A Bi-Level Model for Planning Signalized and Uninterrupted Flow Intersections in an Evacuation Network

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Abstract: The problem to be addressed in this paper is the lack of an advanced model in the literature to locate the optimal set of intersections in the evacuation network for implementing uninterrupted flow and signal control strategies, respectively, which can yield the maximum evacuation operational efficiency and the best use of available budgets. An optimization model, proposed in response to such needs, contributes to addressing the following critical questions that have long challenged transportation authorities during emergency planning, namely: given the topology of an evacuation network, evacuation demand distribution, and a limited budget, (1) how many intersections should be implemented with the signals and uninterrupted flow strategies; (2) what are their most appropriate locations; and (3) how should turning restriction plans be properly designed for those uninterrupted flow intersections? The proposed model features a bi-level framework. The upper level determines the best locations for uninterrupted flow and signalized intersections as well as the corresponding turning restriction plans by minimizing the total evacuation time, while the lower level handles routing assignments of evacuation traffic based on the stochastic user equilibrium (SUE) principle. The proposed model is solved by a genetic algorithm (GA) -based heuristic. Extensive analyses under various evacuation demand and budget levels have indicated that the location selection of uninterrupted flow and signalized intersections plays a key role in emergency traffic management. The proposed model substantially outperforms existing practices in prioritizing limited resources to the most appropriate control points by significantly reducing the total evacuation time (up to 39%).

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1 INTRODUCTION

1.1 Background

Exceptional circumstances occurring in a variety of forms have caused massive economic and social damages as well as loss of lives (Litman, 2006). Many of those exceptional circumstances such as fires and terrorist attacks are unpredictable, which may cause people to be exposed to risks without protection. Even for those predictable events such as hurricanes, during which people have been warned in advance, providing sufficient protection to the affected population and implementing an efficient evacuation in the transportation network remains challenging. To contend with those challenges and mitigate potential losses from disasters, many researchers have attempted to develop methodologies, guidelines, and tools to plan and operate the evacuation process more effectively and efficiently.

In a review of the literature, early efforts tackling evacuation modeling primarily focused on the network flow optimization problems that are designed to optimize various types of measurement of effectiveness (MOE), such as the evacuation time, the network clearance time, the maximum network flow, the total distance by evacuees, and the shortest paths, depending on specific emergency situations and management requirements (Sheffi et al., 1982; Southworth, 1991; Hobeika et al., 1994; Pidd et al., 1996; Urbina and Woloshon, 2003). To represent the evolution of an evacuation process over time, a pioneering work by Chalmet et al. (1982) developed a time-space network flow model with the objective of minimizing the total clearance time, known as the quickest flow problem. Hamacher and Tufekci (1987) further extended the quickest flow problem by taking into account different priority levels for different parts of the evacuation network.
network. Choi et al. (1988) formulated three dynamic network flow problems (i.e., maximum flow, minimum cost, and quickest flow problems) for evacuation and introduced additional constraints to define link capacity as a function of the incoming flow rate. Miller-Hooks and Patterson (2004) proposed the time-dependent quickest flow problem in time varying capacitated evacuation networks, where link travel times and capacities vary with time. Liu et al. (2008) have developed a two-level integrated optimization model to yield concurrent evacuation routing and traffic management plans.

Dynamic traffic assignment (DTA) models have also been applied in evacuation modeling. Sattayhatewa and Ran (2000) have developed an analytical DTA model to minimize the total evacuation time under a nuclear power plant failure. Liu et al. (2006) also applied the DTA approach in a Model Reference Adaptive Control framework for real-time evacuation traffic management. Yuan et al. (2006) formulated the evacuation routing problem with the simulation-DTA models. Other studies have also applied DTA models to generate optimal traffic routing plans concurrently with other control strategies, such as contra flow design (Tuydes and Ziliaskopoulos, 2006; Tuydes, 2005; Mahmassani and Sbayti, 2005), staged evacuation order (Tuydes and Ziliaskopoulos, 2005), and scheduling of the evacuation demand (Chiu, 2004; Sbayti and Mahmassani, 2006).

Traffic signal operation plays a key role in effective emergency traffic management. In research on traffic signal operation during evacuation, Chen et al. (2005) applied the microscopic simulation software CORSIM for two evacuation corridors of Washington, DC, and examined the influence of different signal-timing plans on the evacuation. Sisiopiku et al. (2004) used the signal optimization software SYNCHRO to establish the optimal signal-timing plans for a small area in Birmingham, Alabama, and evaluated the impacts of signal-timing optimization on the selected MOEs. McHale and Collura (2003) applied TRANSYT-7F to generate an optimal signal-timing plan when assessing the impact of emergency vehicles’ preemption strategies in a CORSIM simulator. Despite the recognition of the critical role of signal control in evacuation modeling, most literature either assumed oversimplified signal plans at intersections or applied standard signal optimization practices for normal traffic conditions, but with a high demand. To remedy this deficiency, Liu et al. (2008) have developed a mixed-integer model for the design of arterial signal control strategies during emergency evacuation. Their model applied the critical intersection concept to maximize the efficiency of the primary evacuation arterial, but not to incur excessive waiting time and queues on its side streets. However, their model is only applicable in a single corridor with the assumption that there are only two phases at the critical intersections. Liu and Chang (2011) developed an arterial signal optimization model for oversaturated intersections experiencing spillback and blockages but have not applied it in evacuation.

Although the proper operation of signal timings may improve the effectiveness of the overall evacuation process, traffic delays at many signalized intersections may still be unacceptable. In addition, the control effectiveness may be challenged by aggressive driving maneuvers under frustrating emergency situations (Lajunen et al., 1999; Hamdar et al., 2008). Realizing the disadvantage of operating too many signals at intersections during the evacuation, researchers in recent years have suggested converting signalized intersections into uninterrupted flow ones by properly setting turning restrictions. Cova and Johnson (2003) proposed an innovative lane-based network routing strategy, which provides an effective and feasible approach to reduce traffic delays at intersections. In their research, an intersection with interrupted flow conditions is converted to an uninterrupted flow facility by disabling the existing traffic control device while eliminating traffic conflicts by applying turning restrictions at entries. Removing the stop-and-go traffic control setting has significantly expanded the intersection capacity. Inspired by their pioneering work, Kalafatas and Peeta (2008) and Xie and Turnquist (2010) further expand the capacity of the evacuation network by combining the crossing-conflict elimination and the contra flow design, which have been practically shown to be an efficient strategy to better use the network capacity under evacuation (Mahmassani and Sbayti, 2005; Urbanik, 2000; Shekhar and Kim, 2006; Xie et al., 2010).

1.2 Research motivation and objectives

Despite their effectiveness in reducing intersection delays, those conflict-elimination strategies may result in a substantial increase of detours by the evacuees due to the restriction of certain turning movements at intersections, especially in a large-scale evacuation network. In addition, evacuees may feel confused and frustrated if they are frequently blocked from making preferred turns at intersections or rerouted from their pre-planned routes during the emergency situation. Most importantly, conflict-elimination at many intersections in a large network will be quite time-consuming and will require a large amount of personnel and resources (e.g., barricades or cones), which may not be implementable in real-world evacuation. Therefore, the number of conflict-elimination intersections should be limited considering the evacuee acceptability and the limited resources of evacuation management agencies.
The problem to be addressed in this paper is the lack of a model in the literature to locate the optimal set of intersections in the evacuation network for implementing traffic crossing-elimination and signal control strategies, respectively (see Figure 1), which can yield the maximum evacuation operational efficiency and the best use of available control and management resources. A network optimization model, proposed in this study, contributes to solving the above problem by answering the following critical questions that have long challenged transportation authorities during emergency planning, namely: Given the topology of the evacuation network, evacuation demand distribution, and a limited budget, (1) how many intersections should be implemented with signals and what are their most appropriate locations; (2) how many uninterrupted flow intersections should be implemented and what are their most appropriate locations; and (3) how should turning restriction plans be properly designed for those uninterrupted flow intersections? Such information is critical for emergency managers to allocate the limited resources to the most appropriate control points.

The rest of this paper is organized as follows. The next section details notations used in the model formulation and the evacuation network representation. The network optimization model for location planning of signalized and uninterrupted flow intersections will be described in Section 3. Specific algorithmic designs of the solution method are then elaborated in Section 4. Section 5 illustrates the evaluation results with respect to the model performance and its applicability in a test evacuation network. Section 6 summarizes research findings and potential applications of the proposed optimization models.

2 NETWORK REPRESENTATION

Given a connected network $G = (N, A)$, where $N$ and $A$ represent nodes and links, respectively, this study...
has employed three different types of sub-networks (i.e., signalized intersection sub-network, uninterrupted flow intersection sub-network, and road section sub-network) to depict the operational characteristics of signalized intersections, uninterrupted flow intersections, and road links in the urban evacuation network. A signalized intersection sub-network consists of arcs that are allowed to conflict with each other via the traffic operational settings at the intersection, including signal timing, flow capacity, and saturation degree, while the conflicts among arcs comprising the uninterrupted flow intersection sub-network are prohibited, and arcs function as impedance-free connectors. The arcs in the road section sub-network are directional connectors constrained by their corresponding capacities and the composition of traffic flows.

To better illustrate the network representation concepts, Figure 2 illustrates how different sub-networks are connected and interact. Figure 2A describes an example section composed of an uninterrupted flow intersection, a bi-directional road section, and a signalized intersection, where the solid lines represent road section links and dashed lines denote arcs in the uninterrupted flow and signalized sub-networks. It can be observed that intersections at different locations can only be connected with each other via the road section sub-network. The links in dot and dash at signalized and uninterrupted flow intersection sub-networks represent the travel cost and the connectivity between upstream and downstream links inside corresponding intersections, respectively. Part B in Figure 2 lists several examples of possible allowable turning movements at uninterrupted flow intersections with 3 and 4 legs.

3 OPTIMIZATION MODEL FORMULATION

The proposed network optimization model features a bi-level scheme with the upper level determining the best sets of signalized and uninterrupted flow intersections as well as the corresponding turning restriction plans, and the lower-level problem handling routing assignment of evacuation traffic demand. Figure 3 shows the structure of the proposed bi-level model. The upper level describes the behavior of the policy makers or planners for minimizing the total evacuation cost. The model determines the optimal locations of signalized and uninterrupted flow intersection. The lower-level problem captures the behavior of evacuees in choosing evacuation routes. To facilitate model presentation, notations used hereafter are summarized in Table 1.

3.1 The upper-level problem

The upper-level problem aims to achieve the minimal total evacuation time for the given evacuation network. In this study, we assume a single super destination (evacuation shelter) in the evacuation network, and evacuees would perceive safety when they reach the exit nodes connected with the super destination via impedance free links. The total evacuation time can be represented with the summation of flows on links.
Fig. 3. Structure of the proposed bi-level model.

Table 1
Notation of key model parameters and variables

<table>
<thead>
<tr>
<th>Sets</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N$</td>
<td>Set of nodes, $N = N_r \cup N_m \cup N_s$</td>
</tr>
<tr>
<td>$A$, $a \in A$</td>
<td>Set of links</td>
</tr>
<tr>
<td>$A_m \subseteq A$</td>
<td>Set of inbound links to intersection $m$</td>
</tr>
<tr>
<td>$N_r$, $r \in N_r$</td>
<td>Set of evacuation origin nodes</td>
</tr>
<tr>
<td>$N_s$, $s \in N_s$</td>
<td>Evacuation destination nodes</td>
</tr>
<tr>
<td>$N_m$, $m \in N_m$</td>
<td>Set of intersections</td>
</tr>
<tr>
<td>$Z_{rs}$, $z \in Z_{rs}$</td>
<td>Set of paths between $r$ and $s$</td>
</tr>
<tr>
<td>$\Gamma^{-1}_a$, $\Gamma^{-1}_a \subseteq A$</td>
<td>Set of downstream links of road section link $a$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameters and variables</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi_a$</td>
<td>A connectivity indicator (1 if the downstream of $a$ is an uninterrupted flow intersection; 0 otherwise)</td>
</tr>
<tr>
<td>$q_{rs}$, $r \in N_r$, $s \in N_s$</td>
<td>The traffic demand between $r$ and $s$</td>
</tr>
<tr>
<td>$f_a$, $c_a$, $a \in A$</td>
<td>Flow and capacity at road section link $a$, respectively</td>
</tr>
<tr>
<td>$f_z$</td>
<td>The route flow on path $z$ from $r$ to $s$</td>
</tr>
<tr>
<td>$f_{rs}$</td>
<td>The flow on link $a$ associated with path $z$ from $r$ to $s$</td>
</tr>
<tr>
<td>$f_{ab}$</td>
<td>The flow from link $a$ to link $b$</td>
</tr>
<tr>
<td>$f_{a,T}$, $f_{a,R}$, $f_{a,L}$, $f_{a,opp}$</td>
<td>The through, right-turn, left-turn, and opposing flows for link $a$</td>
</tr>
<tr>
<td>$t_a$</td>
<td>The travel time on road section link $a$</td>
</tr>
<tr>
<td>$t_0^a$</td>
<td>Free flow travel time on road section link $a$</td>
</tr>
<tr>
<td>$d_{ab}$</td>
<td>Delay for flow from link $a$ to link $b$</td>
</tr>
<tr>
<td>$\chi_{ab}$</td>
<td>The set of conflicting flows for flow from link $a$ to link $b$</td>
</tr>
<tr>
<td>$M$</td>
<td>A large enough positive integer</td>
</tr>
<tr>
<td>$C_m$, $m \in N_m$</td>
<td>The cycle length at signalized intersection $m$</td>
</tr>
<tr>
<td>$g^p_{ab,m}$</td>
<td>The effective green time for flow from link $a$ to link $b$ in phase $p$ at signalized intersection $m$</td>
</tr>
<tr>
<td>$B$</td>
<td>The available budget for evacuation management</td>
</tr>
<tr>
<td>$B_m$, $m \in N_m$</td>
<td>The operational cost at intersection $m$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Decision variables</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x_m$, $m \in N_m$</td>
<td>1 if intersection $m$ is signalized; 0 otherwise</td>
</tr>
<tr>
<td>$y_{ab}$, $a$, $b \in A$</td>
<td>1 if flow from link $a$ to link $b$ is allowed; 0 otherwise</td>
</tr>
</tbody>
</table>
multiplied by their corresponding travel times, given by
\[
\min \sum_{a \in A} \sum_{r \in R} \sum_{s \in S} \sum_{z \in Z} t_{a} f_{a,z}^{rs}
\]
where \( f_{a,z}^{rs} \) is the flow on link \( a \) associated with path \( z \) from origin \( r \) to destination \( s \); \( t_{a} \) is the travel time on link \( a \); and \( N_{R}, N_{S}, \) and \( Z \) represent the set of origin nodes, destination nodes, and routes, respectively.

The travel time on link \( a \) depends on its downstream intersection type: signalized or uninterrupted flow. Delays due to the opposing flows at uninterrupted flow intersections or signals can significantly impact the route choice in an urban road network. An underestimation of such delays may result in a traffic distribution far from realistic. To provide a reliable travel time calculation and simplify the model formulation, this research first incorporates a generalized Bureau of Public Roads (BPR) function developed by Horowitz (1997) to account for the potential turning delays for a road section link upstream to an uninterrupted flow intersection. On the other hand, if the link’s downstream intersection is signalized, we consider incorporating turning delays by adopting a flow-weighted method. The travel time on link \( a \) is then given by
\[
t_{a} = T_{a}^{r} + T_{a}^{s}
\]

where \( T_{a}^{r} \) accounts for travel time on link \( a \) if it is approaching an uninterrupted flow intersection; \( T_{a}^{s} \) represents the travel time on link \( a \) if it goes to a signalized intersection. \( \phi_{a} \) is a binary indicator (it equals 1 if \( a \) is upstream to an uninterrupted flow intersection and 0 otherwise); \( T_{a}^{0} \) is the free flow travel time at road section link \( a \); \( f_{a} \) is the flow on link \( a \); \( f_{a,T}, f_{a,R}, f_{a,L}, \) and \( f_{a,opp} \) are the through, right-turn, left-turn, and opposing flows for link \( a \), respectively; \( \phi_{a,T}, \phi_{a,R}, \phi_{a,L}, \) and \( \phi_{a,opp} \) are conversion coefficients for right-turn, left-turn, and opposing flows, respectively; \( c_{a} \) is the capacity of link \( a \); \( \alpha \) and \( \beta \) are function parameters; \( d_{a} \) is the delay at link \( a \) due to the signal at its downstream intersection, given by
\[
d_{a} = \sum_{b \in B_{a}} d_{ab} f_{ab}
\]
where \( f_{ab}, d_{ab} \) represent the flow and delay from link \( a \) to link \( b \), respectively; \( d_{ab} \) can be estimated according to the delay formula in Highway Capacity Manual (Transportation Research Board, 2000), given by
\[
d_{ab} = 0.5C_{m} \left( 1 - \frac{g_{ab,m}^{p}}{C_{m}} \right)^{2} / \left[ 1 - \min(1, X_{m}) g_{ab,m}^{p} \right]
\]

where \( C_{m} \) is the cycle length of signalized intersection \( m; g_{ab,m}^{p} \) is the effective green time for flow from link \( a \) to link \( b \) in phase \( p \) at signalized intersection \( m; X_{m} \) is the saturation degree of intersection \( m \).

The upper-level model is subject to the following constraints:

3.1.1 Capacity constraints. A set of capacity constraints are defined to confine the allowable traffic flows on road section links according to their capacities, given by
\[
\sum_{r \in R} \sum_{s \in S} \sum_{z \in Z} f_{a,z}^{rs} \leq c_{a} \quad a \in A
\]

3.1.2 Conflict elimination constraints. In the proposed model, we implement a traffic conflict elimination strategy only at uninterrupted flow intersections where certain turnings are restricted to avoid conflicts, given by
\[
y_{ab} + \sum_{cd \in X_{ab}} y_{cd} \leq 1 + Mx_{m} \quad \forall a, b \in A, b \in \Gamma_{c}^{-1},
\]

where \( y_{ab} \), \( y_{cd} \), and \( x_{m} \) are binary decision variables (1 if flow from link \( a \) to \( b \) or from link \( c \) to \( d \) is allowed; 0 otherwise); \( x_{m} \) is a binary decision variable to indicate if intersection \( m \) is signalized or not (1-signalized intersection, 0-uninterrupted flow); \( y_{ab} \) is the set of conflicting flows from link \( a \) to \( b \); if intersection \( m \) is a signalized one \((x_{m} = 1)\), then the right-hand side of Equation (6) becomes a large number indicating that conflicting movements at the intersection are allowed; if intersection \( m \) is an uninterrupted flow one \((x_{m} = 0)\), the right-hand side of Equation (6) becomes 1 restricting that only one directional flow is allowed for any conflicting movement set \((cd \in X_{ab})\). Equation (6) guarantees that a turning restriction is only implemented at an intersection determined to set as uninterrupted flows.

3.1.3 Budget constraints. Due to the limited management resources, the total cost for setting uninterrupted flow intersections cannot be greater than the given budget, given by
\[
B \geq \sum_{m \in N_{m}} B_{m}(1 - x_{m}) \quad \forall m \in N_{m}
\]
where $B$ is the budget for evacuation, and $B_m$ is the operational cost at intersection $m$.

3.1.4 Other operational constraints. There are interrelations between the network construction and some variables/indicators given above. Ignorance of such relations may have the model yield unexpected or unrealistic results. Herein, we present constraints mainly concerning the implication among the connectivity of the network and potential operations, given by

$$
\phi_m = 1 - x_m \quad \forall m \in N_m, a \in A_m
$$

Equation (8) ensures that if $m$ is an uninterrupted flow intersection, then all its inbound links must have the $\phi_m = 1$, otherwise, $\phi_m = 0$.

3.2 The lower-level SUE problem

Implementation of signalized and uninterrupted flow intersections will affect the traffic flow pattern in the evacuation network. Improper settings may exacerbate the network congestion and increase impedance to travelers by extending their delays and travel distances. Therefore, the lower level serves to specify the routing assignment of evacuation traffic given the impacts of signalized intersections and turning restriction settings generated from the upper level. Deterministic user equilibrium (DUE) conditions, traditionally adopted to represent the route choice behavior in network design problems, assume that all travelers make route choices based on perfect information about the network condition. However, evacuation is a non-recurrent event and evacuees will have difficulties in observing the costs of their routes and may suffer observational error in their decision-making processes due to imperfect information. Therefore, the stochastic user equilibrium (SUE) principle is better than the DUE to describe the route choice behavior of evacuees under the evacuation circumstances. Herein, we adopt the nonlinear formulations of SUE by Ying et al. (2007) to address the lower-level problem, given by

$$
F_{ab}(f, y) = f_{ab} - \sum_{r \in R_s, s \in N_s, z \in Z^s} q^r_z \frac{\partial W_z}{\partial c_z} \delta_{ab, z} = 0
$$

$$
\forall a, b \in A, b \in \Gamma_a^{-1}
$$

where $f_{ab}$ is the flow on link $a$ going to link $b$; $q^r_z$ is the traffic demand between origin $r$ to destination $s$; $\delta_{ab, z}$ is a binary indicator (it equals 1 if both links $a$ and $b$ are on route $z$ between OD pair $rs$ and 0 otherwise); $W_{rs}$ is the satisfaction function, defined as the expected minimum perceived travel cost from $r$ to $s$, given by

$$
W_{rs} = E\left[ \min_{z \in Z^s} \{c_z^r\} \right]
$$

where $c_z^r$ is the perceived travel cost on route $z$ between OD pair, given by

$$
c_z^{rs} = \sum_{a \in \Gamma_a} t_a + \sum_{a \in \Gamma_a} \sum_{b \in \Gamma_b} M(1 - y_{ab})
$$

$$
\forall r \in N_R, s \in N_S, b \in Z
$$

where $M$ is a large positive constant and represents an additional punishment for travelers who take the restricted turning.

The above SUE formulation can be applied in a variety of route choice models to describe different conditions imposed on the satisfaction function. In this study, the satisfaction function takes the general logit form, given by

$$
W_{rs} = \frac{-1}{\theta} \ln \sum_{z} \exp\left(-\theta c_z^{rs}\right)
$$

$$
\forall r \in N_R, s \in N_S, z \in Z^s
$$

It should be noted that the entire modeling process, from model formulations to solution, does not prohibit the inclusion of other forms of route choice models (e.g., Cascetta et al., 1995; Russo and Vitetta, 2003; Ng and Waller, 2012). The replacement of route choice formulations will not change the model structure as well as the research methodology.

A path-based algorithm by Long et al. (2010) has been adopted in this study to solve the lower-level SUE problem. Considering the path-based algorithm for SUE is restricted in size, path choice set generation methods have received attention in the past decade. Several algorithms (e.g., k-shortest path method) were applied to generate the path set for traffic assignment. Bekhor et al. (2006) have discussed choice set generation and route choice models for large-scale urban networks. In this study, a combination of link elimination method and k-shortest path method was used to generate paths.

In the algorithm, the route choice probability is given by the partial derivative of the satisfaction function with respect to the route travel cost:

$$
P_{rs}^z = \frac{\partial W_{rs}^z}{\partial c_z^{rs}} \quad \forall r \in N_R, s \in N_S, z \in Z^s
$$

One can then obtain the logit SUE by substituting Equation (12) into Equation (13):

$$
P_{rs}^z = \frac{\exp\left(-\theta c_z^{rs}\right)}{\sum_l \exp\left(-\theta c_l^{rs}\right)}
$$

$$
\forall r \in N_R, s \in N_S, z, l \in Z^s
$$
The route flow $f_{z}^{rs}$ and link flow $f_{ab}$ can then be determined by

$$f_{z}^{rs} = P_{z}^{rs}q_{z}^{rs} \forall r \in N_{R}, s \in N_{S}, z \in Z_{s}^{s}$$ (15)

$$f_{ab} = \sum_{rs} \sum_{z} P_{z}^{rs}q_{z}^{rs}\delta_{ab,z}^{rs} \forall r \in N_{R}, s \in N_{S}, z \in Z_{s}^{s}$$ (16)

$$f_{a,z}^{rs} = \sum_{b \in \Gamma_{a}} f_{ab} \forall a, b \in z, a, b \in A$$ (17)

$$f_{a} = \sum_{b \in \Gamma_{a}} f_{ab} \forall a, b \in A$$ (18)

A simple descent direction $\sum_{rs} \sum_{z} P_{z}^{rs}q_{z}^{rs}\delta_{ab,z}^{rs} - f_{ab}$ can then be applied to solve Equation (9) for a given set of location and turning restriction plans. Given the convexity of the lower-level SUE problem, it can be solved by the method of successive weighted averages (MSWA) proposed by Long et al. (2010).

4 A HEURISTIC SOLUTION APPROACH

The difficulty in solving the proposed bi-level programming problem lies in how to evaluate the equilibrium flow pattern for a given vector of binary location pattern and turning restriction decision variables, which is an implicit vector function defined by the lower-level SUE problem. Since 1993, genetic algorithm (GA) has been used as an effective optimization tool for highly nonlinear optimization problems in various areas such as engineering design optimization (Adeli and Cheng, 1993, 1994a, b; Adeli and Kumar, 1995a, b; Kim and Adeli, 2001; Chabuk et al., 2012), construction resource utilization (Cheng and Yan, 2009), highway alignment optimization (Kang et al, 2009), wastewater system planning (Zeferino et al., 2009; Jafarkhani and Masri, 2011), structural control (Jiang and Adeli, 2008), environmental engineering (Martinez-Ballesteros et al., 2010), condition monitoring (Baraldi et al., 2011), and image processing (Hung and Adeli, 1994; Carro-Calvo et al., 2010). Additionally, GA-based heuristics have been successfully demonstrated to yield viable and metaoptimal solutions to a series of bi-level optimization problems in a reasonable time period (Sarma and Adeli, 2001; Mathakari et al., 2007; Teklu et al., 2007; Unnikrishnan et al., 2009; Al-Bazi and Dawood, 2010; Lee and Wei, 2010; Marano et al., 2011; Putha et al., 2012). Considering the computational complexity underlying the proposed formulation, in this section we develop a GA-based heuristic that can yield viable and approximate-optimal solutions in a reasonable time period.

To avoid the extremely long GA chromosome size due to a large-scale network application, this section has designed an external module and an internal module to decompose the entire problem into simpler parts, both of which are solved using the GA. The external module accounts for the location selection for signalized and uninterrupted flow intersections, while the internal module takes care of the optimization of turning restriction plans and provides feedback information for the external module with the evaluation of the objective function containing a traffic assignment process. The overall procedure of the solution algorithm and interactions between the external and internal modules are shown in Figure 4. Specifics on the proposed GA are given further.

4.1 Coding of GA chromosomes

An essential step in the GA search for the proposed optimization problem lies in the efficient coding of chromosomes that can capture the characteristics of the solution structure. In the external module, we generate a binary string $(x_{1}, x_{2}, x_{3}, \ldots, x_{m})$, $m \in N_{m}$, with $x_{m}$ indicating the type of intersection $m$; while for the solution in the internal module, we use a series of binary strings $(l_{1}, l_{2}, l_{3}, \ldots, l_{m})$, where $l_{m}, m \in N_{m}$, is a binary string indicating the state of the turning restrictions applied at intersection $m$. If $x_{m} = 1$ (i.e., intersection $m$ is a signalized one), then the string $l_{m}$ is set to consist of all ones, indicating that no turning restrictions are implemented at intersection $m$.

4.2 Infeasibility handling

According to the coding schemes in 4.1, the candidate solutions in the external module may violate constraint (7). We therefore calculate the infeasibility value (indicating the extent to which a certain solution violates the given constraint; a candidate with a larger infeasibility value has a lower probability to be chosen in the next generation in GA) of each candidate solution $X_{j}$ in the external module with

$$f(X_{j}) = 1/\left\{\alpha_{0}\left[\sum_{m} (1 - x_{m})B_{m} - B\right] + F(X_{j})\right\}$$ (19)

where $\alpha_{0}$ is the parameter for penalization for violation of constraint (7); $F(X_{j})$ is the total evacuation time for candidate $X_{j}$, Equation (19) is used for selection of the new population and elimination of the solutions with the greatest infeasibility values to keep the size of the population. Then, the best solution at each GA generation in the external module can be defined as the one yielding the minimal total evacuation time without...
violating budget constraint (7), given by

\[
\min \quad \{ F(X) | B \geq \sum_m B_m(1 - x_m) \} \quad \forall m \in N_m \quad (20)
\]

For the internal module, the set of cross elimination constraints (6) could be violated if \( x_m \) is determined to be 0 in the external module. To deal with this problem, we relax the cross elimination constraints (6) and compensate for them by adding a penalty term in the original objective function (i.e., Equation (1)), given by

\[
f(L_j) = \sum_{a \in A} \sum_{r \in N_R, s \in N_s} \sum_{z \in Z^r} t_a f_{a,z}^r + \sum_m M(1 - x_m) \cdot \max \left[ 0, y_{ab} + \sum_{c \in T_a} y_{cd} - 1 \right] \quad \forall r \in N_R, s \in N_s, z \in Z^s, a, b \in A, b \in \Gamma^{-1}_a, d \in \Gamma^{-1}_c, m \in N_m \quad (21)
\]

where \( L_j \) is a candidate solution in the internal module.
4.3 Convergence criteria

The convergence criteria of the developed GA are designed as follows:

1. \[
\frac{\left| \min_{t} h(T) - \min_{t+1} h(T) \right|}{\min_{t} h(T)} \leq 0.1 \quad (g \text{ is the number of generations}),
\]
that is, the difference between the minimum objective value in the population list between two adjacent generations is less than 0.1% for a certain number of continuous iterations;

2. The GA will evolve no more than a pre-set maximal number of generations.

where \( T \) represents a solution provided by the internal or external module; \( h(T) \) denotes the objective function value corresponding to a certain solution \( T \). For each generation in the external and the internal module, we check the criteria (1) and (2). If any of them is satisfied, then we stop and provide the optimal solution to the corresponding module.

5 CASE STUDIES

To illustrate the effectiveness and applicability of the proposed model and algorithm, we have performed case studies on a compact downtown network in Huaibei City, in the northern Anhui province, China.

5.1 The test network

As shown in Figure 5, the test network consists of 41 bi-directional links and 26 nodes (nodes 12 and 13 are designated as super destination nodes). All the other 24 nodes are represented as intersections and evacuation origins. The destination nodes are safe areas or shelters, where no signals or turning restriction will be explicitly modeled. Nodes 1, 6, 22, 26, and 17 represent two-leg intersections where traffic conflicts are naturally avoided and therefore could be excluded from the intersection list for implementation of signals or uninterrupted flow strategies. In the test road network, lines in bold represent arterials with higher capacities, while the other lines represent secondary roads.

5.2 Key model parameters

Key model parameters, including the BPR function parameters, turning restriction parameters, and solution algorithm parameters, are set as follows:

1. In the BPR function, \( \alpha, \beta \) are set to be 0.15 and \( 4. \phi_0, R, \phi_a, L, \) and \( \phi_{a,opp} \) are set at 1.0, 1.0, and 0.4 according to Horowitz (1997), respectively;

2. The large enough positive integer \( M \) and penalization \( \alpha_0 \) are set to be 10,000 and 1,000, respectively;

3. The mutation probability for both the external module and the internal module is 0.03;

4. The population size for the external module and the internal module is set to be 200 and 300, respectively;

5. The crossover probability for both the external and the internal module is set to be 0.2;

6. The maximal number of generations for the external module and the internal module is set to be 100 and 200, respectively;

7. If the difference between 2 adjacent iterations is lower than 0.1% for 5 continuous iterations, the algorithms for both external and internal module are terminated.

It should be noted that the parameters used in the GA are tuned from extensive numerical experimentation to fit best with the case study network. The parameters may need to go through the recalibration and updating process for use at other networks.

5.3 Model evaluation

5.3.1 Scenario design. This study has designed various scenarios to evaluate the performance of the proposed model, including four levels of available budgets (A-$10,000, B-$20,000, C-$30,000, and D-$40,000) and three levels of total evacuation traffic demand (Level I-10,000 vph, Level II-20,000 vph, and Level III-30,000 vph). Given an assumed average cost of $5,000 to implement one uninterrupted flow intersection, the maximum numbers of uninterrupted flow intersections that can be implemented under budget plans A, B, C, and D are 2, 4, 6, and 8, respectively.

Hence, the proposed model will be evaluated under a total of 12 scenarios (3 by 4), and their performance will be compared with an alternative traffic management strategy (denoted as “Alternative-I”) that is commonly adopted by authorities in practice. That strategy usually implements uninterrupted flow at intersections between major evacuation arterials and secondary roads to prevent the minor street movements from interrupting the major evacuation directions (e.g., flows on the secondary roads are not allowed to go through or make a left turn).

To make a fair comparison between the proposed model and the Alternative-I, we further apply the proposed turning restriction optimization approach to fine-tune the plans at those intersections selected by the Alternative-I. In this way, the importance for selection of the uninterrupted flow intersection locations can be identified from the comparison.
5.3.2 Analyses and results. The proposed model is implemented in MATLAB on a PC with an Intel Pentium Dual-Core 1.80 GHz CPU and 6 GB RAM. Computational performance of the proposed model under various demand and budget levels is summarized in Table 2. Figure 6 illustrates the convergence process of the GA for budget plan A and demand level I.

Table 3 summarizes the comparison results between the proposed model and the Alternative-I, including the locations of uninterrupted flow intersections and the total evacuation time. The total evacuation time under various demand and budget levels is illustrated in Figure 7. An example of the optimal location and turning restriction plans from the proposed model and the Alternative-I under budget plan B and demand level III are also shown in Figures 8 and 9, respectively.

As shown in Table 3 and Figure 7, there are significant discrepancies in the locations of uninterrupted flow intersections between the proposed model and the Alternative-I. Such discrepancies will result in their differences in the total evacuation time. Such findings show that the location selection of uninterrupted flow and signalized intersections plays a key role during evacuation planning with a limited budget. It can also be observed that the proposed model outperforms the Alternative-I in terms of total evacuation time under all scenarios, which demonstrates the effectiveness of the proposed model in prioritizing resources at the most appropriate control points during the evacuation. In
addition, the proposed model yields higher improvement over the Alternative-I at high demand scenarios for all budget plans, which implies that the proper location and turning restriction plans are even more critical to the evacuation system performance when the demand level is high.

Under a given budget plan, the optimal location plans generated from the proposed model seem not sensitive to the demand levels. For example, under the budget plan C the locations of uninterrupted flow intersections do not change with respect to the increase of demand levels. Another interesting finding is that some nodes (e.g., 8, 9, 16, and 20) should always be converted to uninterrupted facilities no matter what the budget plans are. Such findings indicate that the location plans from the proposed model are relatively stable for a planning-level application, especially for planning the predictable emergency events.

5.4 Sensitivity analysis

To investigate the impact of the number of interrupted flow intersections on the evacuation performance, this study has further performed sensitivity analyses. Figure 10 summarizes the evacuation network performance for each demand level with varying budget plans.

As shown in Figure 10, the total evacuation time monotonically decreases with an increase in the
number of uninterrupted flow intersections for any given demand level. Such a finding indicates that the implementation of more uninterrupted flow intersections is effective to expand the evacuation network capacity and improve the evacuation operational performance.

6 CONCLUSION AND FUTURE RESEARCH

Uninterrupted flow (or crossing-elimination) at intersections has been demonstrated to be one of the most effective strategies for evacuation management and operations due to its advantage in expanding evacuation network capacity. However, implementation of such strategies may require a large amount of personnel and resources, which often exceeds the limited budget of the emergency management agencies. The problem to be addressed in this paper is the lack of an advanced model in the literature to locate the optimal set of intersections in the evacuation network for implementing uninterrupted flow and signal control strategies, respectively, which can yield the maximum evacuation
operational efficiency and the best use of the available budget.

In this study, a bi-level network optimization model for optimal location planning of signalized and uninterrupted flow intersections in an urban network for emergency evacuation has been developed to address the following critical questions that have long challenged transportation authorities during emergency planning, namely: Given the topology of the evacuation network, the evacuation demand distribution, and a limited budget, (1) how many intersections should be implemented with the signals and interrupted flow strategies, respectively; (2) what are their most appropriate locations; and (3) how should turning restriction plans be properly designed for those uninterrupted flow intersections? Such information is critical for emergency managers to allocate the limited resources to the most appropriate control points.
To deal with the combinatorial complexity in combined location selection and turning restriction designs, employing a GA algorithm, this study has designed a heuristic solution framework, including an external module and an internal module, to decompose the entire problem into simpler parts. The external module accounts for the location selection for signalized and uninterrupted flow intersections, while the internal module takes care of the optimization of turning restriction plans with the optimization and the evaluation of the objective function with a traffic assignment process.

Numerical tests of the proposed model and algorithms have shown the following conclusions. (1) The implementation of uninterrupted flow intersections is effective to expand the evacuation network capacity and improve the operational efficiency of the evacuation. (2) The location selection of uninterrupted flow and signalized intersections plays a key role during evacuation planning with a limited budget. The proposed model is effective in prioritizing resources at the most appropriate control points during the evacuation compared with the existing practices. (3) The location plans from the proposed model are relatively insensitive to the variation of the evacuation demand levels. Such a property of the proposed model can better assist policy makers and planners in managing emergency evacuation scenarios with uncertain traffic demands.

Future work along the line will be extending the model into a dynamic setting and introducing stochastic elements into the network flow patterns to accommodate the dynamic process of evacuation. Application and evaluation of the proposed model with a real-world evacuation network and variation in cost for applying uninterrupted control strategy at different locations will also be performed in the next step.

REFERENCES


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