, & Ramezani, Mohsen. 2012. Optimal perimeter control for two urban regions with macroscopic fundamental diagrams: A model predictive approach. *IEEE Transactions on Intelligent Transportation Systems*, **14**(1), 348–359.

Ito, Takehiro, Demaine, Erik D, Harvey, Nicholas JA, Papadimitriou, Christos H, Sideri, Martha, Uehara, Ryuhei, & Uno, Yushi. 2011. On the complexity of reconfiguration problems. *Theoretical Computer Science*, **412**(12-14), 1054–1065.

Kim, Sangho, Shekhar, Shashi, & Min, Manki. 2008. Contraflow transportation network reconfiguration for evacuation route planning. *IEEE transactions on Knowledge and Data Engineering*, **20**(8), 1115–1129.

Kim, Sunghoon, Tak, Sehyun, & Yeo, Hwasoo. 2018. Agent-based network transmission model using the properties of macroscopic fundamental diagram. *Transportation Research Part C: Emerging Technologies*, **93**, 79–101.

Minato, Shin-ichi. 2001. Zero-suppressed BDDs and their applications. *International Journal on Software Tools for Technology Transfer*, **3**(2), 156–170.

Oyama, Yuki, & Hato, Eiji. 2017. A discounted recursive logit model for dynamic gridlock network analysis. *Transportation Research Part C: Emerging Technologies*, **85**, 509–527.