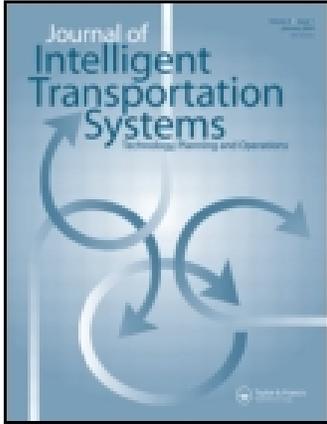


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An Optimization Model for Guiding Pedestrian–Vehicle Mixed Flows During an Emergency Evacuation

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In most metropolitan areas, an emergency evacuation may require a potentially large number of pedestrians to walk some distance to access their passenger cars or resort to transit systems. In this process, the massive number of pedestrians may place a tremendous burden on vehicles in the roadway network, especially at critical intersections. Thus, the effective road enforcement of the vehicle and pedestrian flows and the proper coordination between these two flows at critical intersections during a multimodal evacuation process is a critical issue in evacuation planning. This article presents an integrated linear model for the design of optimized flow plans for massive mixed pedestrian–vehicle flows within an evacuation zone. The optimized flow can also be used to generate signal timing plans at critical intersections. In addition, the linear nature of the model can circumvent the computational burden to apply in large-scale networks. An illustrating example of the evacuation around the M&T Bank Stadium in downtown Baltimore, MD, is presented and used to demonstrate the model’s capability to address the complex interactions between vehicle and pedestrian flows within an evacuation zone. Results of simulation experiments verify the applicability of our model to a real-world scenario and further indicate that accounting for such conflicting movements will yield more reliable estimation of an evacuation’s required clearance time.

Keywords Evacuation; Mixed Flow; Optimization; Pedestrian

INTRODUCTION

Mitigating traffic congestion during emergency evacuation has evolved as a major task for responsible agencies over the past decades. In congested metropolitan areas, commuters are likely to depend either on transit or on other modes for their daily commutes. Thus, during an evacuation process evacuees often need to walk some distance to their designated locations. Hence, although vehicle flows are generated from the massive number of pedestrians, the pedestrian flows often cause a tremendous burden to vehicles in the roadway network.

For example, if an evacuation operation occurs for the M&T Bank football stadium in downtown Baltimore

(see Figure 1), the pedestrians will have to cross the streets to their parking lots or transit stops. Consequently, vehicles will be generated from those locations and conflict with the pedestrian flows in the evacuation process. To effectively coordinate these two flows, one needs to identify the possible paths between pedestrian and vehicle origin–destination (O-D) pairs and provide guidance for them to distribute among the possible paths.

To fully use the roadway capacity while preventing the formation of bottlenecks due to conflicts between vehicle and pedestrian flows is one of the most critical issues in minimizing the evacuation clearance time. Effective control measures can help to improve the evacuation efficiency and reduce the clearance time. To plan for emergency evacuation, responsible agencies often need to make the following decisions: (1) choosing the possible shelters and safe destinations; (2) guiding evacuees from the evacuation zones to their assigned locations; and (3) coordinating the conflicts at major intersections and ramps. Hence, an effective model to coordinate the

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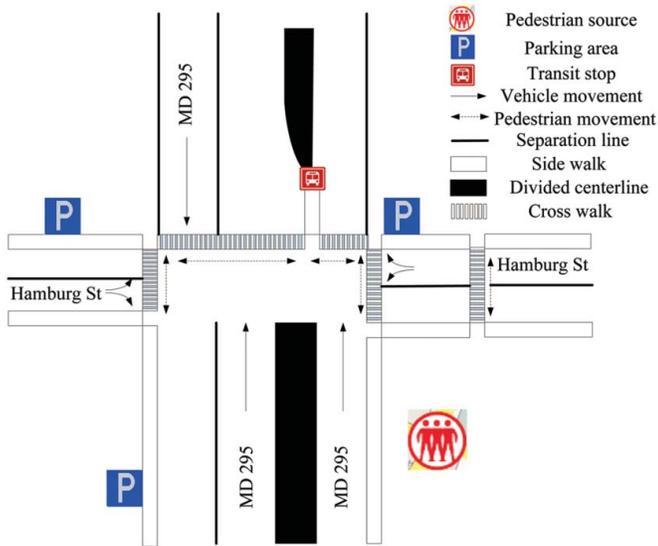


Figure 1 A graphic illustration of Hamburg Street at MD295 near M&T Bank Stadium.

pedestrian and vehicle flows during evacuation operations should have the following key features:

1. Realistically represent the networks of vehicle and pedestrian flows and capture their interactions.
2. Compute the optimal flow distributions in the integrated network to maximize the evacuation efficiency.

Failure to account for the conflicts between vehicles and pedestrians in the mixed flows may cause an evacuation plan to overestimate its efficiency and effectiveness. This article addresses this vital issue. It is organized as follows: The next section reviews the existing literature regarding the evacuation optimization. The third section presents the formulations of the integrated mixed flow network and its components. The fourth section details a linear optimization model that accounts for the interactions between vehicle pedestrian flows within evacuation zones. The fifth section demonstrates the model application with an illustrative example of the M&T Stadium evacuation. The sixth section summarizes the conclusions and future directions.

LITERATURE REVIEW

Evacuation modeling has received sustained attention since the Three Mile Island Nuclear Generating Station incident in 1979. Due to the vast number of studies in the literature, we only review those related to the network flow optimization in this study. The literature review divides all related studies into three categories: vehicle evacuation, pedestrian evacuation, and mixed-flow evacuation.

Vehicle Evacuation Studies

The first category of the studies is related to single vehicle-mode evacuation planning. Most early programs such as NETVAC (Sheffi, Mahmassani, & Powell, 1982), DYNEV (Federal Emergency Management Agency, 1984), MASSVAC (Hobeika & Jamei, 1985; Hobeika, Radwan, Jamei, & Sivasailam, 2005), OREMS (Oak Ridge National Laboratory, 1999), and EITS (PBS&J, 2000) were based on the “trial-and-error” method, relying on either the macro- or micro-simulation tools for performance evaluation. To optimize the vehicle flow distribution during an evacuation, Dunn and Newton (1992) and Campos, Da Silva, and Netto (2002) proposed the use of static network flow models. Hamacher and Tjandra (2002) gave an overview of the mathematical models for various evacuation-related issues, focusing especially on modeling dynamic network flows and route choices, for example, maximum dynamic flows, earliest arrival flows, quickest paths and flows, or continuous dynamic flows. Ziliaskopoulos (2000) proposed a simple linear formulation, based on the cell transmission model, to produce the system-optimal dynamic traffic assignment to single destination. Cova and Johnson (2003) presented a network flow model for identifying optimal lane-based evacuation routing plans in a complex road network. The model is an extension of the minimum cost flow problem. Sbyati and Mahmassani (2006) proposed a system-optimal dynamic formulation to schedule evacuation trips between a selected set of origins and safety destinations. The method of successive average (MSA) was used to find the flow assignment, and a traffic simulator, DYNASMART-P, was employed to propagate vehicles and determine the state of the system. Liu, Lai, and Chang (2006a, 2006b) proposed a cell-based network model to determine the set of optimal starting times and routes for evacuees in different zones. Yuan and Wang (2007) simultaneously optimized the destination and route choices by solving a traffic assignment problem on a modified network structure. Afshar and Haghani (2008) devised a heuristic optimization procedure to provide a system-optimal solution to the time-varying traffic assignment problem. The algorithm allows for the joint optimal choice of destinations, routes, and departure times.

Pedestrian Evacuation Studies

The second category of evacuation studies focused mainly on optimization of pedestrian evacuation. Most of these studies deal with inside the building evacuation scenarios. An early static transshipment network model of building 101 has been widely explored as a benchmark for assessing the applicability of network flow optimization models for building evacuation (Francis, 1979, 1981). Chalmet (1982) expanded it to a dynamic model using the procedure of Ford and Fulkerson (1962) that simultaneously maximizes the total number of people evacuating the building for all time periods and minimizes

the time duration for the last evacuee to exit the building. An application of EVACNET (Francis, 1984, Francis & Kisko, 1985; Kisko, Francis, & Nobel, 1998) was designed later to generate optimal evacuation plans and to estimate evacuation times for the in-building evacuees. Choi (1987; Choi, Hamacher, & Tufekci, 1988) modeled the building evacuation by solving the minimal cost dynamic network flows with side constraints of variable link capacities. He proposed “greedy” algorithms for some special networks and developed solution procedures that take advantage of the unique network structures. Hoppe and Tardos (1995) proposed polynomial time algorithms for the maximum dynamic flow and quickest flow problems with a fixed number of sources and sinks. Lu et al. (Lu, Huang, & Shekhar, 2003; Lu, George, & Shekhar, 2005) developed new heuristic approaches, named single-route and multiple-route approaches, to find a suboptimal evacuation plan with reduced computation cost. However, his proposed algorithm requires the capacity of a link to be constant and independent of the traffic volume at the link. Pursals and Garzo (2009) improved Francis’s model (Francis, 1979, 1981) by incorporating the evacuation routes and movement equations.

Mixed-Flow Evacuation Studies

On the subject of modeling mixed pedestrian–vehicle flows over a congested network, very few studies have been reported in the literature. Zhang and Chang (2010) addressed this issue with an extended cell transmission method (Daganzo, 1994, 1995). There are also some efforts on simulating the pedestrian–vehicle conflicts in recent years. Ishaque and Noland (2007) studied the pedestrian traffic with VISSIM, where vehicle and pedestrian modes are operated independently and controlled by the traffic signals at the potential conflicting areas. This function has later been expanded in VISSIM to model the conflicts between pedestrian and vehicle flows using the gap acceptance model when any of them needs to cross a street (Boenisch & Kretz, 2009).

Based on the preceding review results, one can reach the following conclusions:

1. Despite the increasing interest in studying evacuation-related issues, the complex interaction between the massive pedestrian and vehicle flows within the evacuation zone and at intersections has not been adequately addressed.
2. Many of the evacuation studies ignored the inevitable conflict between the massive vehicle and pedestrian flows during evacuation, especially at critical intersections. Not accounting for such conflicts is likely to yield underestimated evacuation clearance time.
3. Some evacuation studies did consider the flow conflict’s impact on the evacuation, but their formulations are suitable mostly for a small network due to the large number

of variables and the integer nature. For example, Cova and Johnson (2003) adopted a lane-based network flow model and put a restriction on avoiding the conflicts by banning some turning movements. Ziliaskopoulos (2000) explicitly considers the signal timing in the formulation.

4. In our previous study (Zhang & Chang, 2010) on the subject, we also consider explicitly the signal timings with the extended cell transmission method. However, due to the complex nature of the pedestrian–vehicle conflict in a mixed-flow environment, the proposed formulations are nonlinear and have encountered the same computing efficiency concern for large-scale network applications.

To overcome the limitations just described, this study presents a new set of linear formulations to capture the interactions within the mixed flows under the available roadway capacity, which can substantially reduce the computing time for generating the optimal solutions.

MIXED FLOW NETWORK REPRESENTATION

Components of the Mixed Network

Our proposed mixed-flow network consists of three main components: the vehicle network, the pedestrian network, and interactions between them. For the vehicle network, we adopt the common unidirectional node–link concept and use the bidirection link–node notion for the pedestrian network. The flows in these two networks will interact with each other via the connection and conflict nodes. The connection between these two networks is to convert the pedestrian flows to the vehicle flows. In reality, the connection usually takes place at parking areas and pickup locations, whereas the conflicts between these two streams of flows usually occur at intersections or crossing areas.

Modeling of the Vehicle Network

Consider a directed graph $G^V = (V^V, E^V)$, where $V^V = \{1, \dots, n_v\}$ is the set of nodes, and $E^V = \{(i, j) | i, j \in V^V\}$ is the set of directed links. These nodes represent the intersections, and the links denote a one-way street that connects two intersections. To represent the dynamic interactions between different movements, one needs to extend the network presentation with an additional element: connectors. Each intersection node needs to be split into multiple nodes and connected by the connectors that are used to model allowable turning movements. The length of the connector is set to zero and its capacity is equal to the saturation flow rate of the corresponding turning movement. Examples of connector links are given in Figure 2, where the intersection is split into four filled nodes shown in Figure 3b. The four turning movements, denoted with 1 to 4 in Figure 2a, are represented with the four corresponding connectors in Figure 2b.

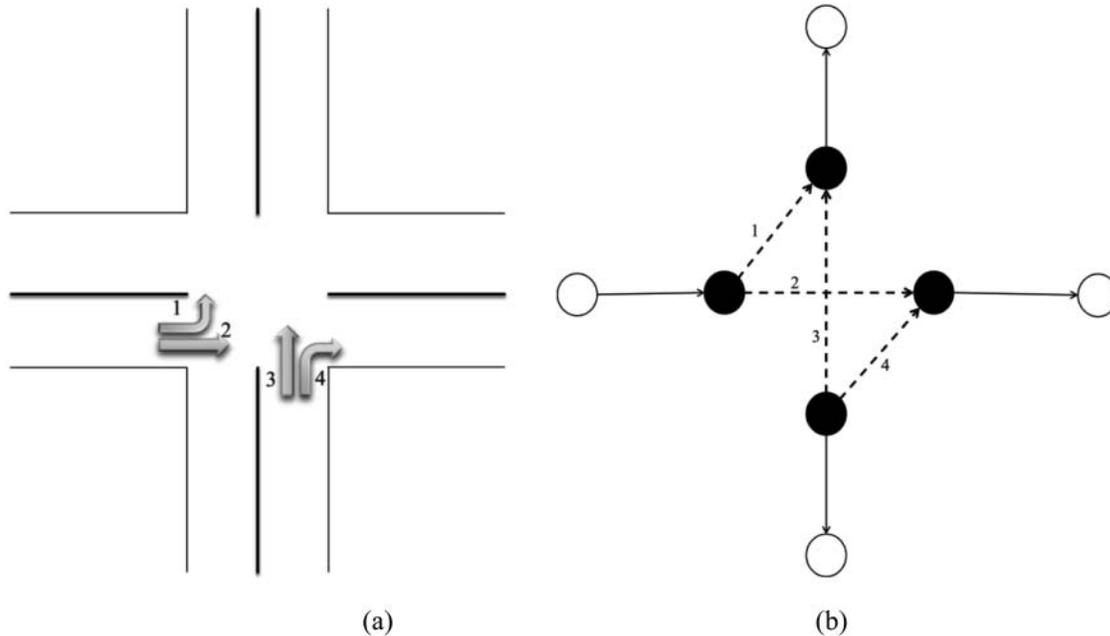


Figure 2 A graphic illustration of connectors.

Modeling of the Pedestrian Network

In general, all pedestrian movements during evacuation may occur in one of the following areas: inside-building area, sidewalks, and intersection crossings. Since the focus is on guiding and controlling pedestrian-vehicle flows within the evacuation zone, this study mainly presents our modeling efforts on guiding the pedestrian flows along sidewalks and at intersections. Similar to the vehicle network modeling, sidewalks and crossings can also be represented with nodes and links. However, it should be noted that the pedestrian network is bidirectional in nature because pedestrians can move toward both directions on each link. Consider a bidirected graph-

$hG^p = (V^p, E^p)$, where $V^p = \{1, \dots, n_p\}$ is the set of nodes, and $E^p = \{(i, j) | i, j \in V^p\}$ is the set of undirected links. These links are used to represent the sidewalks or the crosswalks, and the nodes are for the connections between the sidewalks and the crosswalks. An illustrative example is given in Figure 3, where the solid lines in Figure 3b represent the sidewalks and the dashed lines show the crosswalks.

Representation of the Connections

For evacuees without access to vehicles, their destinations are the pickup points where buses will transport them to safe

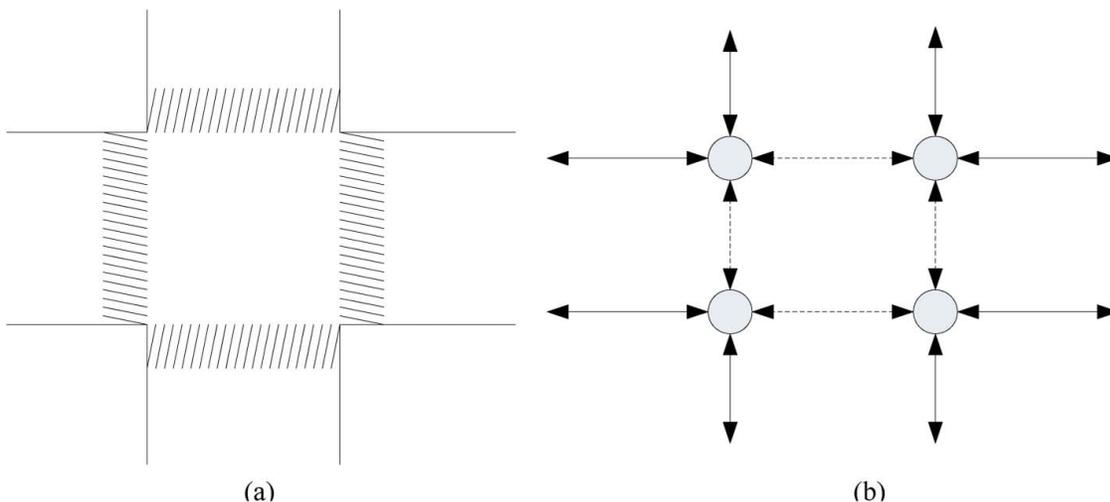


Figure 3 A graphic illustration of the pedestrian network.

areas. For other evacuees, their destinations are the parking lots where passenger cars enter the vehicle network. To realistically capture the interactions between mixed-flow movements, we have designed connectors to transfer the flows between the pedestrians and vehicles. The connection node denotes the locations where the pedestrians will enter the vehicles, for example, the parking lots or the pickup points. Each filled circle in Figure 4b represents a parking lot shown in Figure 4a. During the evacuation process, pedestrians will reach the parking lot and drive their vehicles to join the evacuation traffic flows.

Modeling of the Conflicts in the Mixed Traffic Flows

During the evacuation process, some conflicts may occur between vehicles, between pedestrians, or between vehicles and pedestrians. In practice, one can use an intersection traffic control device or employ traffic enforcement to regulate the sequence and time for each movement. However, explicitly optimizing the signal phases and timings as well as the mixed-flow distributions will render the problem computationally intractable. In this study, the coordination of these conflicts at each intersection is implicitly modeled by introducing the concept of the conflict group, which is defined as the following:

$C_{i,j}^p$: The j -th pedestrian conflict group, consisting of one or more pedestrian links at intersection i .

$C_{i,j}^v$: The j -th vehicle conflict group, consisting of vehicle connectors at intersection i .

$C_{i,j}$: The j -th conflict group, which is also the union of $C_{i,j}^p$ and $C_{i,j}^v$.

The pedestrian conflict group $C_{i,j}^p$ is composed of pedestrian links representing crosswalks; the vehicle conflict group comprises vehicle connectors representing turning movements at

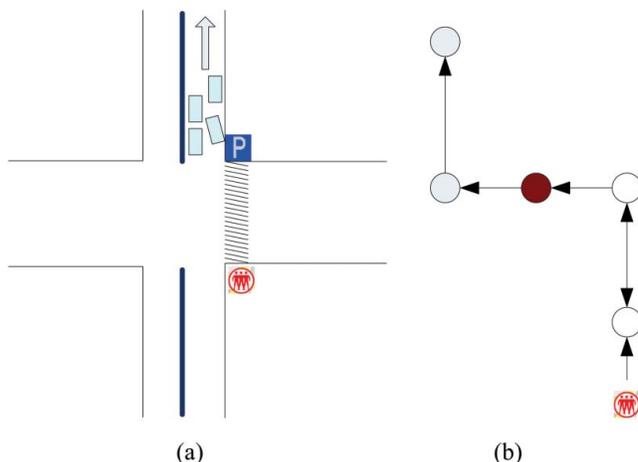


Figure 4 A graphic illustration of the connection between the two networks.

the i -th intersection. The conflict group $C_{i,j}$ is the union of groups $C_{i,j}^p$ and $C_{i,j}^v$. Any element in a valid group, $C_{i,j}$, whether it is a pedestrian link or a vehicle connector, is in conflict with any other elements in the same group. The cardinality of a group is defined as the number of elements within it, including both the pedestrian links and vehicle connectors.

Prior to formulating the optimization problem, the complete set of conflict groups for each intersection needs to be determined first. In theory, the cardinality of a conflict group can be from 2 to the maximum number of possible movements at an intersection. However, in practice, the maximum number of movements that are in conflict with each other seldom exceeds four. Assuming that there is a total of m pedestrian links and vehicle connectors at an intersection, one can use the following steps to find a complete set of conflict groups:

1. Initialize $n = 2$; for every pair of links, connectors, or link/connector at the intersection, determine whether they are in conflict; if yes, then create a conflict group containing the two.
2. For each conflict group with cardinality n , determine whether there is any other link or connector in conflict with all the elements in the conflict group; if yes, create another conflict group with cardinality $n + 1$.
3. If no more conflict groups can be created, go to step 4; otherwise, $n = n + 1$, go to step 2.
4. For every pair of conflict groups G_1 and G_2 that has been created, if $G_1 \subset G_2$, delete G_1 ; if $G_2 \subset G_1$, delete G_2 .

Table 1 gives an example of the complete set of the conflict groups for the intersection in Figure 5. The purpose of listing the conflict groups is to reflect the flow constraints caused by these conflicts. Note that the conflict groups with cardinality less than three are not included, to avoid redundant constraints in our formulation. For example, $\{(1,2) (5,4) (7,8)\}$ is a conflict group with cardinality 3 and it includes the conflict group $\{(1,2) (5,4)\}$ with cardinality 2. If we include the latter in our formulation, it would be satisfied by $\frac{f_{(1,2)}}{C_{(1,2)}} + \frac{f_{(5,4)}}{C_{(5,4)}} \leq 1$, which is redundant because it has already been satisfied by $\frac{f_{(1,2)}}{C_{(1,2)}} + \frac{f_{(5,4)}}{C_{(5,4)}} + \frac{f_{(7,8)}}{C_{(7,8)}} \leq 1$.

All movements in a conflict group compete for the green time. Since the number of movements per intersection is always limited, the complexity of using the proposed algorithm to generate the complete sets for a network with m intersections is $o(m)$.

NETWORK-WIDE MIXED FLOW OPTIMIZATION FORMULATIONS

To maximize the evacuation flows during the response period, this study employs the maximum flow notion to formulate the system-optimum flow distribution for the mixed traffic flows. The decision variables and given variables used in the formulations are listed here.

Table 1 The complete set of the conflict groups.

C (Cardinality = 4)		C (Cardinality = 3)	
C^v	C^p	C^v	C^p
(1,2) (3,8) (5,6) (7,2)		(1,2) (5,4)	(a,d)
(1,2) (3,8) (5,4) (7,8)		(1,2) (5,4) (7,8)	
(1,2) (3,8) (7,2)	(b, c)	(1,2) (7,2)	(b,c)
(1,2) (5,2) (7,2)	(b, c)	(1,2) (7,8) (3,8)	
(1,8) (3,8) (7,8)	(a, b)	(1,8)	(a,d) (a,b)
(3,4) (5,4) (7,4)	(a, d)	(1,6)	(a,d) (c,d)
		(1,6) (3,4) (5,6)	
		(1,6) (3,4) (7,2)	
		(1,6) (3,6) (5,6)	
		(1,6) (7,8)	(c,d)
		(3,4) (5,4) (7,8)	
		(3,4) (7,2)	(b,c)
		(3,4) (5,6) (7,2)	
		(3,6)	(b,c) (c,d)
		(3,8) (5,6) (7,2)	
		(3,8) (5,6)	(a,b)
		(3,8) (5,4) (7,4)	
		(3,8) (5,4) (7,8)	
		(3,8) (5,4)	(a,b)
		(3,8) (7,8)	(a,b)
		(3,8) (7,2)	(b,c)
		(3,8)	(a,b) (b,c)
		(5,6) (7,2)	(c,d)
		(5,2) (7,2)	(b,c)
		(5,2)	(a,b) (b,c)
		(5,4) (7,4)	(a,d)
		(5,4)	(a,b) (a,d)
		(5,4) (7,8)	(a,b)
		(7,4)	(a,d) (c,d)
		(7,2)	(b,c) (c,d)

Given variables:

- $\Gamma^v(i)$: The set of vehicle nodes directed to a node.
- $\Gamma^{v+}(i)$: The set of vehicle nodes directed from a node i .
- $\Gamma^p(i)$: The set of pedestrian nodes directed to a node.
- $\Gamma^{p+}(i)$: The set of pedestrian nodes directed from a node i .
- $S_{i,j}^v$: The saturation flow rate of the vehicle link/connector (i,j) .
- $S_{i,j}^p$: The saturation flow rate of the pedestrian link (i,j) .
- E^v : The set of vehicle links in the vehicle network.
- E^p : The set of pedestrian links in the pedestrian network.
- O^v : The set of origin nodes for vehicles.
- O^p : The set of origin nodes for pedestrians.
- D^v : The set of destination nodes for vehicles.
- D^p : The set of destination nodes for pedestrians.
- λ_i : The carpooling rate for the connection node i .
- U_i : The destination capacity for the vehicle destination node i
- $C_{i,j}^p$: The j -th pedestrian conflict group consisting of conflicting pedestrian edges at intersection i .
- $C_{i,j}^v$: The j -th vehicle conflict group consisting of conflicting vehicle connectors at intersection i .

We can then formulate the entire network-wide mixed flow optimization problem as follows:

$$\text{Maximize : } \sum_{i \in O^p} \sum_{j \in \Gamma^{p+}(i)} x_{i,j}^p \quad (1)$$

Subject to:

$$x_{i,j}^v \leq S_{i,j}^v, \forall (i,j) \in E^v \quad (2)$$

$$x_{i,j}^p + x_{j,i}^p \leq S_{i,j}^p, \forall (i,j) \in E^p \quad (3)$$

$$\sum_j x_{i,j}^v - \sum_j x_{j,i}^v = 0, \forall i \notin (O^v \cup D^v) \quad (4)$$

$$\sum_j x_{i,j}^p - \sum_j x_{j,i}^p = 0, \forall i \notin (O^p \cup D^p) \quad (5)$$

Decision variables:

- $x_{i,j}^v$: The rate of vehicle flows that moves from node i to node j in the vehicle network.
- $x_{i,j}^p$: The rate of pedestrian flows that moves from node i to node j in the pedestrian network.

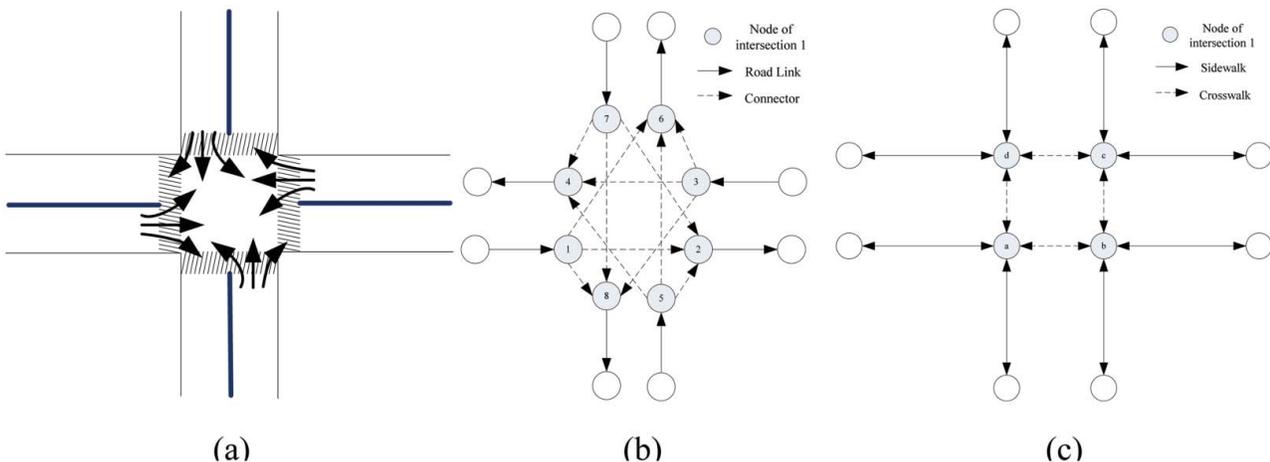


Figure 5 Examples of the network representation of an intersection.

$$\sum_j x_{i,j}^v = \frac{\sum_j x_{j,i}^p}{\lambda_i}, \forall i \in O^v \cup D^p \quad (6)$$

$$\sum_{(i,j) \in C_{k,l}^v} \frac{x_{i,j}^v}{S_{i,j}^v} + \sum_{(i,j) \in C_{k,l}^p} \frac{x_{i,j}^p + x_{j,i}^p}{S_{i,j}^p} \leq 1, \forall k \quad (7)$$

$$\sum_{i \in D^v} \sum_{j \in \Gamma^v(i)} x_{j,i}^v \leq U_i \quad (8)$$

$$x_{i,j}^v \geq 0, \forall (i,j) \in E^v \quad (9)$$

$$x_{i,j}^p \geq 0, \forall (i,j) \in E^p \quad (10)$$

In the preceding model, the objective is to evacuate as many evacuees as possible during a given time window, which is also the total number of evacuees arriving at the final destinations. However, since this is a mixed-flow network, one can only acquire the total vehicle flow reaching their final destinations. The objective function seeks to maximize the total pedestrian flow that can be loaded into the network. Constraints 2 and 3 give the upper bound of the vehicle and pedestrian flows, respectively. Since any pedestrian link (i,j) is bidirectional, the sum of the flows from both directions should not exceed the total capacity of that link. Constraints 4 and 5 are the flow conservation functions for the intermediate vehicle and pedestrian links, respectively. Constraint 6 converts the pedestrian flow to the vehicle flow. For different connection locations (i.e., parking garages or transit stops), the carpooling rate can be varied with the vehicle type. Constraint 7 deals with the conflicting movements. These two items $\frac{x_{i,j}^v}{S_{i,j}^v}$ and $\frac{x_{i,j}^p + x_{j,i}^p}{S_{i,j}^p}$ can be interpreted as the ratio of

time that the vehicle movement or the pedestrian crossing is given the right of way to cross the street, which is similar to the concept of using green time ratios for movement control. Since at a given time any two vehicle movements or pedestrian links in a conflict group cannot coexist, the sum of these ratios should not exceed 1. Constraint 8 ensures the flow entering a vehicle destination (e.g., shelters) will not exceed its capacity. Constraints 9 and 10 are the nonnegativity constraints for the mixed flows.

Note that the vehicles in the preceding formulations need to be generated from a connection node that is also the destination for pedestrians. The reason to convert vehicles to pedestrians is that the main objective is to evacuate most evacuees rather than vehicles. If there is a known vehicle source where the rate of its loading into the network is known, the mean carpooling rate needs to be obtained and a pseudo pedestrian source node can be created to connect to the vehicle source node in order to fit in our formulations. It should be mentioned that all links in the preceding formulations are assumed to carry only one-directional flow during the evacuation.

ILLUSTRATIVE EXAMPLE AND SYSTEM APPLICATIONS

This section presents an illustrative case with the proposed model, using the M&T Bank Stadium in downtown Baltimore, MD. It is assumed to have 20,000 individuals who need to evacuate the stadium. The satellite image and the parking lot layout around the M&T stadium are depicted in Figure 6 and the network layout is depicted in Figure 7.

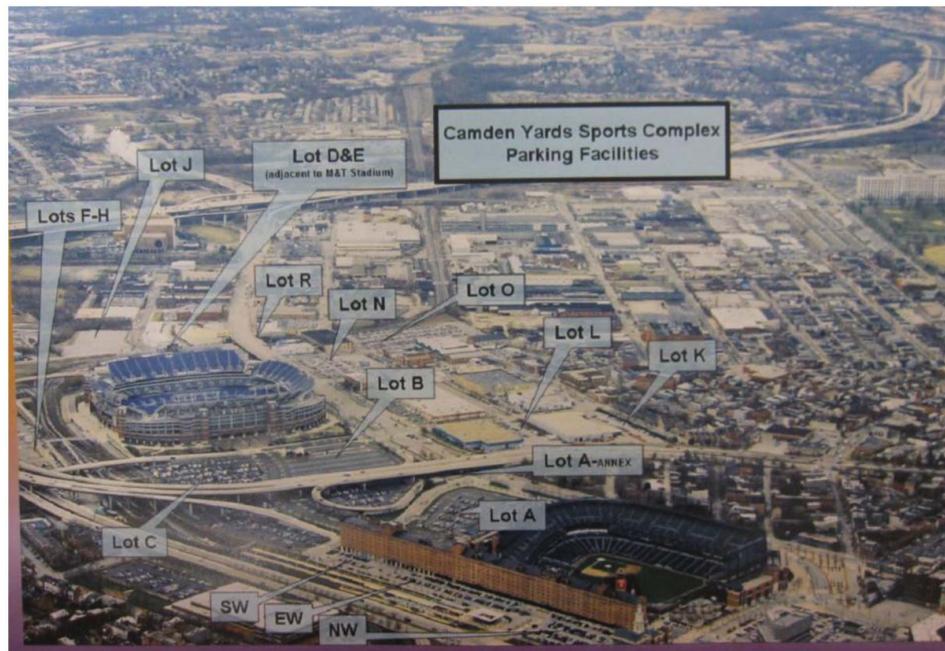


Figure 6 Layout of the M&T Bank Stadium in Baltimore city.

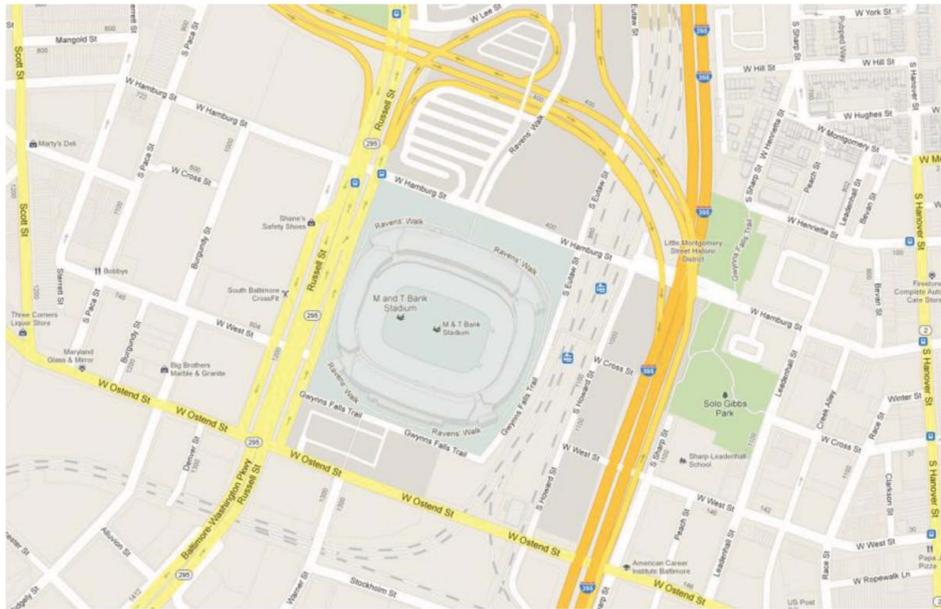


Figure 7 Road layouts in the stadium area. (Map data ©2013 Google.) © Google. Reproduced by permission of Google. Permission to reuse must be obtained from the rightsholder.

The following input information is created based on the target area for model implementation

- Pedestrian network layout (see Figure 8).
- Locations of parking areas and pick-up points, and their corresponding capacities (see Figure 8 and Table 2).
- Total number of evacuees, initial positions, and assigned destinations (see Table 2).

- Vehicle network layout (see Figure 9).
- Vehicle destinations (see Figure 9).
- The complete sets of conflicting movements (see Table 3).

The layout of the pedestrian network is shown in Figure 8. It is assumed that pedestrians can move toward either direction on sidewalks or crosswalks. Nodes 1 to 49 are intermediate pedestrian nodes. Node 1000 is a pedestrian source node that represents the stadium; the sink nodes from 101 to 105 are parking lots; and the sink node 106 is the pickup point for those without access to passenger cars. The solid arrow lines are sidewalks and the dashed arrow lines are crosswalks.

The demand of each pedestrian destination is estimated with the capacity of the available parking lots and is listed in Table 1. For the parking areas, we assume that the pedestrian flows will be generated to vehicle flows based on the car-pooling rate and the average accessing delay. For those transit stops, this study assumes that the buses are available upon the arrivals of the evacuees. Once the bus is fully loaded with evacuees, it will enter the vehicle network.

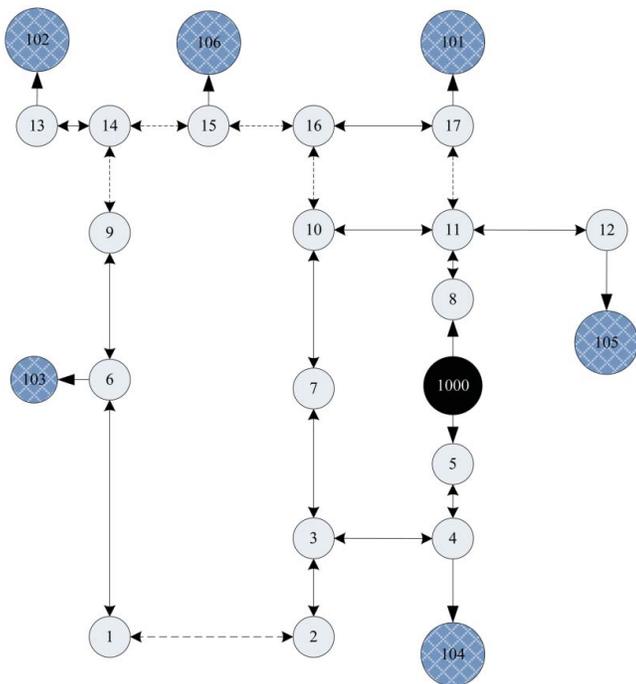


Figure 8 Representation of the pedestrian network.

Table 2 Pedestrian demand and parking capacity.

Destination	Estimated demand (number of individuals)	Estimated parking capacity (vehicles)
101	6800	4000
102	1700	1000
103	3400	2000
104	850	500
105	4250	2500
106	3000	Transit stop

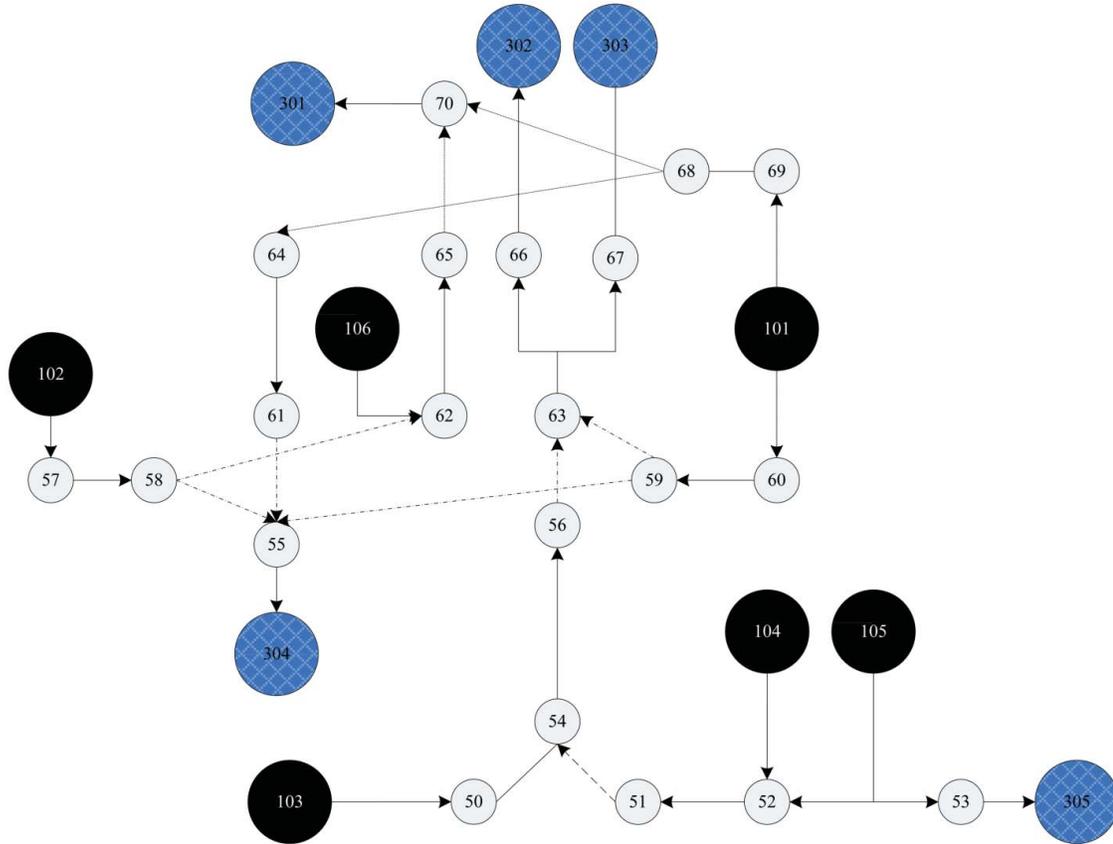


Figure 9 Representation of the vehicle network.

The vehicle network is presented in Figure 9. Those arrows indicate the possible flow directions between nodes. Nodes 50 to 70 are ordinary vehicle nodes, whereas nodes 101 to 105 are vehicle source nodes, which are also the pedestrian sink nodes. Sink nodes 301, 302, 303, 304, and 305 can be viewed as the destinations for vehicles intended to get onto I83, US40, I395 South, MD295 South, and MD2, respectively. The solid lines represent the vehicle roads and the other lines denote the connectors or the turning movements. The dashed lines of the same type represent turning movements at the same intersection.

There are three intersections in Figure 9 where conflicts may occur, and the conflict sets are listed in Table 3.

Table 3 The complete set of conflict groups.

Intersection	Conflict group	Vehicle connectors	Pedestrian crosswalks
1	1.1	(50,54), (51,54)	(1,2)
	2	(56,63), (59,63)	(15,16)
		(56,63), (59,55)	
	2.3	(58,55), (61,55), (59,55)	
	2.4	(58,62), (61,55)	(14,15)
3	2.5	(59,63)	(16,10)
	3.1	(68,70), (65,70)	
	3.2	(68,64), (65,70)	

Since all formulations in the model are linear, one can solve the model with the popular linear solver CPLEX. The available output data for evacuation planning are:

- Optimized flows on each pedestrian walkway.
- Optimized flows on each vehicle roadway.
- Total pedestrian throughput towards different destinations over time.

In order to evaluate the result generated by our model that accounts for massive vehicle–pedestrian conflicts, we carried out the following experiments:

1. Entered the optimized flows and signal plan estimated from these flows into the commercial simulation software, and compare the output measure of effectiveness such as link flows, time-dependent throughput and clearance time.
2. Obtained the optimal solution without considering the conflict constraints in the formulation, and conducted the similar comparison as in (1).

To evaluate whether our model is capable of realistically representing interactions between flow and roadway capacity, we performed a simulation of the optimized evacuation plan. The pedestrian and vehicle flow patterns estimated from the

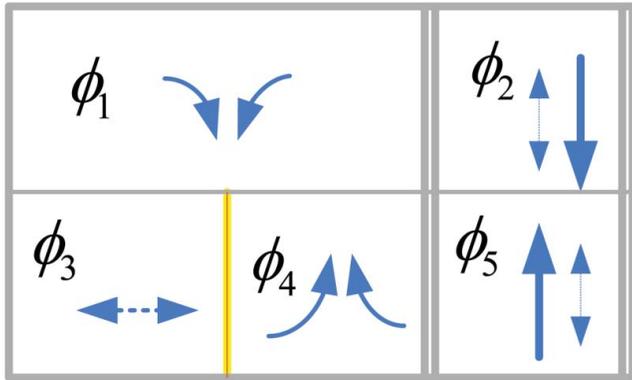


Figure 10 A predefined signal phase for Russell St at MD295.

procedures are entered into the micro-simulation software Transmodeler 2.5 to generate the target output. Although we did not optimize the signal timing explicitly, one can employ a predefined phase and cycle length, and then assign the green split of each phase based on the flow ratios from the optimally assigned results. The detailed procedure for designing signal green splits from the movement flows can be found in the references such as Roess, Prassas, and McShane (2004). In this study, we employed the phase plan, including the pedestrian walking phase (phase 2, 3, and 5) in Figure 10, and the predefined cycle length of 200 seconds for intersection of Russell St at MD295. The green splits for each cycle are estimated from the optimization vehicle and pedestrian flows.

In the illustrative example, we performed the following two experiments:

- Solving the optimized evacuation flow distribution with our proposed model.
- Simulating the optimized plan with a microscopic simulation program.

The comparison between the optimized and simulated pedestrian flows on the critical crosswalks at the intersections are listed in Table 4, and the comparison between the optimized and simulated vehicle flows on the critical roads are listed in Table 5. It can be found that the results are quite close, indicating a good match of our model in terms replicating the traffic flow conditions.

Table 4 Pedestrian flows on the critical crosswalks.

Intersection	Crosswalk	Hourly flow (number of pedestrians/hour)	
		Optimized	Simulated
Russell St at MD295	(15,16)	1782	1721
	(14,15)	1634	1670
	(9,14)	0	0
	(10,16)	1873	1782
Ostend St at MD295	(1,2)	832	789
M&T Stadium at Hamburger St	(11,17)	2850	2711

Table 5 Vehicle flows on the critical roads.

Road name	Vehicle link	Hourly flow (number of vehicles/hour)	
		Optimized	Simulated
MD295 North	(62,65)	596	581
	(70,301)	1174	1123
MD295 South	(64,61)	654	601
	(55,304)	1124	1089
N MLK Blvd	(66,302)	878	821
S MLK Blvd	(67,303)	859	860
W Lee St	(69,68)	1209	1101
Hamburg St West	(60,59)	1011	992
Hamburg St East	(57,58)	1012	1003
Ostend St East	(103,50)	597	530
Ostend St West	(52,51)	604	593
	(53,305)	1200	1187

The throughput and clearance time comparison is plotted in Figure 11. It takes about 160 minutes for the simulation and about 140 minutes for the optimization process to complete the evacuation. The slight difference in the clearance time is probably due to the initial warming period for the network to become saturated from its initial state. This numerical comparison clearly indicates that our proposed model has reasonably captured the interactions between the mixed flows and the available roadway capacity, and all optimized results are feasible and realistic for implementation.

Note that most existing evacuation models deal with pedestrians and vehicles independently, thus, assigning their flows in a separate network and not fully considering the complex interactions and conflicts between them. To demonstrate the needs of incorporating such conflicts into an evacuation model, we have relaxed the conflict constraints in our model and conducted the following two experiments:

- Solving the optimization problem without the conflicting constraint 7, which is identical to most existing methods for evacuation operations; and
- Running a micro-simulation based on the optimization plan from step (a).

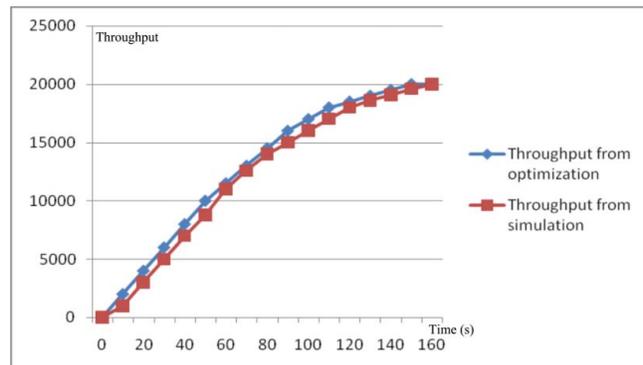


Figure 11 Comparisons between the optimized and simulated throughput.

Table 6 Pedestrian flows on the critical crosswalks.

Intersection	Crosswalk	Hourly flow (number of pedestrians/hour)	
		Optimized	Simulated
Russell St at MD295	(15,16)	3700	1672
	(14,15)	3200	1445
	(9,14)	0	0
Ostend St at MD295	(10,16)	3200	1554
	(1,2)	1600	651
M&T Stadium at Hamburger St	(11,17)	3300	3276

The comparison between the optimized and simulated pedestrian flows without considering their conflicts is listed in Table 6, and the comparison between the optimized and simulated vehicle flows on critical intersection crosswalks is listed in Table 7. It can be observed that the optimized flows for both the pedestrians and vehicles are largely overestimated without considering the potential conflicts specified in the formulations.

Note that there exists significant difference in the flow rates on those crosswalks and at critical intersections where the conflicts are most likely to occur. For example, on the east–west crosswalk link (15, 16) and (14, 15), the flow rates are more than doubly overestimated if done without considering the conflict from the north–south vehicle traffic. Similarly, the MD 295 South evacuation flows on link (55, 304) are also far overestimated if done without considering the crossing evacuees. For other links without pedestrian–vehicle conflicts, such as the north–south crosswalk (11, 17) from the stadium area to one nearby parking lot F and the Ostend Street West traffic on link (53, 305), the resulting flow distributions are quite close.

The throughput and clearance time comparisons are plotted in Figure 12. It takes about 170 minutes for the simulation to clear all the traffic, while the estimation from the non-conflict-optimization model needs only 100 minutes. The significant difference clearly indicates that neglecting the interactions and

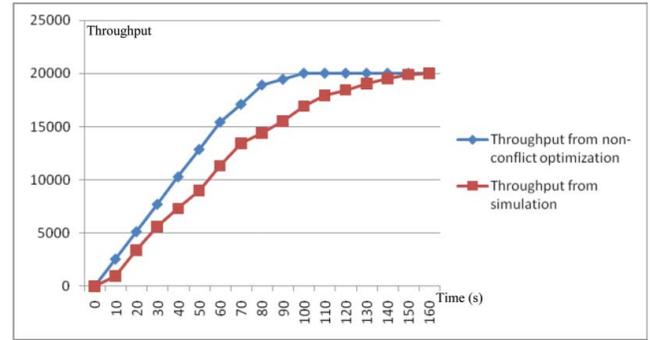


Figure 12 Comparisons between the non-conflict-optimized and simulated throughputs.

conflicts between vehicles and pedestrian flows could significantly overestimate the evacuation flow rate for both pedestrians and vehicles, especially at links where conflicts exist. Thus, one can conclude that without considering the vehicle–pedestrian interactions in our formulation, the optimized evacuation plan for guiding the evacuees will unrealistically underestimate the required clearance time and cannot be implemented in the actual evacuation process.

Overall, the preceding experiments clearly indicate the following conclusions:

1. Our proposed model is capable of capturing the consequence caused by the complex interactions between the pedestrian and vehicle flows, and the optimized results are consistent with those generated by the simulation software under the same condition.
2. The flow constraints of the conflict sets are essential for our model’s representation of the actual flow conflict at critical intersections. Neglecting such constraints could generate infeasible solutions and significantly overestimate the evacuation flow rate for both pedestrians and vehicles.

Note that the preceding optimization model for guiding the distribution of pedestrian–vehicle mixed flows during an emergency evacuation is a principal module of the Baltimore Emergency Evacuation System (BEES) that has been used by

Table 7 Vehicle flows on the critical roads.

Road name	Vehicle link	Hourly flow (number of vehicles/hour)	
		Optimized	Simulated
MD295 North	(62,65)	810	632
	(70,301)	1560	1031
MD295 South	(64,61)	750	521
	(55,304)	2450	1314
N MLK Blvd	(66,302)	1250	863
S MLK Blvd	(67,303)	1250	821
W Lee St	(69,68)	1500	1439
Hamburg St West	(60,59)	1800	972
Hamburg St East	(57,58)	1600	984
Ostend St East	(103,50)	800	531
Ostend St West	(52,51)	800	549
	(53,305)	1200	1134

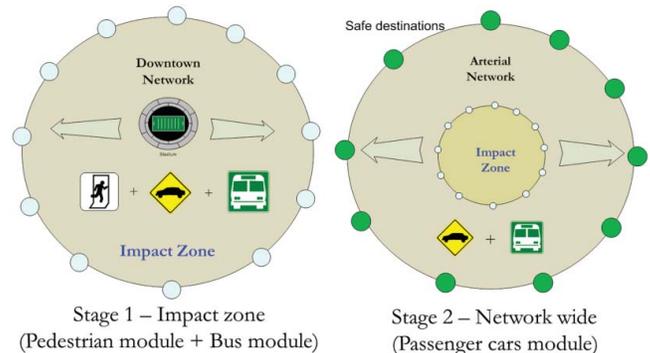


Figure 13 A two-stage evacuation process for Baltimore downtown.

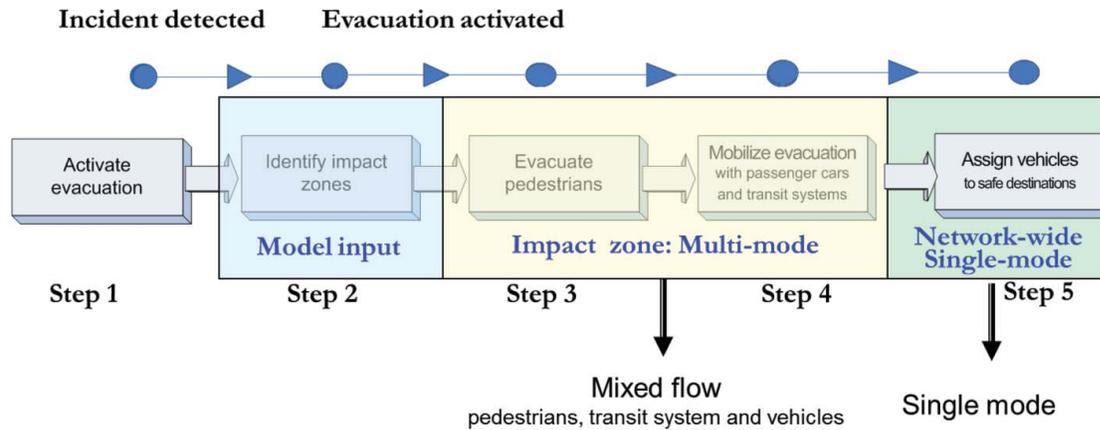


Figure 14 The multimodal evacuation process.

the Baltimore Metropolitan Council for both planning and potential real-time operations.

BEES, designed for any potential emergency in the Baltimore Inner Harbor, divides the entire Baltimore City within its I695 Beltway into impact and evacuation zones (see Figure 13), and take five steps to exercise the entire evacuation process (see Figure 14). Step 2 of the evacuation process is first to estimate the boundaries of the evacuation zones based on nature of the emergency events, and then to approximate the number of evacuees with and without access to passenger cars. Since the evacuation traffic within the impact zone would include evacuees to parking garages and becoming vehicle flows and those guided to transit stations for evacuation, the network within the impact zone at the stage-1 operations would inevitably be congested by pedestrian-vehicle mixed flows. To prevent formation of excessive congestion in an evacuation process caused by such mixed traffic flows, the model presented in this article will be used by BEES at step 3 and step 4 to:

- Compute the optimal number of evacuees to be guided to each available path between impacted zones and garages (or transit stations).
- Generate the optimal distribution of path flows to guide (or control) vehicles from both garages and bus stations to exit control points in the stage-2 network evacuation.
- Optimize the signal plan at each critical intersection within the evacuation network to maximize the system's total throughput.

With the preceding vital information from the proposed model, the Baltimore evacuation system can then proceed to execute the stage-2, single-modal operations because all evacuees at this stage will be in either passenger cars or transit vehicles. Notably, the subject of single-modal (but not for multimodal mixed flows) network evacuation has been extensively investigated by transportation researchers with various methods such as system-optimum assignment or max-flow models. The model presented in this article, designed to

tackle the most challenging issue of optimizing the mixed flow distribution in an evacuation network, thus constitutes the core of BEES. Furthermore, the developed mixed flow optimization model can be used for both planning and real-time applications as long as a sufficiently powerful computer is available. An online version of BEES for real-time operations can be found from the website <http://attap.umd.edu/umdtest.htm>.

SUMMARY AND CONCLUSION

This article has presented an enhanced model for optimizing the pedestrian and vehicle movements within the evacuation zone that considers the conflicts between congested vehicles and pedestrian flows. The proposed model has used the common node-link concept to represent the pedestrian and vehicle networks, but used connectors to represent turning movements at intersections. The connection node is designed to convert the pedestrian flows to vehicle flows. Based on the distribution of pickup points for evacuees using transit systems and parking garages for those having access to vehicles, the proposed model is capable of producing a set of effective routing strategies for guiding pedestrians and vehicles and for signal timing design. A set of constraints representing conflicts is employed in the model to capture the interactions in the mixed flows during the evacuation process.

An illustrative example presented in the article seems to indicate that the proposed model offers some promising properties to address the complex interactions between vehicle and pedestrian flows within an evacuation zone. Results of simulation experiments also indicate that the failure to account for the conflict movement will yield unrealistic evacuation plans such as underestimated evacuation clearance time.

Despite the promising results for this study, we fully recognize that much remains to be done in developing an efficient and operational evacuation system that can guide evacuees effectively to the most proper mode and direct

various types of traffic flows to the most efficient routes. Our ongoing research along this line is to explore the dynamic nature of the evacuation process and to develop a dynamic model to generate the routing strategies, based on the time-varying demand. Optimized signal designs along with pedestrian phases under emergencies scenarios are also our ongoing research subjects.

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