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Development of a Multimodal Microsimulation-Based Evacuation Model

Jahedul Alam[1], Muhammad Ahsanul Habib[1,2], and Uday Venkatadri[3]

Abstract

This study presents a multimodal evacuation microsimulation modeling framework. The paper first determines optimum marshal point locations and transit routes, then examines network conditions through traffic microsimulation of a mass evacuation of the Halifax Peninsula, Canada. The proposed optimization modeling approach identifies marshal point locations based on transit demand obtained from a Halifax Regional Transport network model. A mixed integer linear programming (MILP) technique is used to formulate the marshal point location and transit route choice problem. The study proposes a novel approach to solving the MILP problem, using the “branch and cut” algorithm, which demonstrates superiority in computation time and production of quality solutions. The optimization model determines 135 marshal points and 12 transit routes to evacuate approximately 8,400 transit-dependent individuals. Transit demand and marshal point locations are found to be concentrated at the core of the peninsula. The microsimulation modeling takes a dynamic traffic assignment-based approach. The simulation model predicts that it takes 22 h to evacuate all auto users but just 7 h for the transit-dependent population. The study reveals that the transit system has excess capacity to assist evacuees who switch from auto and other modes. Local traffic congestion prolongs the evacuation of a few densely-populated zones in the downtown core of the peninsula. The findings of this research help policy-makers understand the impacts of marshal point locations and transit route choice decisions on multimodal evacuation performance, and provide insights into emergency planning of multimodal evacuations under "mode switch" and transit-based evacuation scenarios.

Multimodal evacuation is critical to evacuate all citizens, including transit dependent populations, from an area affected by a natural or manmade disaster. It is difficult to observe disaster-related evacuation events and consequently many coastal cities lack comprehensive multimodal models for evacuation planning (*1*). In addition, existing evacuation plans primarily focus on auto-based evacuation (*2*). However, it is also important to utilize transit systems during an evacuation to meet the transportation needs of the transit-dependent group. A special committee of the Transportation Research Board produced a report entitled “The Role of Transit in Emergency Evacuation” explaining how transit can play a critical role in emergency evacuation (*3*). The committee reviewed the literature and examined emergency response and evacuation plans of the 38 largest urban areas in the United States. The study asserted that it is a major concern that not all modes of transportation, including transit, were included in evacuation plans. Notably, the New Orleans evacuation is an example of the importance of effective evacuation planning for transit-dependent groups. In 2005, Hurricane Katrina hit New Orleans, and 36% of the population did not evacuate for the sole reason of not having a car (*4*). Another example occurred in 2005 during Hurricane Rita, when there were limited plans to evacuate the transit-dependent population along the Gulf Coast of the U.S. In this scenario, public transportation and school buses were not readily available, and the city declared ten pick-up locations in an ad-hoc fashion having no prior evaluation of the needs for transit demand (*5*). Therefore, to evacuate the whole population of an area adequately, the transportation needs of transit-dependent groups should

[1]Department of Civil and Resource Engineering, Dalhousie University, Halifax, NS, Canada
[2]School of Planning, Dalhousie University, Halifax, NS, Canada
[3]Department of Industrial Engineering, Dalhousie University, Halifax, NS, Canada

Corresponding Author:
Address correspondence to Muhammad Ahsanul Habib: ahsan.habib@dal.ca

be taken into consideration. Although the elevated risk experienced by transit-dependent populations are well identified and realized (*2*, *4–6*), deficiencies still exist in public transportation planning for emergency evacuation (*7*, *8*). In the absence of multimodal transportation modeling, transit systems may not be able to support emergency mass evacuations (*5*). Accordingly, transit agencies need to establish pick-up locations and transit routes proactively and develop plans for resource allocation. In summary, there is a limited number of studies on transit evacuation planning, and clear gaps exist in the literature. Unaddressed topics include the determination of emergency pick-up locations, also known as "marshal point" locations, transit evacuation routes and the testing of network conditions with multimodal evacuation plans. This study addresses the deficiency in the existing traffic evacuation modeling by incorporating the planning decision components (e.g., marshal point location and transit route choice decisions) within the microsimulation modeling platform to evaluate a multimodal evacuation plan. The multimodal evacuation microsimulation model to be developed in this study evaluates the impacts of strategic planning decisions on overall evacuation performance.

Therefore, the objectives of this study are: (i) to develop an optimization model to determine marshal point locations and transit routes while addressing evacuation transit demand, and (ii) to incorporate marshal point locations and transit route choice decisions within a microsimulation model for testing and evaluation of a multimodal evacuation operation. A mixed integer linear programming (MILP) technique is used to formulate the marshal point location and transit route choice problem. A novel solution approach using the "branch and cut" algorithm is implemented to determine marshal point locations and transit routes. The study demonstrates the effects of the MILP branch and cut strategy on computation time. The method improves runtime and quality of solutions compared with traditional methods. The microsimulation model implements a dynamic traffic assignment process which resembles actual dynamic traffic diffusion in the network. The advantage of dynamic traffic assignment is that it captures the routing policies of drivers and traffic congestion propagation simultaneously within the proposed microsimulation model.

Literature Review

Evacuation research has recently attracted interest and has evolved a focus on traffic operation management to evaluate hypothetical evacuation scenarios during an emergency and to develop evacuation plans and policy directions. For example, Urbina and Wolshon (*9*) studied methods to improve hurricane evacuation. The study suggested that contra flow on limited access evacuation routes can potentially maximize highway capacity. Coordinated evacuation, including staged evacuation (*10*), is also an efficient operational strategy to improve network performance under evacuation conditions. The outcomes of these studies are evaluated using traffic simulation models, which have recently emerged as powerful tools for forecasting traffic flows. Specifically, they are advantageous for developing, comparing, and contrasting evacuation plans under different emergency conditions and providing insights into traffic congestion and bottlenecks during the evacuation. Many studies have developed traffic simulation models for testing and evaluating different evacuation scenarios. Lieberman and Xin (*11*) developed a macroscopic traffic simulation model to evacuate the Emergency Planning Zone of Indian Point Energy Center located in Buchanan, NY. This simulation model also includes a kinematic flow and a lane assignment model for regulating the traffic flow into the links. The network congestion was initially high; however, after 5 h from the start of the evacuation, the congestion disappeared from the Emergency Planning Zone. Shao et al. (*12*) developed an evacuation model within the VISSIM platform to test an evacuation process for vehicles in the Beijing National Stadium parking lot. This study estimated a clearance time of 27 min for evacuation of all the vehicles in the parking lot. Several evacuation studies (*13*, *14*) have evaluated the strategy of limited access to some facilities and roads, to improve the total evacuation time and the time required to evacuate only the population within the most dangerous areas. Alam et al. (*15*) developed an evacuation traffic microsimulation model, which suggested that it would require 15 h to evacuate the Halifax Peninsula by auto under a flood scenario of 7.9 m water level. Zhang et al. (*16*) developed a mesoscopic traffic simulation model in TRANSIM to test evacuation performance in the Gulf Coast road network under six evacuation scenarios. Table 1 includes a brief review of studies on evacuation modeling and operational strategy. It illustrates the extent of the evacuation studies using different methods including optimization, macro, micro and agent-based simulation modeling. Moreover, it categorizes the studies based on the utilization of different modes in evacuation. Most of these studies focus on auto-based evacuation and do not adequately address the transportation needs of transit-dependent groups in an evacuation. It is now obvious that multimodal traffic simulation modeling is essential to assist transit-dependent citizens and to forecast network conditions reliably by including all potential modes of transportation in an emergency evacuation.

The importance of public transportation in an emergency evacuation has been highlighted since Hurricane Katrina and Hurricane Rita in the U.S. There are limited studies on multimodal or transit-based evacuation

Table 1. A List of Studies on Evacuation Modeling and Improvement Strategy Development

Authors	Methods	Location	Evacuation type	Findings
Chao Li et al. (*17*)	Dynamic traffic assignment within DYNASMART-P	Greater Jackson area as destination for an evacuation of New Orleans	Auto-based	ITS strategy could increase existing highway capacity by 20%. Contraflow plus ITS strategy could increase evacuation capacity from 38% to 79%.
Zou et al. (*18*)	Optimization modeling and microscopic traffic simulation modeling within CORSIM	Ocean City, Maryland	Auto-based	Six new evacuation plans are compared within an emergency evacuation system.
Kaisar and Parr (*19*)	Microscopic traffic simulation modeling within AIMSUN	Evacuation of 22 zones of Baltimore Downtown	Auto-based	Comparison of different evacuation improvement strategies. Contraflow nearly doubles the evacuation capacity.
Church and Sexton (*20*)	Traffic simulation modeling utilizing PARAMICS	Mission Canyon community evacuation because of wildfire	Auto-based	Recommendations such as using only the vehicles that are needed, elevate awareness and educate citizens using the simulation model.
Shao et al. (*12*)	Traffic microsimulation modeling within VISSIM	Beijing National Stadium parking lot	Auto-based	Total clearance time found to be 27 min.
Wang et al. (*21*)	Dynamic traffic assignment within DynusT	17.3 km^2 of Jackson Downtown	Auto-based	3 h required to evacuate 55,281 evacuees. Vehicle message sign is a promising strategy to improve evacuation performance. Contraflow should be carefully used for low demand.
Abdelgawad and Abdulhai (22)	Constraint programming approach	Evacuation of City of Toronto without notice	Transit-based	TTC fleet can evacuate all transit-dependent population in 2 h on average. Four subway lines of the City of Toronto can evacuate all subway riders in 154 min on average.
Sayyady and Eksoglu (*23*)	Mixed integer linear programming and mesoscopic traffic simulation modeling within DYNASMART-P	Evacuation of an area of 1-mile radius without notice	Transit-based	CPLEX found to be time intensive compared to Tabu search and the model offers minimized casualties and evacuation time.
Abdelgawad and Abdulhai (*24*)	Optimal spatio-temporal evacuation modeling and MDTCPD-VRP Mesoscopic traffic simulation modeling within DynusT	City of Toronto	Multimodal	On average auto clearance time is 2 h and net clearance time is 8 h. Average transit-based evacuation time for TTC fleet is on average 2 h.
Naghawi and Wolshon (*25*)	Traffic microsimulation modeling within TRANSIMS	Southeastern Louisiana including Orleans and Jefferson Parishes	Multimodal	Traffic impact analysis for a multimodal evacuation operation with given network loading and transit scenarios.
Yuan and Puchalsky (*26*)	Dynamic user equilibrium assignment within VISUM	Philadelphia, Pennsylvania	Multimodal	Evaluates scenarios regarding changing demand and traffic control conditions and offers insights into planning questions including evacuation time, the effects of transit on evacuation.
Wang et al. (*27*)	Near-field tsunami evacuation modeling using agent-based programming in NetLogo	Seaside, Oregon	Multimodal evacuation by car and on foot	Mainly presents the impacts of variation in evacuees' decision making, including decision making time and mode choice on the coastal community life safety, that is mortality rate.

modeling. Naghawi and Wolshon (*25*) utilized a multimodal evacuation simulation model to evaluate different network loading scenarios for an evacuation. The study considered 17 pick-up locations to evacuate the carless population using six bus corridors. The study concluded that average delays and queue length increased on Interstate evacuation routes. Yang et al. (*28*) developed a microsimulation-based multimodal evacuation model following linear programming to evaluate evacuees' waiting time taking into consideration the cooperative behavior of evacuees. However, the establishment of transit demand-sensitive emergency marshal point locations and evacuation routes for a multimodal evacuation is of paramount importance for better understanding the critical role of transit in an emergency evacuation.

In relation to identifying marshal point locations and transit routes, several studies (*23*, *29*, *30*) utilized optimization techniques, such as local search technique, linear and integer programming, and MILP. A study (*31*) utilized a "branch and price" algorithm in solving an integer programming problem to determine pick-up locations for a small-scale network of 500 m radius and 14 bus stops under a hypothetical evacuation scenario. Kulshrestha et al. (*32*) utilized a "cutting plane" scheme to identify pick-up points for a network of 22 nodes. Kaisar et al. (*33*) developed a linear programming model to determine pick-up locations; however, MILP is more effective, particularly when one or more decision variables are restricted to integer solution space. Another study (*34*) suggested that "branch and bound" is an efficient and reliable algorithm to solve an MILP problem. The disadvantage of these algorithms, however, is that they are slow, unreliable, or both; for example, a cutting plane scheme is unreliable, while the branch and bound algorithm is slow (*34*). Therefore, this study adopts a novel approach which combines "branch and bound" and "cutting plane scheme" to solve the proposed MILP-based optimization problem in relation to the determination of marshal point locations and transit routes. The combined solution approach is named the "branch and cut" algorithm.

The resulting transit marshal points and routes are utilized to develop a multimodal evacuation microsimulation model. The microsimulation model simulates a multimodal evacuation of the Halifax Peninsula and analyzes the evacuation performance in relation to the clearance time, percent hourly evacuation, and traffic congestion. Evacuation performances by auto and transit are compared and evaluated for developing policy recommendations.

Context and Problem Statement

Halifax, the capital of Nova Scotia, is a city situated on a peninsula with narrow roads and limited exit/entry points. There is considerable marine movement through Halifax Harbor, located alongside the peninsula. Furthermore, Halifax is on a hurricane path that has previously caused devastation, as demonstrated in Alam et al. (*15*). In 2003, Hurricane Juan made landfall in the Halifax Regional Municipality, causing eight fatalities. Just five months after Hurricane Juan, a winter storm nicknamed White Juan caused heavy snowfall in Halifax. Therefore, the Halifax Peninsula is a suitable candidate for empirical application of the proposed multimodal evacuation microsimulation model. This study considers a scenario in which residents of the Halifax Peninsula need to evacuate upon a mandatory evacuation order during emergency conditions. In response to the evacuation order, residents who own cars can evacuate themselves, while transit-dependent residents require assistance to move to safe locations. In the case of transit users, when the evacuation order is released, it is assumed that transit-dependent people from different zones (traffic analysis zones in this case) will gather at specified pick-up locations. Transit buses will be allocated to pick up evacuees waiting at pick-up locations and transport them to the shelters. The current Halifax evacuation plan considers almost all existing bus stops as pick-up locations. Therefore, marshal point locations and transit evacuation routes need to be established prior to commencing multimodal evacuation. This study develops an optimization model to determine the marshal point locations and transit routes to evacuate the transit-dependent population within a minimum time. The study does not consider the delays experienced by evacuees or the time it takes them to arrive at the marshal point locations. The planning decisions regarding marshal point locations and transit route choice are then incorporated into the traffic microsimulation model to test the multimodal evacuation plan.

Model Formulation Approach for Optimization

To ascertain emergency transit marshal point locations and routes, this study uses a two-phase method to determine evacuation routes: (i) determination of marshal point locations, and (ii) determination of bus routes. The proposed optimization model determines the location of marshal points based on transit demand obtained from a Halifax Regional Transport network model (*35*) and minimizes total walking distance from zone to marshal points. Data for walking distance from zones, alternatively known as traffic analysis zones (TAZs), to bus stops is obtained from the 2012 Halifax Geodatabase. Buses are allocated to the transit routes following the Halifax transit schedule within the microsimulation model. A bus can serve multiple marshal points until it has reached its capacity. This study uses multiple depots to dispatch buses. It is assumed that all buses are gathered in the depots before dispatch. All transit routes start from any of the depots and are extended to the shelters. As a transit route contains multiple marshal points, a bus can keep serving evacuees until it reaches its capacity. Transit evacuation routes are chosen such that all marshal points are contained within the routes and total travel time is minimized.

Model Formulation for Determination of Marshal Point Location

Let $z \in Z$ denote a TAZ, where $Z = \{1, 2, 3 \ldots .N\}$ is the set of all TAZs, and let $s \in S$ represent a bus stop, where $S = \{1, 2, 3 \ldots .N\}$ is the set of all bus stops. Each stop has a capacity of q_s. A binary variable y_{zs} is used to make the marshal point location choice decision, where it takes 1 if a bus stop s is selected as the marshal point for zone z and 0 otherwise. Bus stops located within a threshold walking distance $d_{\text{threshold}}$ of a candidate TAZ are considered for evaluation through the optimization process for the selection of marshal points of that TAZ. A variable x_{zs} is used to determine the share of total demand at TAZ z that approaches bus stop s if s is selected as the marshal point for z. The transit demand of TAZ z is denoted D_z. Following the descriptions and notations, the optimization model of marshal point location choice decision is developed such that overall walking distance is minimized during an evacuation. The model formulation and the solution approach are described as follows:
Objectives:

$$\text{Minimize} \sum_{z \in Z} \sum_{s \in S} y_{zs}{}^{*} d_{zs} \tag{1}$$

Subjected to:

i. $y_{zs}{}^{*} d_{zs} \leqslant d_{\text{threshold}}, \forall z, s$
ii. $\sum_{s \in S} x_{zs} \geqslant D_z, \forall z$
iii. $\sum_{z \in Z} x_{zs} \leqslant q_s, \forall s$
iv. $x_{zs} \leqslant y_{zs}{}^{*} M, \forall z, s$
v. $x_{zs} \geqslant 0, \forall z, s$
vi. $y_{zs} = \{0, 1\}$

Constraint (i) ensures that walking distance from the centroid of any TAZ to a marshal point does not exceed a maximum threshold, constraint (ii) requires that all residents in a zone must evacuate, constraint (iii) ensures that the capacity of a marshal point is respected, constraint (iv) ensures that no flow can be assigned to a stop if it is not selected as a marshal point, where M is a large number, and constraint (v) and constraint (vi) describe decision variables as positive integer and binary.

The proposed "branch and cut" algorithm is implemented within the Mathematical Programming Language (MPL) Gurobi solver platform. This study utilizes default "branch and cut" in MPL with all the conservative Gurobi cuts enabled. The cuts include clique, cover, generalized upper bound (GUB), mixed integer rounding (MIR), mod-K, and network cuts, implied bound cuts, flow cover and path cuts, mixed integer program (MIP) separation and sub-MIP cuts, and zero-half cuts. Advantages of the proposed solution approach include that it (i) improves constraint propagation and reduces the search space, and (ii) reduces number of nodes by improving relaxation bounds. This optimization model provides marshal point locations which are further used for the bus route optimization model in the next section.

Model Formulation for Bus Route Determination

The marshal point locations obtained from the previous section identify nodes of the network that will become the skeletal emergency transit network. The bus routes are identified from the existing set of bus routes. This study uses existing bus routes because of the network familiarity of transit users, drivers, and control room operators being an important factor for an efficient evacuation. The existing set of bus routes was obtained from the 2012 Halifax Geodatabase. Marshal points contained within each route in the existing set are spatially identified. Marshal points contained in more than one transit route are separately identified. The scheduled travel time is obtained from Halifax Transit. If a set of transit routes is R, then the existing set of routes can be expressed as:

$$R = \{r_1, r_2, r_3, r_4 \ldots\ldots\ldots\ldots r_n\} \tag{2}$$

where r_i is the route identity.

If the set of marshal points identified is M, and the set of travel time for routes is T_R, then these two sets are presented as below:

$$M = \{M_1, M_2, M_3, M_4 \ldots\ldots\ldots\ldots M_n\} \tag{3}$$

$$T_r = \{T_1, T_2, T_3, T_4 \ldots\ldots\ldots\ldots T_n\} \tag{4}$$

Next, a parameter a_{nr} is introduced to denote whether a marshal point lies on a route. Below is a description of the parameter:

$$a_{nr} = \left\{ \begin{array}{l} 1, \text{if } M_n \text{ is on route}, r_i \\ 0, \text{ Otherwise} \end{array} \right\} \tag{5}$$

The following problem is then solved to determine the optimum bus routes, which yields minimum travel time and assigns at least one route to each marshal point.
Objectives:

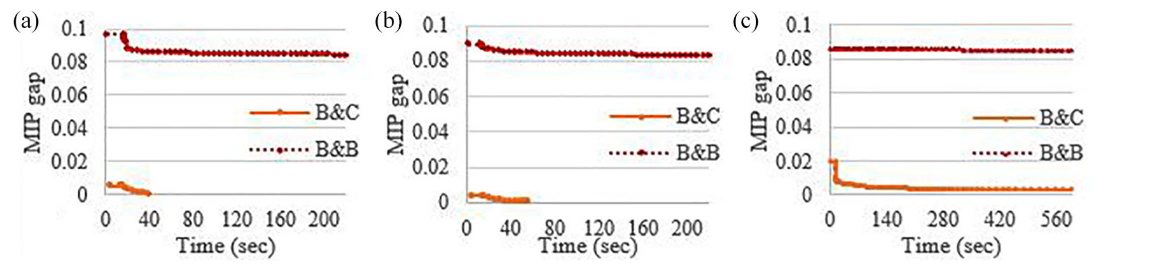

Figure 1. Efficiency of B&B and B&C algorithms in combination with a linear programming relaxation solution algorithm: (*a*) primal simplex; (*b*) dual simplex; (*c*) barrier algorithm.
Note: MIP = mixed integer program.

$$\text{Minimize} \sum_{r \in R} p_r{}^* T_r \tag{6}$$

Subjected to:

vii. $\sum_{r \in R} a_{nr}{}^* p_r \geqslant 1, \forall n$
viii. $p_r = \{0, 1\}$

p_r is a binary variable which takes a value of 1 if route r_i is selected; otherwise, it takes a value of 0. There are two constraints in the formulation: constraint (vii) where each marshal point must be assigned to at least one route, and constraint (viii) which describes the binary variable.

In total, 135 marshal points out of 488 bus stops for two sides of the links are identified through optimization modeling of marshal point location choice. The number of marshal points chosen per route for one direction ranges from nine to 22. The optimization process determines 12 bus routes to serve all 135 marshal points.

Evaluation of Solution Approach

The computation time is significantly smaller in the case of the proposed solution approach compared to traditional methods. To illustrate the improvements, the MILP problem is solved using the "branch and bound" method and the performance result is compared to that of the proposed method. Figure 1*a, b*, and *c* demonstrate the improvement in relative MIP gap over time for two methods. The MIP gap refers to the fractional gap between the integer objective and the objective of the best remaining node. Moreover, performance of primal (Figure 1*a*) and dual (Figure 1*b*) simplex, and barrier algorithm (Figure 1*c*) in solving linear programming relaxation is also observed in combination with the "branch and bound" (B&B) and "branch and cut" (B&C) methods.

The results in Figure 1 suggest that the B&C algorithm performs better in all cases. It expeditiously achieves the desired gap and provides the optimal solution. The B&B method decreases the relative gap gradually with time and cannot provide the optimal solution within the same time used by the B&C method. In all cases, the relative gap is always higher in the B&B method, while the optimum solution is obtained by the B&C method with negligible gap. Moreover, simplex methods are found to provide the optimum solution of the linear programming relaxation in less time than the barrier method. The reason could be that the barrier method does not visit vertices and wander through the interior region until convergence occurs. However, dual simplex is preferred as it describes the B&C algorithm by starting with an optimal solution and then adding constraints or modifying the right-hand side of a few existing constraints.

Microsimulation Modeling of Multimodal Evacuation

Network Coding

This study develops a multimodal evacuation microsimulation model by including necessary components of the transit network into an auto-based evacuation microsimulation model, which was developed by Alam et al. (*15*) for the city of Halifax. The revised microscopic traffic simulation model used in this study includes five entry/exit points for evacuation which are represented by the two bridges, two highways, and a roundabout. The earlier network coding is updated, and the final network model contains altogether 1,784 links and connectors, resulting in a road network of a total length of 480 km. The model contains 41 major signalized and stop-sign controlled intersections with 2,813 resolved turning conflicts in the network. Signal controllers are coded within the model to replicate the actual traffic flows through the intersections. Signal time data has been obtained from the 2014 Public Works Traffic Study of Halifax Regional Municipality. The updated evacuation microsimulation model contains 56 TAZs on the peninsula, in

Table 2. Thirteen Combinations of the Driving Behavior Parameters Designed by the LHS Method

Combinations #	Average standstill distance (ax_avg)	Additive part of the safety distance (bx_add)	Multiplicative part of the safety distance (bx_mult)
1	1.00	2.62	2.38
2	1.00	2.62	0.70
3	1.00	1.85	1.83
4	1.00	0.60	0.70
5	1.00	0.60	2.38
6	1.88	0.60	2.38
7	1.88	1.85	1.83
8	1.88	0.60	0.70
9	1.88	2.62	0.70
10	1.88	2.62	2.38
11	2.62	0.60	0.70
12	2.62	0.60	2.38
13	2.62	1.85	1.83

Note: LHS = Latin hypercube sampling.

alignment with the zoning system of the Halifax Regional Transport network model (*35*). The total evacuation demand over all TAZs is estimated to be 65,000 by auto and 8,400 by bus utilizing the Halifax Transport network model. In total, 12 transit routes and 135 marshal points obtained from optimization models are coded within the updated traffic evacuation microsimulation model. The number of waiting passengers (x_{zs}) at marshal points is estimated through the optimization model and used to develop a bus-boarding-volume profile at each marshal point. The bus schedule is coded for each bus route. In total, 174 60-seat buses from Halifax Transit are used to evacuate the transit-dependent population; this was an average figure for Halifax Transit, while standing room or articulated buses with higher capacity could be considered. The two designated shelters used for evacuation in this study are C. P. Allen High School and Nova Scotia Community College (NSCC). The first shelter is located 9 km away from the peninsula, taking the two bridges as travel routes. The second one is 15 km away from the peninsula, located at the end of the Bedford Highway, and can also be reached through Highway 102 and two bridges. Other external zones located within and outside of Nova Scotia, for instance, Cape Breton, can be used for residual evacuees who cannot be accommodated in the shelters.

Calibration and Validation of the Microsimulation Model

Calibration of Driving Behavior Parameters. A dynamic traffic assignment procedure is implemented within the evacuation microsimulation model. The model is calibrated and validated utilizing a Latin hypercube sampling (LHS) technique for business as usual traffic conditions. The details of LHS can be found in Alam et al. (*15*). Three driving behavior parameters of the simulation model are calibrated for urban traffic conditions: (i) average standstill distance, (ii) additive part of safety distance, and (iii) multiplicative part of safety distance. The relationship between the parameters can be captured through Equations 7 and 8 (*36*):

$$d = ax + bx \tag{7}$$

where:

d = safety distance;

ax = average standstill distance.

bx adjusts time requirement values which can be expressed as:

$$\mathrm{bx} = (\mathrm{bx\_add} + \mathrm{bx\_mult}^{*}z)^{*}\sqrt{v} \tag{8}$$

where, z is a value of range [0, 1], which is normally distributed around 0.5 with a standard deviation of 0.15, and v is vehicle speed.

The LHS results in 13 combinations of the values of the parameters as shown in Table 2. Route choice calibration, as described below, is also performed to improve the gap between observed and simulated traffic volume.

Route Choice Calibration. Route choice parameter calibration is performed by imposing additional cost to links which anticipate higher traffic flow than expected. An iterative process is adopted and, in total, 24 links are assigned a cost ranging from 30 to 500. Route choice calibration is not carried out for buses, as they follow pre-defined static routes and schedules in this study. For validation purposes, traffic volume data has been obtained from the Miovision-based video image processing data the 2014 Public Works Traffic Study of Halifax

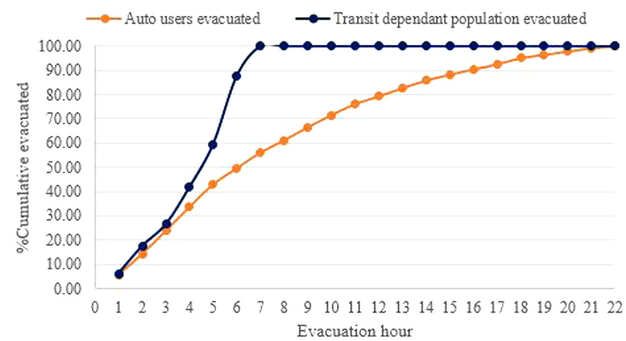

Figure 2. Percentage cumulative evacuation of auto and transit users with the progression of evacuation time.

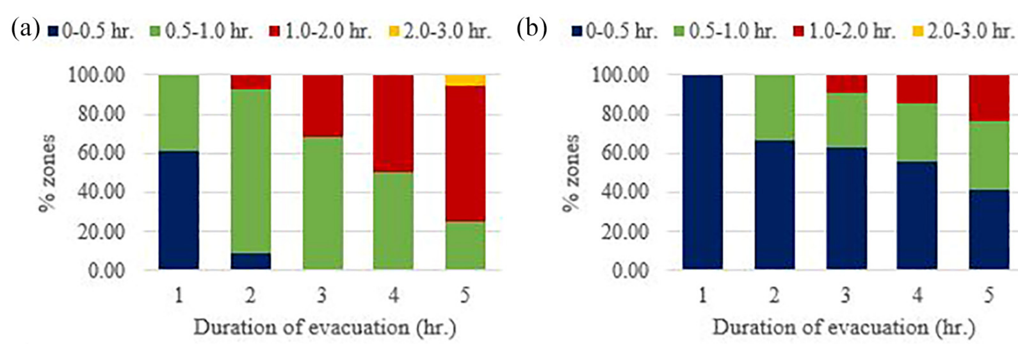

Figure 3. Average travel time distribution at different cut-off times of the evacuation from zones to (*a*) shelter 1 and (*b*) shelter 2.

Regional Municipality. The validation result reveals that parameter combination #4 provides the best goodness-of-fit of the model, with R^2 values of 0.81 and 0.82 for the hours 7:00 to 8:00 a.m. and 8:00 to 9:00 a.m. respectively.

Results and Discussions

Performance Evaluation of Multimodal Evacuation. This study evaluates the performance of a multimodal evacuation from all TAZs to designated shelters through the Halifax transport network. Figure 2 shows the percentage cumulative arrival of auto users and the transit-dependent population in each hour of the multimodal evacuation. The results reveal that it requires 22 h to evacuate auto users from the peninsula, while evacuation of the transit-dependent population can be completed within 7 h. The longer duration of auto evacuation is mainly because of "at once" evacuation at peak time through the narrow roads of a historical city like Halifax with limited access points. The transit evacuation results demonstrate an excess capacity of the transit system to provide transportation assistance for additional evacuees who might switch from auto and other modes. The simulation assumes that buses use full capacity depending on the demand at marshal points. Hence, evacuation of the transit-dependent population is rapid compared to the evacuation of auto users, when only transit-dependent populations are assumed to be evacuated by buses. At the ninth hour of evacuation, 70% of auto users arrive at shelters, which demonstrates a complete evacuation of 90% of zones in the peninsula. The remaining 10% of the zones, predominantly in the downtown area, have a higher evacuation demand. The introduction of a larger demand of this nature within a short period creates local congested traffic conditions in the downtown network, particularly across arterial and key loading links, resulting in a slower evacuation process for these zones. Therefore, it can be concluded that there are certain zones that show significant delays in evacuation, which warrants a consideration for a staged evacuation.

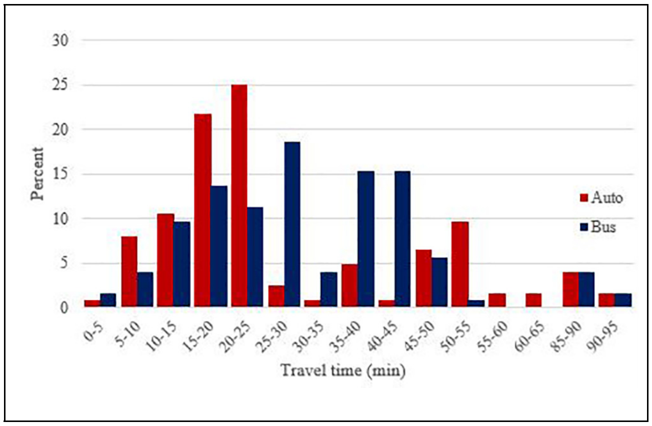

Figure 4. Mode-specific travel time distribution for multimodal evacuation of the Halifax Peninsula.

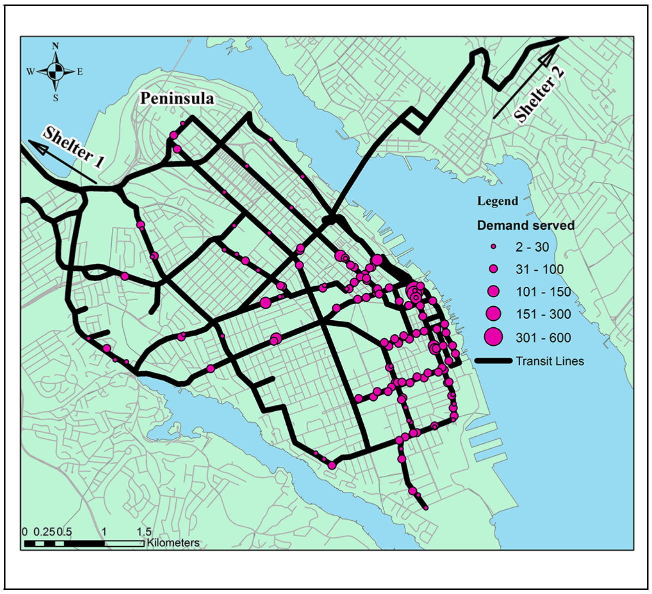

Figure 5. Marshal point locations and transit routes with a spatial distribution of transit demand served at different marshal points.

Table 3. Transit Demand Served by Different Categories of Marshal Points

Marshal points served by transit lines	Total transit demand served (%)	Average demand served by each marshal point (%)
1	58	1.04
1+	19	1.8
2+	15	2.7
3+	8	0.7

Figure 3*a* and *b* present average travel time distribution at different cut-off times of the evacuation from all zones to shelter 1 and shelter 2, respectively. Results in Figure 3 show that after 3 h of evacuation, average travel time increases significantly for most of the zones. Travelling to shelter 1 requires relatively higher travel time, which can be 2–3 h at maximum. In this case, residents of 70% of the zones experience an average travel time of 1–2 h to arrive safely at shelter 1 between the three- to five-hour periods of evacuation. This study also examines mode-specific travel time for multimodal evacuation. The simulation results suggest that average travel time is 31.44 min for auto and 37.76 min for bus. Figure 4 presents a frequency distribution of travel time for both auto and bus. The results show that approximately 69% of drivers experience a travel time equal to or less than average travel time (31.44 min), while the fraction is around 78% for buses, corresponding to an average travel time of 37.76 min. Half (50%) of autos require a travel time of 25 min or less, while 50% of buses require 30 min or less. Arguably, additional time is added to average bus travel time because of stops at marshal points. Travel time is longer for individual transit users; however, with the benefit of higher bus capacity, the complete evacuation of transit users is faster than the evacuation of auto users, as shown in Figure 2.

Performance Evaluation of Transit Evacuation

Transit Demand Served. Further analysis of transit evacuation focuses on demand served at different marshal points along transit lines. Figure 5 illustrates all transit lines and marshal points obtained from the optimization models and presents the spatial distribution of transit demand served during the evacuation. The results show that most of the marshal points are concentrated in the downtown core and the south end of the peninsula, where a higher percentage of transit demand is served. The derived transit lines overlap in different parts of the peninsula, particularly in the downtown core, which results in 43 marshal points out of 135 being served by multiple transit lines. This study measures the performance of marshal points served by 1, 1+ , 2+ and 3+ transit lines. Table 3 shows that percentage average demand served by 2+ marshal points is 2.7%, while this value is 1.04% and 1.8% for 1 and 1+ marshal point respectively.

Traffic Congestion along Transit Lines and Critical Links. Spatial and temporal variation of traffic congestion along transit lines are examined in relation to average speed. Average speed is estimated at link level for different times of evacuation. Figure 6 presents the average speed distribution for all transit lines in the network. The simulation results suggest that average speed is relatively lower near exits, across key links of the downtown core, and at the south end of the peninsula. The north end of the peninsula should experience better traffic conditions during an evacuation. Transit lines passing over arterial streets experience significant traffic congestion, as these streets primarily

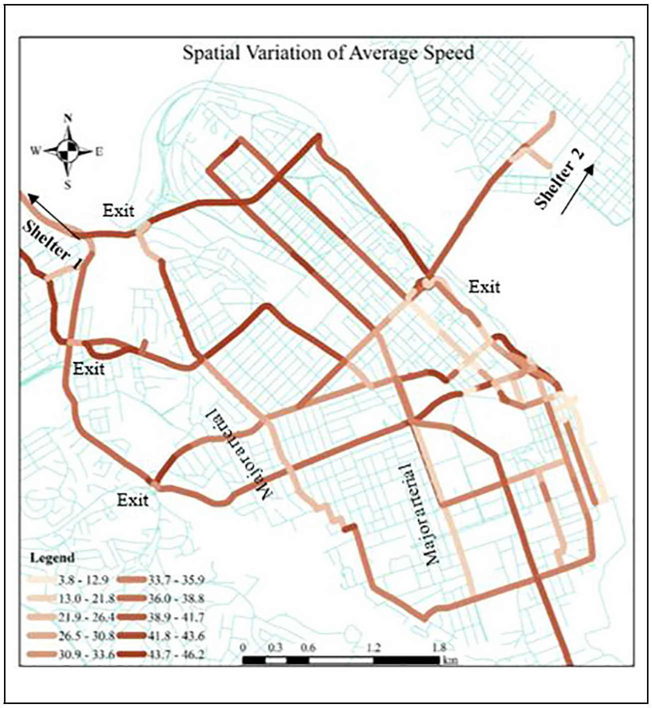

Figure 6. Spatial variation of traffic congestion propagation measured in relation to average speed (km/h) along transit lines and critical links.

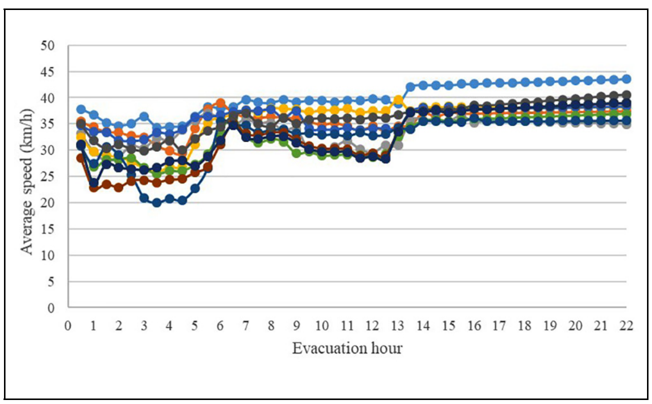

Figure 7. Temporal variation of traffic congestion propagation measured in relation to average speed along transit lines.

lead traffic to shelter 1 through highways and the roundabout. This study also presents temporal variation of traffic congestion during evacuation. Figure 7 shows that average speed is below 30 km/h for most transit lines until the fifth hour of evacuation. Following this, average speed improves, and traffic operates at around 35 to 40 km/h. This result will help determine the offsetting time of transit operations during an emergency.

Pick-Up and Arrival of Transit Users. The study also analyzes the pick-up and arrival patterns of transit users.

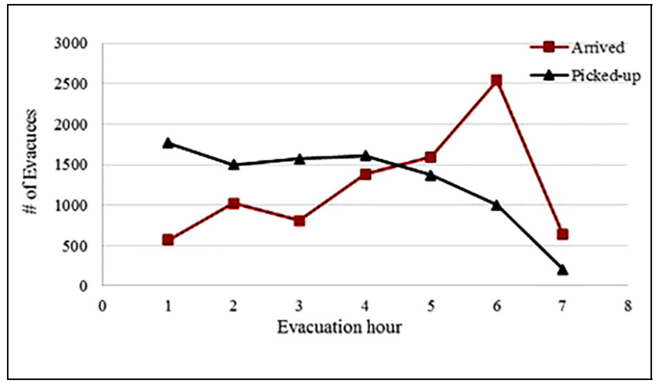

Figure 8. Pick-up and arrival pattern of transit dependent population with progression of evacuation time.

The simulation results, as shown in Figure 8, suggest that pick-up rate decreases and arrival rate at shelters increases with the progression of evacuation time.

Initially, the deviation between the number of individuals picked up and those arriving at shelters is higher. After 4.5 h, demand for pick-up becomes lower in the network than the number of transit users who arrive at shelters. Figure 8 shows that the arrival of transit users at shelters peaks in the sixth hour of evacuation. At this hour, buses are best utilized and 30% of buses operate in the network to serve marshal points.

Conclusion

This study presents a multimodal evacuation microsimulation model which incorporates strategic planning decisions, including marshal point location and transit route choice. The model tests and evaluates network conditions with multimodal evacuation plans. One of the key contributions of this study is that it develops a novel solution, the B&C approach, to solve the proposed MILP-based marshal point location and transit route choice problem while addressing transit demand under emergency conditions.

The proposed framework was empirically tested using a case study in Halifax, Canada. This study addressed the transportation needs of the transit-dependent population to evaluate a mandatory multimodal evacuation of the Halifax Peninsula. The optimization solution approach used in this study achieved optimum results faster with a negligible relative MIP gap compared with other traditional methods. The optimization process identified 135 marshal points and 12 transit routes to serve around 8,400 transit-dependent individuals. This study simulated a transit evacuation operation where buses continued to pick up evacuees until they reached capacity or no demand was left at marshal points, depending on which occurred first. The optimization results informed the multimodal evacuation scenario-building process for the simulation model. The simulation of multimodal evacuation anticipated a duration of 22 h to evacuate all auto users, which is alarming for an area of 24.75 km^2. However, the transit-dependent population was completely evacuated within the seventh hour of the evacuation. The results also revealed that traffic congestion was the highest at the core of the peninsula and that average speed was lower near exits. The congestion results will help to identify critical time segments of evacuation for transit operations.

The findings of this research are relevant for other coastal cities with densely populated urban cores and limited access points. The study found that evacuating all citizens at once takes a longer time since spillback gridlocks the narrow roads of the town. In this regard, bus-based and staged evacuation can be prioritized. Moreover, lessons learned from this study can be useful to understand the types of network vulnerabilities that could result during a multimodal evacuation and are replicable to other similar coastal cities. This study has certain limitations; for example, evacuation of the people who use active transportation, residents with mobility issues, or both, was not considered in this study. Shelter capacity was not evaluated for the multimodal evacuation scenario. In addition, development of an optimization model for marshal point location and transit route choice was done separately. Immediate future studies should address the limitations regarding the population using active transportation modes, citizens with mobility issues, and shelters. An extension of the study is also required to incorporate both marshal point location and transit route choice within one integrated large optimization model. Dynamic optimization modeling with consideration of the temporal variation in simulated travel time could provide more ideal evacuation conditions. In addition, a heuristic/meta-heuristic needs to be developed for larger evacuation problems or integrated optimization. The scenario "auto users switching to transits" should be tested for a better understanding of the modeling of the marshal point location choice and the resultant multimodal evacuation performance. Lastly, the optimization of marshal point location choice in this paper is based on transit demand and walking distance. Optimizing the number of marshal points based on the traffic simulation would be an interesting consideration for future research.

Nevertheless, this study contributes to the literature by developing a multimodal evacuation microsimulation model that evaluates network conditions for a multimodal evacuation. The results provide insight into public transportation planning, including marshal point locations, and transit route choices for emergency evacuation, and managing multimodal evacuation traffic operations. The results help emergency professionals and engineers to identify the excess capacity of the transit system that can accommodate additional evacuees who might switch from other modes.

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Author Contributions

The authors confirm contributions to the paper as follows: study conception and design: MAH, MJA; model formulation: MJA, UV, MAH; data collection: MJA, MAH; analysis and interpretation of results: MJA, MAH, UV; draft manuscript preparation: MJA, MAH. All authors reviewed the results and approved the final version of the manuscript.

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