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Modeling Gate Control Strategy for Traffic Management in Emergency Evacuation

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Abstract

The paper demonstrates the effectiveness of using a gate control strategy for traffic management in an emergency evacuation when people within a localized Protective Action Zone (PAZ) must be evacuated with a short notice. Selected nodes on the PAZ boundary with access and volume capacities could be treated as gates for evacuation traffic to be guided through with a higher priority over traffic using the non-gate nodes. In the paper, an optimization process is sought to minimize the total travel cost of the evacuation trips with a gate control strategy while traffic constraints and networkequilibriums are considered. The effectiveness of the model is tested by the computation results drawn from an assumed evacuation network. The computation results show that the gate control strategy could improve the performance of an evacuation by reducing the numbers of conflicts in trip routes and traffic movements.

Keywords: *emergency evacuation, protective action zone, gate traffic control, traffic assignment, optimization*

1. Introduction

A no-notice or short notice incident is one that occurs unexpectedly or with minimal warning which does not allow emergency responders sufficient time to prepare for it [1, 2]. Evacuations that result from such incidents generally involve a large number of evacuees, possibly from more than one community or even jurisdiction, who need to move away from the at-risk area as soon as possible. This will require intensive efforts on the roles of emergency managers, first responders, law enforcement officers, and transportation professionals to coordinate, guide, transport, and shelter the affected population.

In contrast to a natural disaster such as a hurricane or flood that may result in a large scale regional emergency evacuation, a man-made incident such as a hazardous material spill due to a derailed train usually affects a localized area and only the population within the affected area needs to be evacuated. After a localized incident happens, normally the affected area of the incident with a boundary would be estimated and depicted with a confidence of safety, which is referred to as the Protective Action Zone (PAZ) or Evacuation Planning Zone (EPZ). In an evacuation study using traffic assignment simulations, a traffic assignment program tends to model the trip of an evacuee who seeks to leave the origin point within the PAZ for a safe destination point outside the PAZ as a "shortest path", which corresponds to a driver's behavior under a normal traffic operation condition [3]. However, a reconsideration of the evacuation problem would reveal that the most effective strategy of evacuating a large number of people (in the format of vehicles hereafter) under a PAZ emergency evacuation situation would be a 2-stage process: 1) first move all the evacuees out of the PAZ in the least amount of total time, and 2) then

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starting from the boundary of the PAZ the evacuees continue on their trips to their destinations via their respective shortest paths. Intuitively, if every evacuee individually seeks the shortest path to leave the PAZ area for a safe destination, the possibility of conflicts of traffic movements among these "shortest" trip paths would be high considering the tremendous number of evacuation trips suddenly generated under a no-notice evacuation. These increased conflicts of traffic movements and trip paths can cause widespread cascading traffic congestion within the PAZ and hinder the evacuation effort. Instead of seeking shortest paths for the trip segments within the PAZ, evacuation traffic could be encouraged or guided to go through selected "gate" nodes on or near the PAZ boundary with large access and throughput capacities to reduce the otherwise conflicts of traffic movements and delays. The objective of this study is to develop a theoretical model for the gate traffic control strategy and to demonstrate the effectiveness of the gating strategy on reducing conflicts in evacuation trip paths and traffic movements in the PAZ of a no-notice localized evacuation.

The remainder of this paper proceeds as follows: After the literature reviews on emergency management for PAZ evacuation and shortest path based methods for evacuation studies in background, the study methodology and the gate control strategy are described in the next two sections. An optimization model for evacuation trip assignment with gate control for a PAZ network is formulated. The solutions of numerical experiments for different gate control scenarios are conducted and analyzed, followed by a summary of the findings of the study.

2. Background

An emergency evacuation aims to moving a large disaster affected population through a transportation network toward safer areas quickly and efficiently. In emergency and critical infrastructure management, the adoptions of optimal evacuation routes and effective traffic management strategies could well improve the evacuation performance by relieving heavy traffic congestion generated by the sudden surge of the evacuation traffic demand [4]. For a no-notice or short-notice emergency evacuation, the evacuee's perception of emergency would be very time sensitive. Hence, how to develop an exit strategy for effectively moving the affected population out of the PAZ under a localized emergency scenario is the major research task of this study.

2.1. Protective Action Zone of Emergency Incident

Localized emergency evacuations due to chemical spill incidents were reported from time to time. The accidents involving release of more than 60 tons of chlorine were located at Festus, Missouri, Graniteville, South Carolina, and Macdona, Texas [5]. To characterize the various chemical spills in history, Zhu et al. [6] developed the Chemical Spill Incident knowledge Base (CHESIBASE) to provide information of chemical spills that occurred in the past in the US and help guide the practice of chemical spill emergency management. Atmospheric transport and dispersion (AT&D) models using Computational Fluid Dynamics (CFD) modeling along with meteorological and atmospheric modeling and weather information to forecast path of the ongoing release of heavy toxic gas such as pressurized liquefied chlorine have been made available to emergency managers [7]. Six of such models, widely-used for dense gas dispersion, are ALOHA, HGSYSTEM, SLAB, SCIPUFF, PHAST, and TRACE. After a spill incident, these dispersion models can be run in minutes to depict the affected area with a boundary outlined. The information on the PAZ area can help the emergency management agency assess the scope of an evacuation action [5].

Clearly, from an emergency manager's perspective, the priority would be to move the affected population out of the PAZ as soon as possible, and once an evacuee reaches the boundary of the PAZ the evacuation of the particular evacuee is considered accomplished

even if the evacuee may have a reminder trip segment before reaching the trip destination at home or a shelter. Unfortunately, the difference of priority in treating the trip segment inside the PAZ and the trip segment outside the PAZ was not adequately considered in many evacuation studies.

2.2. Traffic Assignment Methods for Evacuation Studies

The modeling and design of a more effective emergency evacuation plan has been rigorously investigated using simulation programs [3, 8, 9, 10] since the early studies dealing with traffic management under emergency conditions. These studies shared some similarities in traffic assignment procedures. Evacuation demand in terms of origin-destination (O-D) matrix was determined for each evacuation scenario and a GIS based roadway network was available for a simulation program to assign traffic for each trip O-D pair. The result of the traffic assignment was a trip trajectory, which is a "shortest path" with a sequence of nodes and links connecting the origin to the destination. These studies considered shortest-path traffic assignments for the whole routes of all evacuation trips even under a PAZ situation.

In contrast, the following two studies considered the priority in the evacuation trip segments inside the PAZ. Lu *et al.*, [11] developed a Super Node-based Trip Generator (SNTG) algorithm to generate an OD matrix in evacuation traffic assignments for the proposed Multiple-Source-Nearest-Destination Shortest Path (MSNDSP) problem. In the study, the destinations were assigned to the exits of the affected area by assuming a super-node and ignoring the travel to the real destinations outside the affected area. Zheng *et al.*, [12] developed an optimal evacuation strategy for assigning vehicular traffic flow route based on an optimization–simulation approach. Evacuees would follow optimal routes to safe locations outside the affected zone and then select behaviorally realistic routes to their final destinations.

Furthermore, according to the study of Murray-Tuite *et al.*, [13] and Lindell and Prater [14], in emergency evacuation, evacuees often seek familiar routes instead of selecting the routes contributing to relieve the traffic congestion and decrease the travel cost. Meanwhile, as individual drivers all attempted to use shortest routes of their own, some or all of the road network links and intersections on evacuation routes become over utilized due to unresolved conflicts of traffic movements, which caused traffic congestion and potential blocking along the routes in the evacuation zone [15]. These study results have well suggested that aggregate optimization of traffic assignments and route selection overweighed individual "shortest paths" and the importance of traffic guidance for evacuation traffic even under a no-notice localized evacuation situation.

3. Methodology

In this study, a simplified roadway network with origin nodes inside the PAZ, destination nodes outside the PAZ, boundary nodes on or near the boundary of the PAZ zone, and links connecting the nodes was created along with defined evacuation traffic demand for each of the O-D pairs to emulate a PAZ evacuation situation.

A gate control strategy was developed to set selected nodes on the PAZ boundary with large capacities as the main egress nodes to guide a majority of the evacuation traffic to leave the PAZ through the designated egress nodes to possibly speed up by reducing the traffic conflicts on the routes. Hence, this study sought an optimization process to obtain the optimal traffic route assignments for an evacuation network implemented with the gate control strategy to minimize the total travel cost for the evacuation trips inside and outside the PAZ zone by reducing conflicts of traffic movements and trip routes inside the PAZ.

4. Problem Description

Considering an incident, for example, a toxic gas spill or chemical explosion has happened at or near a public venue place, such as a stadium when it is fully seated. The PAZ Zone due to the emergency incident is then determined by emergency management officials using an atmospheric transport and dispersion program such as the ALOHA. An evacuation is then ordered to the affected population inside the PAZ and a large amount of evacuation traffic demand is generated in the affected area. For an emergency evacuation of a highly populated area, there will be a surge of evacuation demand, and congestion will be likely to build. After an emergency incident happens, a large number of evacuees will quickly rush towards the intersections that lead to their ensuing trips. Due to the nature of randomness or individual perception of best evacuation trip route, conflicts of movements or paths are highly possible and frequently unresolved and therefore heavy congestion would occur at the intersections. The congestion caused by the sudden surges of evacuation traffic from the densely populated spots such as a stadium, workplace building, school campus, or hospital may further propagate along the links and routes in the whole network, which could decrease the performance of the network and performance of the evacuation. As a result, a large number of evacuees could not be evacuated out of the PAZ in a timely manner.

In order to resolve this difficulty, a new traffic flow assignment method was theoretically built and tested based on system optimization modeling. It utilizes a gate control strategy for the network nodes and links at or near the PAZ boundary and actively manages the evacuation trip routes inside the PAZ by suggestively guiding the evacuees to leave the PAZ.

4.1. Gate Control Strategy in Evacuation Network

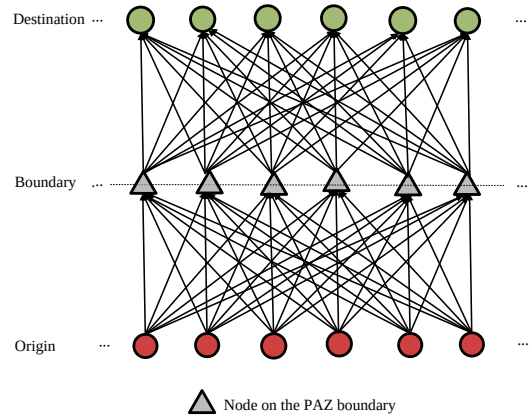
In the proposed gate control strategy, a node on the PAZ zone boundary having a large volume capacity can be set as an evacuation egress gate, for example an arterial intersection, or an entrance to a freeway ramp. In modeling the network, the following steps will be taken to set a node on the PAZ boundary as a gate node:

(1) Increase the capacity of the gate node, including the inbound links and the outbound links; and

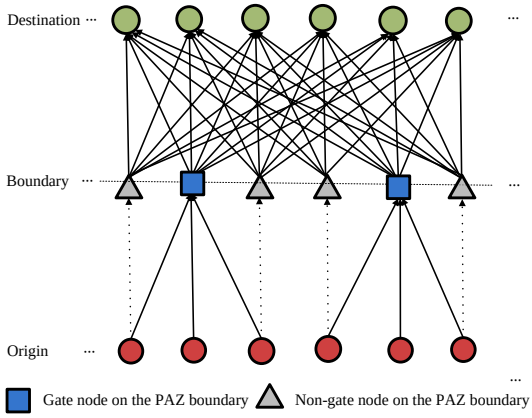
(2)Restrict conflict inducing traffic such as the turning movements at non-gate nodes on PAZ boundary. This restriction may have a reducing effect on capacity of the node.

The gating strategy is schematically described in Figure 1. An origin node is representing an origin zone, which is one of the traffic analysis zones (TAZ) inside or partially inside the PAZ zone. Evacuation traffic is generated from each of the TAZ zones. A destination node represents a destination zone, where a home or a temporary shelter is located. A boundary node is a node located on the PAZ boundary separating the affected zones and the safe zones in the evacuation network of the problem. The figure shows the intuitional performance improvement after setting the gate nodes on the PAZ boundary for the evacuation need. Figure 1(a) shows the situation without setting any gate node. When the emergency incident happens, the evacuees first respond to the incident by “running away” (equivalently taking the shortest paths) from the origin zones in the affected area to their destination zones which are out of the PAZ zone. The evacuees can freely choose any route which they believe to be the shortest path without knowing whether the route in the PAZ is congested or not, and most likely the decision on the route is made in a big hurry and/or based on previous experience. As a result, there are tremendous numbers of movement conflicts due to the many route crossovers and therefore heavy congestion will be soon produced in multiple places in the PAZ. These

points of congestion will decrease the evacuation traffic mobility and eventually the performance of the emergency evacuation.



(a) Before Using Gating Strategy



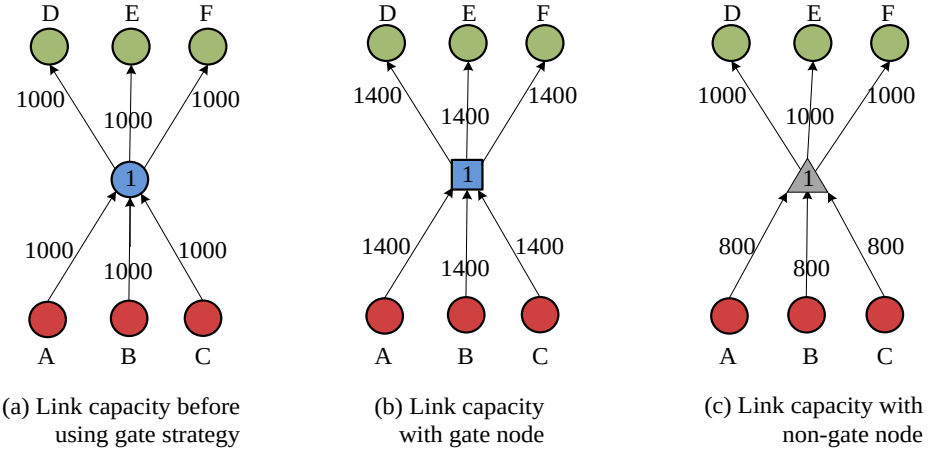
(b) After Using Gating Strategy

Figure 1. Schematic Gating Strategy in Evacuation Network

Figure 1(b) shows that gates with large or increased volume capacities are selected and set among nodes on the boundary to help relieve the heavy congestion points in the PAZ. Under the gating strategy, evacuation trips are suggestively guided through designated gates to leave the PAZ and then continue to their destinations through the network outside the PAZ zone. Since the evacuation trips are guided to the designated gates based on traffic assignment method to minimize path crossovers, unnecessary conflicts of traffic movements are significantly reduced. It is noticeable that the gate nodes must have increased capacities to sustain the processing of the majority of the traffic. Meanwhile, the non-gate nodes are still passable but may only allow limited traffic movements (with dashed lines in the figure). Since the gating strategy aims to minimize path crossovers and conflicts of traffic movements, the cascading effect of congestion could be controlled and the evacuation performance could be improved.

4.2. Gate Control Configuration

Figure 2 shows an illustration of the link capacity change before and after using the gate control strategy. In Figure 2(a), each of the inbound links such as link (A, 1), link (B, 1), and link (C, 1) or outbound links such as link (1, D), link (1, E), and link (1, F) to and from node 1 respectively has a volume capacity of 1000 vehicles per hour before implementing the gate control strategy.



(a) Link capacity before using gate strategy

(b) Link capacity with gate node

(c) Link capacity with non-gate node

Figure 2. Link Capacity Changes before and after using Gate Strategy

After applying the gate control strategy, for the node selected as a gate, all the inbound links and outbound links will increase capacity from 1000 vehicles per hour to 1400 vehicles per hour, as shown in Figure 2(b). For nodes on the boundary but not selected as gate nodes, all the inbound links will decrease volume capacity from 1000 vehicles per hour to 800 vehicles per hour.

As to the methods or technologies that can be used to increase node and link capacities, it has been quite popular practice to enhance the throughput capacity of evacuation corridors by using the shoulder as a travel lane and Intelligent Transportation System (ITS) devices such as a portable dynamic/variable message sign (DMS or VMS) board in evacuation traffic operations. On the other hand, capacity reduction can be easily implemented by restricting some traffic movements just like the traffic control for a work zone. It should also be noted that the aforementioned numbers for volume capacity and capacity change for a gate control strategy are only used as an example for the purpose of illustration. More parameter settings and scenarios were used in the modeling and the development of numerical experiments of the problem.

5. Traffic Assignment Model

5.1. Assumption

In order to simplify the problem in study, we assume that the inbound and outbound links of selected nodes on the evacuation PAZ boundary could be implemented with either a contraflow or a work zone strategy and all major streets in the study area have shoulder lanes that are useable as extra traffic lanes under an emergency situation. We also assume that necessary traffic control or traffic management strategy, such as law enforcement, dynamic/variable message signs (DMS/VMS) are available to be used in or around the PAZ in order to guide the evacuees to leave from the affected area through the gate egress nodes as smoothly as possible. In addition, we assume the traffic operations on all links of the model are in free-flow conditions. Therefore, travel time for each link will not be related to the traffic volume of the link. A state dependent queuing model that considers saturation state near link/node capacity and congested flow of traffic will be used to relax this assumption for a future study of the problem. However, the simplifications made to the problem are still good enough to serve the research objective of the study.

5.2. Description of Parameters and Variables

5.2.1. Sets The sets used in the model include:

N	Set of nodes in the evacuation network;
O	Set of origin nodes in the evacuation network;
D	Set of destination nodes in the evacuation network;
M	Set of intermediate nodes in the evacuation network;
E	Set of links in the evacuation network;
E_1	Set of links within PAZ;
E_2	Set of links outside of PAZ;
o	Index of originsin the evacuation network, $o \in O$;
d	Index of destinations, $d \in D$;
m	Index of intermediate nodes, $m \in M$;
i, j	Indices of nodesin the evacuation network, $i, j \in N$;
(i, j)	Index of traffic link between adjacent nodes i and j, $(i, j) \in E$

5.2.2. Input parameters The input parameters in the model include:

cap_{ij}	General capacity of link(i, j) in the evacuation network;
$\Delta cap_{i_j}^{+}$	Capacity increase change of link(i, j) in the evacuation network;
$\Delta cap_{i_j}^{-}$	Capacity decrease change of link(i, j) in the evacuation network;
cap_o	Demand of the origin node $o$in the evacuation network, $o \in O$;
cap_m	Capacity of the intermediate node $m$in the evacuation network,$m \in M$;
DE_{od}	Evacuation trip demand between o-$d$in the evacuation network, $o \in O$, $d \in D$;
c_{ij}	Travel cost of link(i, j).

5.2.3 Decision variables The decision variables include:

x_{odij}	Evacuee volume from o to d on network link (i, j).

5.3. Formulation of optimization model

In the model, there are flow equilibrium constraints, evacuation demand constraints, and link capacity constraints.

5.3.1. Flow Equilibrium Constraints

$$\sum_{i\epsilon O}\sum_{j\epsilon M}\sum_{o\epsilon O}\sum_{d\epsilon D} x_{odij} = \sum_{i\epsilon M}\sum_{j\epsilon D}\sum_{o\epsilon O}\sum_{d\epsilon D} x_{odij} = \sum_{o\epsilon O}\sum_{d\epsilon D} DE_{od} \tag{1}$$

$$\sum_{o\epsilon O}\sum_{d\epsilon D} DE_{od} = \sum_{o\epsilon O} cap_o \tag{2}$$

Constraint (1) ensures that the total evacuation demand generated from all the origin nodes equals the total flow volume arriving at all the destination nodes, also equal to the total evacuation demand in the evacuation network. Constraint (2) is evacuation demand constraints.

$$\sum_{o\epsilon O}\sum_{d\epsilon D}\sum_{i\epsilon O} x_{odim} = \sum_{o\epsilon O}\sum_{d\epsilon D}\sum_{j\epsilon D} x_{odmj} \qquad \text{for } \forall\, m \in M \tag{3}$$

Constraint (3) ensures that the total flow volume from all the origin nodes to one intermediate node equals the total flow volume from that intermediate node to all the destination nodes.

$$\sum_{j\epsilon M} x_{odoj} = \sum_{i\epsilon M} x_{odid} \quad \text{for } \forall o \in O, \forall d \in D, \tag{4}$$

Constraint (4) ensures that each *od* demand is assigned to the intermediate nodes and the assigned volumes conserve during the traffic assignment.

5.3.2. Link/Node Capacity Constraints

$$\sum_{o\in O}\sum_{d\in D} x_{odij} \le cap_{ij} \quad \text{for } \forall (i,j) \in E \tag{5}$$

$$\sum_{o\epsilon O}\sum_{d\in D}\sum_{i\in O} x_{odim} \le cap_m \quad \text{for } \forall\, m \in M \tag{6}$$

Constraint (5) ensures that the total flow volume from o to d on link (i,j)could not exceed the capacity of that link(i,j). Constraint (6) ensures the total volume to any intermediate note does not exceed the node capacity.

5.3.3. Non-negative and Integer Constraints

$$x_{odij} \ge 0 \qquad \text{for } \forall o \in O, d \in D, \qquad \forall i,j \,\epsilon\, N, i \neq j \tag{7}$$

5.3.4. Objective Function

The objective of the model is to minimize the total travel cost in the evacuation network. The objective function is:

$$min\ Z = \sum_{(i,j)\in E_1}\sum_{o\in O}\sum_{d\in D} c_{ij}x_{odij} + \sum_{(i,j)\in E_2}\sum_{o\in O}\sum_{d\in D} c_{ij}x_{odij} \tag{8}$$

5.3.5. Solution of Linear Programming Problem

The above optimization model including equations or formulations (1) through (8) is a typical linear programming problem that could be rewritten in the following matrix format:

$$\min\{cX\} \ \text{ subject to: } AX \ge b, X \ge 0$$

where *A* is an m by *n* matrix, *c* an n-dimensional row vector, *b* an m-dimensional column vector, and *X*an n-dimensional column vector of variables or unknowns. The problem can be considered as an Integer Programming (IP) problem since the decision variables normally take integer values.

For different gate control scenarios, the following equation can be used to set the capacity of the links connected to a gate or a non-gate.

$$\widetilde{cap}_{ij} = cap_{ij} + \Delta cap_{ij}^{+} \cdot \delta_{ij}^{+} - \Delta cap_{ij}^{-} \cdot \delta_{ij}^{-} \tag{9}$$

$$\delta_{ij}^{+} + \delta_{ij}^{-} = 1 \tag{10}$$

where $\widetilde{cap}_{ij}$ is the updated link capacity due to a specific gate control setting, and δ_{ij}^{+} andδ_{ij}^{-} are 0-1 variables associated with the gate or non-gate status of a node on the PAZ boundary. If $\delta_{ij}^{+} = 1$, (which means $\delta_{ij}^{-} = 0$), the link (i,j) is associated with a gate node and is to increase the capacity by Δcap_{ij}^{+}. If $\delta_{ij}^{-} = 1$(and therefore $\delta_{ij}^{+} = 0$), then link (i,j) is inbound associated with a non-gate node to decrease the capacity by Δcap_{ij}^{-}. Otherwise, capacity of link $(i,j)$is unchanged and should take the original general capacity value.

5.4. Formulation of Optimization Model

For the traffic assignment results with the minimum total travel cost in the evacuation network, the degree of conflict of any two links of traffic flow will be evaluated by using the following formula:

$$y = \sum_{i_1,i_2 \epsilon O} \sum_{j_1,j_2 \epsilon M} x_{(i_1,j_1)} . x_{(i_2,j_2)} . \left(\beta_{(i_1,j_1)(i_2,j_2)}\right) \tag{11}$$

where, y is the degree of traffic flow conflicts throughout the network inside the PAZ. $x_{(i_1,j_1)} = \sum_{o\epsilon O} \sum_{d\epsilon D} x_{odi_1j_1}$ and $x_{(i_2,j_2)} = \sum_{o\epsilon O} \sum_{d\epsilon D} x_{odi_2j_2}$ are the traffic flows on link $(i_1, j_1)$and link (i_2, j_2); $\beta_{(i_1,j_1)(i_2,j_2)}$is a 0-1 variable denoting whether or not link (i_1, j_1) and link (i_2, j_2) are conflicting with each other. If $\beta_{(i_1,j_1)(i_2,j_2)}$= l, then traffic flows on link (i_1, j_1) and link (i_2, j_2) are conflicting with each other in their evacuation trip routes inside the PAZ zone; Otherwise$\beta_{(i_1,j_1)(i_2,j_2)}$= 0. Equation (11) defines the total degree of traffic conflicts for the PAZ network as the summation of the products of all conflicting traffic flows within the PAZ network. Intuitively, this measurement is linearly related to traffic delay. When the traffic flow on any of the conflicting links increases, the degree of traffic conflicts increases, and the amount of delay would alsoincrease, accordingly.

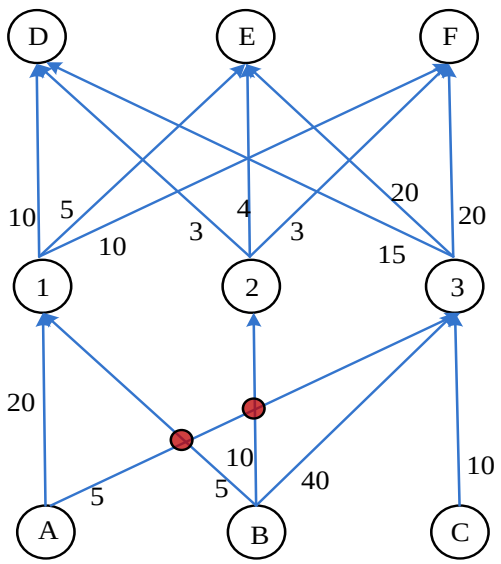


Figure 3. Traffic Conflicts in PAZ Evacuation Network

The calculation of the total degree of traffic conflicts is explained and shown in Figure 3. There are two traffic flow conflicts in the network inside the PAZ. One is traffic flow conflict between link (B, 1) and link (A, 3), and the other one is traffic flow conflict between link (B, 2) and link (A, 3). The flow volume is marked on each link in the figure. The total traffic conflict degree is $y = 5 \times 5 + 5 \times 10 = 75$.

6. Numerical Experiments

The proposed optimization model was implemented in VB in Visual Studio 2013 using IBM ILOG CPLEX 12.5 as a black-box MIP solver. The network used in the numerical experiments is shown in Figure 4.

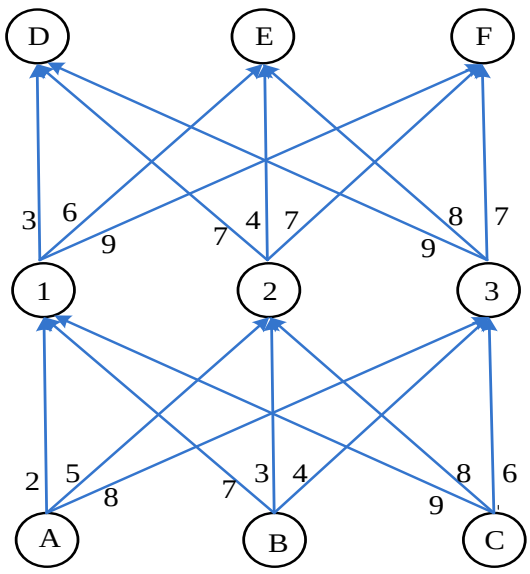


Figure4. Network used in the Numerical Experiments

There are nine nodes in the network. Node A, node B, and node C are three origin nodes respectively. Node D, node E, and node F are three destination nodes. Node 1, node 2, and node 3 are three intermediate nodes on the PAZ boundary. The links connections between the nodes are shown in the figure with travel costs marked. The model input parameters for the evacuation network such as link/node capacities and traffic demand are defined in the following paragraphs.

6.1. Model Parameters

Tables 1 and 2 list the input data for the parameters used in the optimization model.

Table 1. Input Parameters of Evacuation Demand

Origin Node (o)	Destination Node(d)	Evacuation Demand DE_{od}(veh/hr)	Origin Node Evacuation Demand cap_o(veh/hr)
A	D	600	1800
A	E	600	
A	F	600	
B	D	600	1800
B	E	600	
B	F	600	
C	D	600	1800
C	E	600	
C	F	600	

Input parameters for evacuation trip demands for O-D pairs are shown in Table 1. The input parameters for the link features of link/node capacities and link travel cost used in the experiments are shown in Table 2.

Table 2. Input Parameters of Link/Node Features

Link/node (i, j)	Capacity (veh/hr) (cap_{ij}/ cap_m)	Travel Cost (min) (c_{ij})
(A, 1)	1000	2
(A, 2)	1000	5
(A, 3)	1000	8
(B, 1)	1000	7
(B, 2)	1000	3
(B, 3)	1000	4
(C, 1)	1000	9
(C, 2)	1000	8
(C, 3)	1000	6
(1, D)	1000	3
(1, E)	1000	6
(1, F)	1000	9
(2, D)	1000	7
(2, E)	1000	4
(2, F)	1000	7
(3, D)	1000	9
(3, E)	1000	8
(3, F)	1000	7

It should be noted that the constant values for the travel costs are based on the free-flow assumption mentioned earlier.

6.2. Experimental Scenarios

The experimental scenarios of different gate control plans are shown in Table 3. Consideringthe fact that network connectivity attributes affect the performance of gate nodes, potential nodes with large capacitiesnear the PAZ boundary are selected as gates for the experiments.

Table 3. Experimental Scenarios for Demand/Capacity(veh/hr)

Scenario ID	Demand at Each Origin Node	Demand for Each OD Pair	GateLink Capacity	Non-gateLink Capacity
No gate	1800	600	NA	NA
Gate 1	1800	600	1400	300~1000
Gate 2	1800	600	1400	300~1000
Gate 3	1800	600	1400	300~1000
Gates 1,2	1800	600	1400	300~1000
Gates 1,3	1800	600	1400	300~1000
Gates 2,3	1800	600	1400	300~1000

In order to verify the effectiveness of the gate control strategy theoretically built using the optimization model, experimental scenarios were designed to conduct a sensitivity analysis to test the validity of the gate control strategy.Two gate control levels were tested, with one level using one intermediate node as the gate, and the other level using two nodes as the gates. Seven control plans were designed: 1) No gate, namely, no node was selected as gate node; 2) Gate 1, node 1 was selected as gate node; 3) Gate 2, node 2 was selected as gate node; 4) Gate 3, node 3 was selected as gate node; 5) Gates 1,2, namely, both node 1 and node 2 were selected as gate nodes; 6) Gates 1,3, both node 1

and node 3 were selected as gate nodes; and 7) Gates 2,3, both node 2 and node 3 were selected as gate nodes. In each scenario, each link capacity (both inbound and outbound) of the gate node was increased to 1400 vehicles per hour and each link capacity inbound to a non-gate node was decreased in the range from 1000 to 300 vehicles per hour.

6.3. Experiments of Gate Control Scenarios

The experiments on gate control scenarios were conducted to identifythe node(s) on the boundary that would impact the evacuation performance in decreasing the total travel cost in the network, if the control scenario is selected.

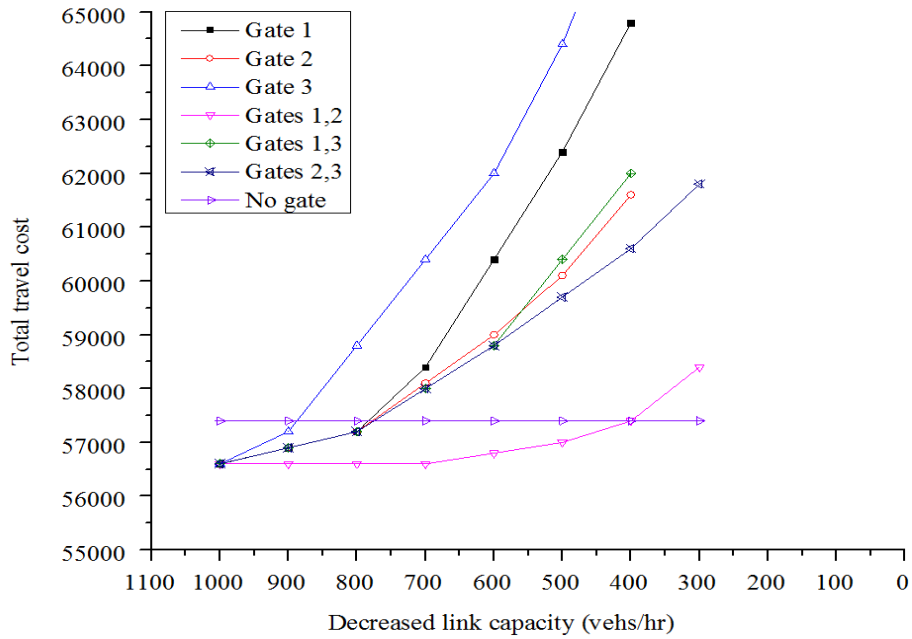


Figure 5. Objective Function Values of Different Gate Control Scenarios with Decreased Non-Gate Link Capacity

The computational result of the optimization objective function for different gate control plans along with the decreased link capacity for inbound links of non-gate nodes are shown in Figure 5. It should be noted that the reduced link capacity applied to the inbound links to all the non-gate nodes in the scenarios with gate controls, but not to the scenario without any gate control. The experiments results in Figure 5 show that before using any gate control, the objective value was 57,400, which is shown as a horizontal line serving as a benchmark reference for comparison. Apparently, before the link capacity of the non-gate nodes dropped below around 800 vehs/hr,most of the six scenarios with gate control could effectively improve the evacuation performance by obtaining a smaller total travel cost value than the benchmark of no gate control.

In Figure 5 it shows that the six gate control scenarios could reach to a similar objective function value (the initial point for the gate-control curves in the figure), which means the gate control level of increased link capacity was not binding in the model constraints. Other parameters such as the node capacities may have become the binding constraints that prevented the objective function from further going down even with more boundary nodes being included and configured as gate nodes. This result may suggest that a link capacity enhancing traffic control strategy such as a contra-flow deployment on an evacuation corridor must be coupled or coordinated with proper traffic management strategies at important nodes such as an urban intersection (*e.g.*, traffic signalization

and/or law enforcement) or a ramp access point (*e.g.*, ramp metering) to a freeway to increase the system network capacity in order to improve evacuation performance.

Figure 5 also shows that with the increased capacities of inbound and outbound links of the gate node(s), the reduction of the capacity of the inbound links to the non-gate nodes increased the objective function values and therefore caused the increase of the total travel cost. This is quite understandable and expected to happen when the capacities of the inbound links were decreased due to traffic control. Therefore, in Figure 5, the objective function curves for the six gate-control scenarios started from an initial value lower than the no-gate scenario and then go up along with the reduction of inbound link capacity at the non-gate nodes, until surpassing the benchmark value for the no-gate scenario. However, the slopes of the climbing curves show that the scenarios with more than one gate node generally have smaller slopes than those of the scenarios with only one gate node. The scenario Gates 1,2 is shown to have the smallest climbing slope which suggests the best gate control configuration among all the seven scenarios. The next best gate-control scenario would be scenario Gate 2, due to its good performance as well as its advantage for requiring only one gate node in setting up.

6.4. Degrees of Traffic Conflict in Gate Scenarios

The degrees of traffic conflict for the seven gate-control scenarios were calculated using the model in Equation (11) and are listed in Table 4.

Table 4. Degree of Traffic Conflict in the Network ($\times 10^4$)

Scenario ID	Capacity of Non-gate Associated Links (veh/hr)						
	1000	900	800	700	600	500	400
No gate	208	208	208	208	208	208	208
Gate 1	152	158	128	-	-	-	-
Gate 2	152	148	160	-	-	-	-
Gate 3	152	162	-	-	-	-	-
Gates 1,2	152	152	152	139	160	162	160
Gates 1,3	152	146	164	-	-	-	-
Gates 2,3	152	148	144	-	-	-	-

For the six scenarios where at least one boundary node was configured for gate control, the degrees of traffic conflict for the experiments of reducing inbound link capacities for non-gate nodes are also listed in the table. The empty cells in Table 4 denote higher objective function values or total travel cost values than the benchmark value at the no gate control scenario and accordingly degree of traffic conflict were not calculated for these situations.

As shown in Table 4, the degree of traffic conflict result for the scenario with no gate control was valued the highest at 208×10^4, compared with the other scenarios with at least one boundary node configured with gate control. It is noticeable that the calculated values for the degree of traffic conflict for almost all of the six scenarios with effective gate controls show a decreasing trend as the capacities of the inbound links to the non-gate nodes were reduced. This result confirms the earlier concerns by the authors that the "shortest-path" based traffic assignment may have underestimated the effect of traffic congestion due to the conflicts of trip routes and traffic movements especially within the PAZ zone. Among all the six gate control based scenarios, scenario Gate 1 could most effectively relieve the traffic conflicts and the calculated value for the degree of conflict under Gate 1 scenario was the smallest at 128×10^4. Scenario Gates 1,2 is the second best effective strategy among all by achieving 139×10^4 in the degree of traffic conflict. The scenario also exhibits a long scope for reducing the link capacity to the inbound links to

the non-gate nodes. However, with the decreases of inbound link capacities to the non-gate nodes, most of the gate control scenarios show a brief reducing trend followed by a steady increase in the degree of traffic conflict, which means the strategy of reducing non-gate node/link capacities would be difficult to be effectively implemented in an evacuation operation.

7. Conclusions

This study proposed an optimization model to seek improved traffic flow assignment with a minimization of the total travel cost in a localized no-notice evacuation network. The gate control strategy was introduced as constraints in the optimization model by increasing the link capacity connected to the selected gate nodes and decreasing the link capacities of inbound links to the non-gate nodes. Flow equilibriums, evacuation traffic demand, and link/node capacities were also considered in the model to theoretically establish the model. Numerical experiments were conducted to verify the effectiveness of the model by showing the evacuation traffic flow assignment results with improved travel costs and reduced degrees of traffic conflicts that may result in delay and congestion. Based on the study we also have the following observations:

(1) The numerical experiment results show that the implementation of a gate control strategy by increasing the capacities of the inbound and outbound links of the selected node(s) on or near the PAZ boundary could effectively decrease the total travel cost to guide the evacuees to evacuate from the PAZ through the gate nodes.

(2) The numerical experiment results show that reducing the capacities of the inbound links to the non-gate nodes on or near the PAZ boundary has a limited effect on reducing the degree of conflicts of traffic movements and trip routs inside the PAZ of the network, but may cause significant increase in total travel costs;

(3) The numerical experiment results show that in a no-notice or short notice evacuation for a PAZ, which node(s) on the boundary should be selected for a gate control plan impacts the evacuation performance. The results also show that the number of nodes selected for a gating strategy may also impact the evacuation performance.

This study theoretically verifies the effectiveness of the proposed system optimization model based on a gate control strategy to obtain the optimal traffic flow assignment solutions with a minimum total travel cost in the network of free-flow traffic. How to apply the gate control strategy or concept to a real-world situation in a simulation study with congested/queued traffic flows and more advanced modeling and computation challenges to solvea large-scale evacuation problem with a realistic network will be included in another paper.

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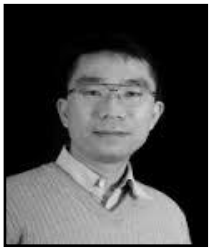

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