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Evacuation planning for persons with mobility needs: A combined optimization and traffic microsimulation modelling approach

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ABSTRACT

This study presents a framework of optimization and traffic microsimulation modelling that account for a mass evacuation of persons with mobility needs. The study optimizes emergency vehicle and destination allocation and implements an emergency evacuation route within the traffic microsimulation model. The emergency vehicle and destination allocation follow an integer programming optimization approach within a mathematical programming language modelling system. This study tests two evacuation scenarios that consider emergency vehicle operations with and without a dedicated route for the evacuation of five hundred and twelve persons, requiring mobility assistance from six hospitals and nursing homes. Additionally, the evacuation modelling framework considers collision risks in assessing evacuation process, particularly, how it affects evacuation of this group of vulnerable population. Optimization results indicate that this group can be evacuated by ninety emergency vehicles, and it takes 19.5 h for an optimal allocation of emergency vehicles. Traffic simulation results suggest that it takes 21 h to evacuate all persons with mobility needs using ninety emergency vehicles. The study found that travel time along the evacuation route is reduced by 32.31% compared to a sceanrio without a dedicated route. Results also indicate that implementing a dedicated evacuation route yields a reduction of 6 min and 25.2 min in average and the maximum trip time for emergency vehicles, respectively. On the other hand, 68% of emergency vehicles make 0.5–3.5 fewer tour to a case without the collision, leading to an incomplete evacuation (72.2%). This research will provide emergency professionals with insights into the challenges associated with the evacuation of persons with mobility needs and help develop proactive evacuation plans to accommodate the special requirements of the vulnerable population.

1. Introduction

Carrying out mass evacuations from disaster-prone areas is a difficult task with many operational challenges in egress [1], corresponding traffic congestion [2,3], shelter selection [4,5], and evacuation site management [6]. Evacuation of vulnerable populations is more challenging as it entails multiple types of risks and factors, which are often overlooked in emergency planning and evacuation

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literature. As *Renne* et al. [7] posit, evacuation procedures often omit targeted responses for the preparedness of carless and mobility-limited residents, including a disproportionate share of persons with functional limitations. A national survey of hurricane evacuation revealed that low mobility and special needs groups are underrepresented in evacuation plans [8]. The overarching problem with evacuating persons with mobility needs is the lack of suitable planning that ascertains the appropriate shelter allocation, optimum emergency vehicle utilization, and emergency route implementation to avoid any unprecedented traffic congestion in the network [9]. Additionally, other concerns with the evacuation of mobility-limited residents include the loading and unloading time associated with accommodating vehicles, such as ambulances, the general availability of emergency vehicles and appropriate shelters, namely hospitals (Hs) and nursing homes (NHs). The associated facts highlight the importance of studying evacuation of persons with disability from both planning and operational perspectives. Modelling evacuations by auto and buses using different optimization and simulation techniques [10–12] provide valuable insights into evacuation time and traffic congestion. However, robust evacuation modelling is limited in addressing the challenges and operational complexities in evacuations resulting from the movement of people with disability from the endangered areas to safe shelters.

To date, most studies for persons with disability (PWD) and mobility needs focus on localized, small-scale approaches, including buildings or small facilities evacuation [13]. In other instances, scholars have identified unique challenges in evacuating hospitals and care centers [1], as others have with evacuating high-rise buildings [24] Therefore, there is a gap in knowledge and practical application considering the mass evacuation of this group of vulnerable population at a city or regional scale, including suitable shelter identification, vehicle allocation, and evacuation route planning simultaneously. Thus, this research aims to develop an integrated modelling approach that is demonstrably critical in accounting for resource constraints and traffic operation issues to holistically assess the evacuation of persons with disability. Also, it is critical that evacuation modelling for persons with mobility needs addresses the network operation challenges, including collisions, and seeks to accommodate traffic operation improvement measures to ensure that emergency vehicles are not rendered immobile due to congestion. For example, during Hurricane Katrina's evacuation in 2005, a mammoth traffic fleet created unprecedented traffic congestion. This congestion caused vehicles to run out of fuel due to long clearance times of approximately 20 h, leaving many people, including the population groups, in need of transportation assistance, with no option but to remain in place [14].

Therefore, the objectives of this study are (1) to develop an optimization model that simultaneously updates the availability of emergency vehicles and suitable shelters for optimizing the evacuation of persons with functional limitations, and (2) to implement evacuation scenario for persons with mobility needs obtained from the optimization model within a traffic evacuation microsimulation model for testing and evaluations. The study advances an integer programming approach to allocate ambulances to different facilities while the model updates vehicle and destination availability information at a specific time interval to achieve the objectives. This study implements a dedicated evacuation route for emergency vehicle operation within the traffic microsimulation model. It also implements traffic operation improvement measures, namely contraflow, along the route, as suggested in evacuation route identification study by *Habib et al.* [15]. The simulation model evaluates two scenarios: (1) evacuation without a dedicated evacuation route, and (2) evacuation through a dedicated evacuation route. Additionally, this study incorporates collision risk to demonstrate the practical applicability of the proposed evacuation modelling framework for persons with mobility needs. Finally, this research provides a benchmark for measuring evacuation performances. The baseline understanding of evacuation trip time, zonal clearance time, emergency vehicle and destination allocation will help us to improve the real-world application processes.

2. Literature review

An enhanced and more urgent call for effective and inclusive mass evacuation planning has been the subject of an increasing volume of academic literature over recent decades. Notably, since Hurricane Katrina in 2005, researchers and emergency management professionals have repeatedly referenced significant shortfalls in the accommodation of vulnerable population, including persons with disabilities (PWDs) and mobility needs during evacuations. As *Bloodworth et al.* [16] argues that the City of New Orleans was not equipped with the knowledge and preparation to meet the needs of vulnerable populations during an active evacuation and sheltering. Although the body of literature is growing, a limited amount of research exists that links the mass evacuation of persons with mobility needs within more extensive networks and modelling frameworks. As *Stough and Kang* [17] point out in a content analysis of disaster risk reduction strategies, the concepts of accessibility, inclusion and universal design are frequently acknowledged as challenges in emergency scenarios; however, international standards for PWDs accommodation are limited. Other literature, such as *Apte et al.* [18], suggest that, in an active mass evacuation, it cannot be expected of PWDs to converge to pick-up locations, which is often a departure from the traditional evacuation approaches adopted in existing models. For PWDs with no personal means of transportation, this means reliance on emergency vehicles, including ambulances, transit, or paratransit. Although in one estimation, up to 20% of a total population of evacuees may be defined as requiring personal and continued assistance [8], in the content analysis of evacuation policies, *Wolshon* [19] found that only 23 out of 150 specifically addresses PWDs unique requirements.

To a greater degree, elderly people comprise a region's most vulnerable and mobility-assistance seeking groups. *Li et al.* [20] found that elderly persons are more vulnerable due to residing within hospitals and long-term care facilities, not often co-located within existing evacuation routes. On the other hand, *Nakanishi et al.'s* [21] study in the context of flood evacuation behaviour found that vulnerable and slow-moving elderly people pose a significant increase in evacuation time even when located on existing evacuation routes. Still, as paired with an already limited evacuation policy emphasis, these groups show a significant extension in evacuation time given the absence or inability of personal motor vehicle options. Adding to this, *Yazdani et al.'s* [22] findings reveal a particular vulnerability of residential healthcare infrastructure to evacuation-inducing disasters or climate events. This vulnerability further compounds the need for expeditious planning, and to prioritize and streamline a region's slowest moving and assistance-needing persons. Within the literature, there is consensus that evacuation plans specific for vulnerable populations, which contain a disproportionate number of elderly and mobility-impaired persons, are limitedly considered in existing metrics during and post-evacuation [23].

Renne et al. [7] in their seminal research on the evacuation of carless and otherwise mobility-restricted individuals examined the role of government and public agencies in emergency preparedness. Importantly, they found that PWDs are more likely to reside in areas that lack the critical evacuation infrastructure and are therefore at an increased risk of being exposed to hazards by remaining in place. Additionally, they found that any specific response plan for the evacuation of PWDs should incorporate multi-mobility concepts. Further, *Sritart et al.* [6] through a geospatial multiple criteria analysis found that most assessed evacuation shelters were vulnerable and not suitable for PWDs. In large, the current academic evacuation modelling literature focuses on indoor egress [15] and small-scale simulation [24]. However, many of these methodologies may expand to a larger, city or regional mass evacuation scale. For example, *Hashemi* [1] outlined the movement speeds of PWDs according to the passage width, gender, surface type, and severity of mobility impairment. These approximations may then be applied to determine the mobilization time for PWDs in mass evacuation modelling. In other evacuation modelling scenarios, such as that performed by *Noh et al.* [25], it was found that adverse effects such as congestion and blocking may be significantly reduced by proposing a partially dedicated strategy that allocates a defined path for relative high-speed subpopulations and vehicles, leaving an unobstructed path for slower-moving subpopulations such as PWDs separate from other traffic. Through this research, *Noh et al.* [25] posited that the average evacuation time of a high-rise building could be optimized to take up to 10% less time on average. Further, these concepts may prove valuable in larger-scale implementation with dedicated routes such as highway lane and urban street route assignments for vulnerable populations utilizing route-based transportation.

Although in a small amount, some evacuation research suggest computational modelling methodologies for persons with functional limitations. For example, *Kaiser et al.* [26] examined urban evacuation using public transit for special needs residents using a linear programming optimization model and determined optimal locations for stops. Through this research, *Kaiser et al.* [26] determined that between a mathematical and simulation model, the former yields the best results in terms of effectiveness and computational speed using 20, 30, 40, 50, and 60 bus stop allocations. In another study, *Dulebnets et al.* [27] applied a mixed-integer programming model to assign individuals to specified emergency shelters. Both an exact optimization algorithm and a heuristic algorithm were created to achieve this. In their conclusion, *Dulebnets et al.* [27] stated that the heuristic algorithm showed a greater degree of success than the exact optimization method given the multitude of variables and unknown factors within a large-scale environment. In a subsequent study, *Dulebnets et al.* [28] introduced a multi-objective optimization model to minimize total evacuation time and mental and physical demand. Unlike other similar studies, *Dulebnets et al.* [28] especially accounts for critical social characteristics and the demands placed on evacuees. Finally, *Ebrahimnejah et al.* [9] applied optimization techniques to retrieve and transfer PWDs from designated locations to previously identified shelters. In this study, *Ebrahimnejah et al.* [9] utilized small-sized cars and medium-sized vans in the fleet of evacuation vehicles, which significantly reduced the time for tours travelled. Although most of the studies mentioned above rely on automobiles in terms of simulation modelling, several focused on bus-based evacuation of only the transit-dependent population, leaving persons with functional limitations and mobility needs with no option but to stay in designated locations during mass evacuations.

These studies assume that all carless, and PWDs that are freely mobile gather at the pick-up locations and move to public shelters. However, immobile persons may require a curbside pick-up using special vehicles, including ambulances. For the evacuation of persons with mobility needs, hospitals and nursing homes are strong candidates for shelter locations as they would already have many of the required amenities and equipments to provide for persons with special requirements. Moreover, mobilization time is also critical when evacuating immobile evacuees and it needs to be addressed within the modelling framework. Additionally, various risks, such as traffic congestion and other uncertain threats, add further complexity to evacuation processes in the network. Saying that, it is critical to consider the interactions with threats within the evacuation modelling framework to ascertain the practical applicability of the model. On the other hand, literature [29,30] suggests that traffic operation improvement plans alternatively countermeasures have the potential to ensure efficient emergency traffic operations for an evacuation. For example, contraflow is a countermeasure that involves turning one or more inbound road links outward of the city under risk to increase the road capacity. This countermeasure is proven to provide a traffic flow with no hindrance from background and shadow traffic along the treated network link. The novelty of this study is that it combines an optimization and a traffic microsimulation model to account for multicriteria, including mobilization time, shelter identification, emergency vehicle allocations, and traffic operation improvement measures in assessing the evacuation of persons with mobility needs. This study also incorporates a collision scenario to demonstrate the impacts of uncertain threats on the overall evacuation process. The modelling approach in this study updates the vehicle and shelter availability information at a specific evaluation time interval and informs the optimization process accordingly. The optimization model feeds the traffic microsimulation model developed by *Alam et al.* [31] with information regarding the emergency vehicle activity schedule to relocate PWDs from the Halifax Peninsula to Hs and NHs.

3. Evacuation area context

This study considers the Halifax Peninsula a case study to test a short-notice mandatory evacuation of the residents, including the persons with mobility needs due to any natural hazard. The Halifax Peninsula region of the Halifax Regional Municipality (HRM), in the Province of Nova Scotia, is one of Canada's most densely populated urban communities [32]. This study considers 10:00am as a starting time of evacuation when the population doubles in the peninsula due to work. Evacuees can choose one of the five exit points of the network to leave the city by using personal vehicles (e.g., auto owners), buses (e.g., transit-dependent population) and emergency vehicles, including ambulance (e.g., persons with disability and mobility needs).

Demographic and geographical characteristics, and road network structure make the Halifax Peninsula a suitable selection for an evacuation study. Recent population growth, particularly, a rising number of persons with disability necessitates a more inclusive evacuation planning for carless and mobility-assistance-requiring persons in this area. Since 2016, the HRM has experienced an unprecedented rate of population growth of 9.1% compared to the provincial average of 5.0% and the national average of 5.2% [33]. Table 1 presents an overview of population characteristics for the peninsula. Based on 2017 data, the HRM planning growth targets project 18,000 new residential units by 2031 bringing the area's population to an estimated 130,000 [34]. This rapid growth has prompted the Province of Nova Scotia to accelerate its push for accessibility adaptation, projecting that, by 2030, persons with a disability will reach 25% of the total population, adding to the already highest percentage of any Canadian Province [35]. Therefore, now represents a vital time to recognize and plan for the evaluation of vulnerable residents, requiring mobility assistance in the event of a short-notice evacuation of the city's most dense communities.

Table 2 below illustrates the personal mobility capacities of HRM residents by region according to most recent Nova Scotia travel activity survey (NovaTRAC) data as of 2018 [37]. As it shows, the Regional Centre, encompassing the Halifax Peninsula, holds the lowest city-wide ownership of a driver's license and the greatest amount of transit pass ownership. Further, personal vehicle ownership data shows the lowest figures in the city. Therefore, given recent and projected growth trends, an anticipation of persons with mobility needs, paired with already low personal vehicle ownership, there is a pressing need for literature on specific short-notice mass evacuation procedures for carless and mobility-assistance-seeking individuals in the area.

4. Methodology

This study develops a sequential modelling framework to evacuate persons with mobility needs from hospitals (Hs) and nursing homes (NHs) using emergency vehicles owned by the Nova Scotia Emergency Health Services (EHS). The framework comprises several components that predict emergency vehicle dwelling time at a facility, optimizes destination allocation to the emergency vehicle fleet and incorporates traffic operation improvement measures to guide emergency vehicles through an efficient route leading to destinations. Hence, the methodology of this study is three-fold: (1) developing a Monte Carlo simulation-based emergency vehicle dwelling time distribution model for Hs and NHs, (2) Integer Programming (IP) optimization modelling for a dynamic destination allocation to emergency vehicle tours, and (3) traffic microsimulation modelling of an evacuation of persons with mobility needs considering countermeasures in effect. This study updates optimization modelling parameters, including traffic demand, vehicle, and destination status at an hour interval to capture the dynamic changes in vehicle and destination availability over time. The destination locations and tour times identified through optimization are further used to prepare an emergency vehicle activity schedule for testing an evacuation scenario within the traffic microsimulation model. Fig. 1 presents an overall framework illustrating all components required for evacuating persons with mobility needs from Hs and NHs.

4.1. Modelling of emergency vehicle dwelling time distribution

The study develops a Monte Carlo simulation-based dwelling time prediction model using the data obtained from the Nova Scotia provincial Emergency Medical Service (EMS) administrative database. Data reveals that Halifax emergency vehicle demand cases obtained from January to December 2012 comprise a total of 24,403 instances of emergency transportation to hospitals in Halifax. This total represents approximately 40% of total emergency vehicle demand cases during this given period. This dataset includes the pickup locations (longitude and latitude), age and gender of the service user, and service time of emergency vehicles. The Monte Carlo simulation is conducted to determine a dwelling time distribution for emergency vehicles. In this study, a tour time of a vehicle comprises a start time, a dwelling time and total travel time required to make a round trip between origin and destination. The tour time is minimzed within the optimization model when determining suitable destinations for all drop-offs at an hour interval. The following steps are carried out to conduct a Monte Carlo simulation to generate dwelling times for emergency vehicles at Hs and NHs.

- Step 1: Process the data to identify and calculate the data distribution attributes, such as the measures of central tendency and variance of the data
- Step 2: Determine average dwelling time (*ADT*) and the data's inter quartile range (*IQR*). *IQR* can be calculated using the following equations

$$IQR = Q_3 - Q_1$$

where Q_1 and Q_3 represent the first and third quartile values of the entire data, respectively.

- Step 3: Initiate the Monte Carlo simulation, *r*

Table 1
Population changes in the HRM (2016–2021) [33,36].

Item	2016	2021
Population	403,131	439,819
Population percentage change from last census	3.3	9.1
Total private dwellings	187,338	200,473
Population density per Sq. Km	73.4	80.3
Land area (Sq. KM)	5490.35	5475.57

Table 2
Average license, transit pass, and vehicle ownership [37].

Area	License and Transit Ownership		Vehicle Ownership		
	Driver's License	Monthly Transit Pass	Average	0	1 +
All HRM	87.1%	8.5%	1.6%	9.2%	91.4%
Regional Centre	80.9%	13.7%	1.2%	19.6%	80.3%
Suburban	88%	7.3%			
Rural	95.3%	4.7%			

- Step 4: Determine the *ADT* and IQR of the simulated data
- Step 5: Determine the deviation between the observed and simulated distributions using the *ADT* and *IQR* values, where,

$$D_{avg.} = |ADT_{obs.} - ADT_{sim.}|$$

$$D_{IQR} = |IQR_{obs.} - IQR_{sim.}|$$

- Step 6: Stop simulation if the $D_{avg.} < \zeta$ and $D_{IQR} < \zeta$
- Step 7: If the conditions are not met in Step 6, go back to Step 3 to run the simulation $r + 1$

In this study, it has taken 685 Monte Carlo simulation runs to achieve a distribution deviated by only 1% of the observed dwelling time distribution for emergency vehicles.

4.2. *Optimization of destination and emergency vehicle allocation*

This study develops a dynamic tour-based Integer Programming (DynTIP) optimization model to allocate destinations to emergency vehicles. The objective of the DynTIP model is to minimize the total tour time (TT_{vfd}) of the emergency vehicle fleet accounting for emergency vehicle dwelling time, vehicle, and destination availability. The model incorporates a time window component to track the destination and vehicle availability at a certain time interval t within the optimization framework. The optimization model is run at interval t until the target demand is completely evacuated from all the facilities.

4.2.1. *Assumptions and DynTIP formulation*

This study identifies all hospitals and nursing homes within 100 km of the Halifax Peninsula to prepare a destination choice set for the optimization model. Fig. 2 identifies the contextual geography as well as the departing and receiving locations used in this study. The study assumes that an origin or destination facility can process three emergency vehicles at a time due to limited pick-up and drop-off space. Currently, there are 180 total emergency vehicles in the Province of Nova Scotia. For this study, a fleet availability of 50% is assumed to be readily available to carry out the evacuation of the Hs and NHs in the Halifax Peninsula.

For the optimization model, let $v \in V$ denote an emergency vehicle, where $V = \{v_1, v_2, v_3, \ldots\ldots\ldots v_n\}$ is the set of all emergency vehicles; suppose $f \in F$ denote a facility, where $F = \{f_1, f_2, f_3, \ldots\ldots\ldots f_n\}$ is the set of all facilities; and let $d \in D$ represent a destination, where $D = \{d_1, d_2, d_3, \ldots\ldots\ldots d_n\}$ is the set of all destination locations. Demand at a faiclity is denoted by D_f and each destination has a capapcity of Q_d. A binary variable y_{vfd} takes a value of 1 if a destination d is selected for an emergency vehicle v serving the facility f and 0 otherwise. A variable x_{fdt} is used to determine the share of the total demand shifted from the facility f to the destination d at time t. Each variable of the IP model is updated at the interval t. The IP model is presented below.

Objective

$$\min \sum_{t \in T} \sum_{f \in F} \sum_{d \in D} y_{vfd} * TT_{vfd}$$

Subjected to:

$$(i) \sum_{t \in T} \sum_{d \in D} x_{fdt} \geq D_f, \ \forall f$$

$$(ii) \sum_{f \in F} x_{fdt} \leq Q_d, \ \forall d, t$$

$$(iii)\ x_{fdt} \leq y_{vfd} * M, \ \forall t$$

$$(iv)\ t \leq T, \ \forall t$$

$$(v)\ x_{fdt} \geq 0$$

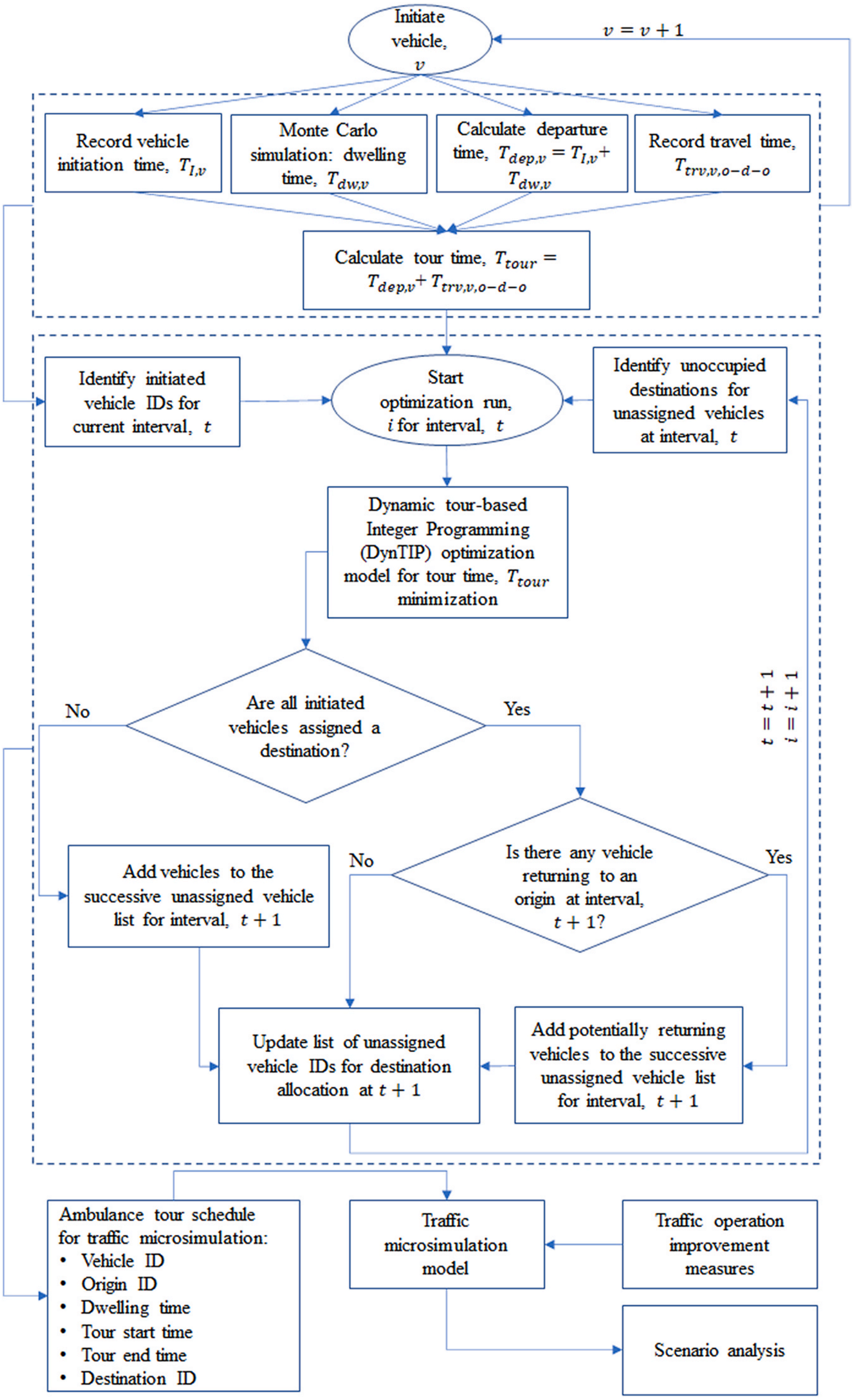

Fig. 1. A Conceptual framework for evacuating persons with disability utilizing emergency vehicles.

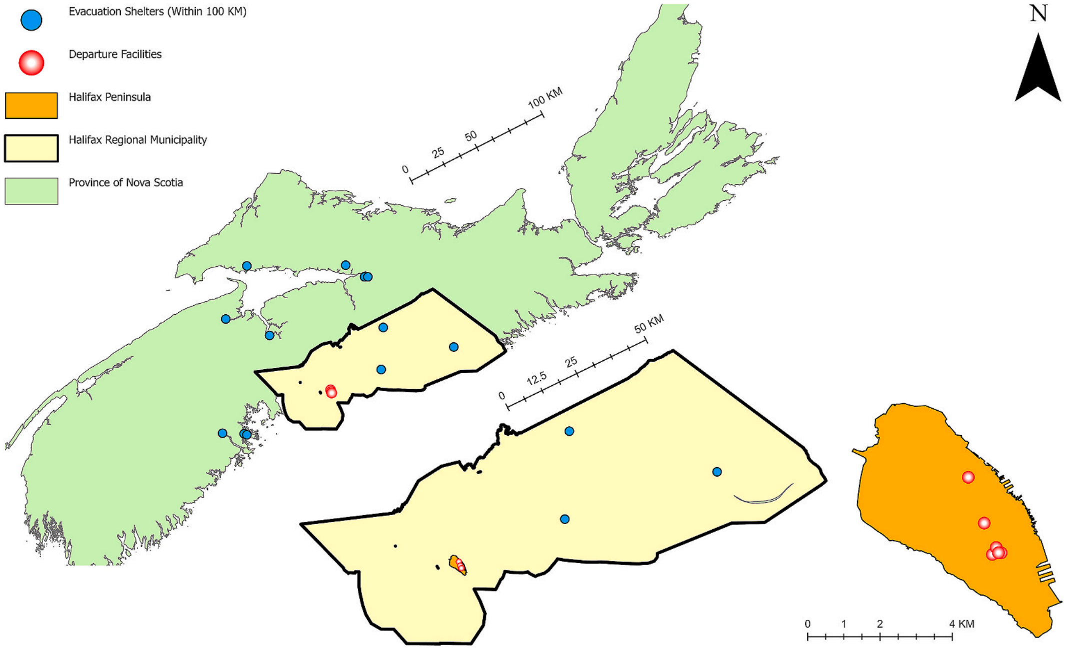

Fig. 2. Halifax Peninsula contextual geography with receiving and departing locations.

$(vi)\ y_{vfd} = \{0,\ 1\}$

Constraint (i) ensures that all demand of a facility is shifted to destination locations, constraint (ii) confirms that the destination capacity is respected, constraint (iii) ensures that the demand will be moved to only the selected destination locations, constraint (iv) requires that the destination allocation to the emergency vehicles take place until emergency vehicle service is available. Further, the last two equations confirm that x_{fdt} is a positive integer and y_{vfd} is a binary variable. The DynTIP model is implemented within a Mathematical Programming Language modelling system platform. The model utilizes several inputs, including vehicle fleet information, demand at facilities, tour time, and destination capacity. The optimization updates all the inputs impacted by the preceding hour destination allocation to the emergency vehicles for successive optimization iterations. Each vehicle is tracked with its associated travel information, such as the start and end time of a tour and the destination location assigned to the vehicle. The information is further utilized within a traffic microsimulation model for testing traffic operations considering an evacuation of persons with mobility needs using emergency vehicle fleets.

4.3. Traffic microsimulation modelling of PWD evacuation

This study employs a traffic evacuation microsimulation model developed by *Alam et al.* [31] to test emergency vehicle operations in the network when considering the evacuation of persons with mobility needs. A brief overview of the model is provided in the following Table 3.

A total of 512 persons, requiring mobility assistance are evacuated using ambulances. Additional 65,000 normal traffic estimated from a Halifax Regional Transport Network Model [39] are simulated to replicate the traffic congestions due to evacuating and background traffic. The model includes passenger cars, transit buses, and ambulances in evacuation. Alam et al. [31] conducted an

Table 3
Traffic microsimulation modelling elements, description, and applications.

Items	Description
Road network elements	Links & connectors# 1784; signalized intersection# 41; stop signed intersection# 12; traffic analysis zone# 56; total evacuation demand: 65,000; persons with mobility needs#: 512; emergency vehicle# 90
Assignment process	Dynamic traffic assignment
Calibration and validation	Three driving behaviour parameter calibration: average standstill distance – 1.0, additive part of safety distance – 0.6, and multiplicative part of safety distance – 0.7; Traffic volume-based validation: $R^2 = 0.82$ and 0.84 for two morning peak periods respectively
Application	Twenty evacuation scenarios: a base case evacuation scenario and the rest scenarios are reagrding flood risk, collision risks and countermeasures [11,31,38]
Key results from earlier applications	It takes 22–33 h to evacuate the peninsula, depending on the nature and the severity of the disruptions to evacuation traffic flows

extensive calibration and validation of the traffic simulation model using a Latin Hypercube Sampling (LHS) technique. Three driving behaviour parameters [40,41] are calibrated to replicate the actual traffic flow in the simulator. The parameters and calibration results are presented in Table 3. A traffic volume-based validation process is implemented that yields a R^2 value of 0.82 and 0.84 for two morning peak periods, respectively (Table 3).

4.3.1. Traffic simulation modelling assumptions and modifications for PWD evacuation

Traffic microsimulation model is modified to incorporate emergency vehicles, a dedicated evacuation route, a countermeasure and collision risks in assessing an evacuation of persons with mobility needs.

Emergency vehicle - Each emergency vehicle is assumed to be single occupant ambulance. To implement an ambulance operation within the traffic simulation model, the following tour attributes are identified, and estimated utilizing the Monte Carlo simulation and DynTIP optimization model.

- Vehicle and trip ID.
- Tour start time – Tour start time is the departure time of a vehicle from a hospital or nursing home and is calculated through DynTIP.
- Tour end time – Tour end time refers to the time when a vehicle returns at the origin facility for the next pick-up. This time is obtained through DynTIP.
- Origin and destination – Origin refers to Hs and NHs within the peninsula, and destination are the Hs and NHs located outside the peninsula.
- Dwelling time – Processing time for pick-up and drop-offs at Hs and NHs obtained through a Monte Carlo simulation.

Evacuation route and countermeasure - An ambulance performs more than a tour to pick up persons with mobility needs from Hs and NHs and drop them off at the selected Hs, and NHs. Each vehicle is tracked by facilty locations and unique IDs and analyzed for performance metrics.

This study assumes that all ambulances utilize a dedicated emergency evacuation route to move persons from Hs and NHs within the Halifax Peninsula to the identified destination locations. In this study, the traffic microsimulation model is modified in three ways as it (1) incorporates a dedicated evacuation route that implements a contraflow traffic operation during an evacuation, (2) creates eighteen new zones representing Hs and NHs in the HRM, and (3) adds a tour schedule for implementing ambulance operations within the updated traffic microsimulation model. As mentioned earlier, contraflow is an engineering technique to reverse all the inbound lanes towards outbound of the city to increase the netwrok capacity [29,30]. Most studies illustrated contraflow on a highway. Alternatively, *Habib et al.* [15] identified an evacuation route through the congested urban transport network and recommended contraflow traffic operation with necessary suggestions regarding network configuration changes. The authors conducted a Strength, Weakness, Opportunity, and Threat (SWOT) analysis to determine the rankings of nine potential candidate evacuation routes and selected the final route based on comparative scores. The contraflow traffic operation is implemented along the selected evacuation routes by carrying out the alterations of road network elements suggested by *Habib et al.* [15]. The traffic simulation model developed

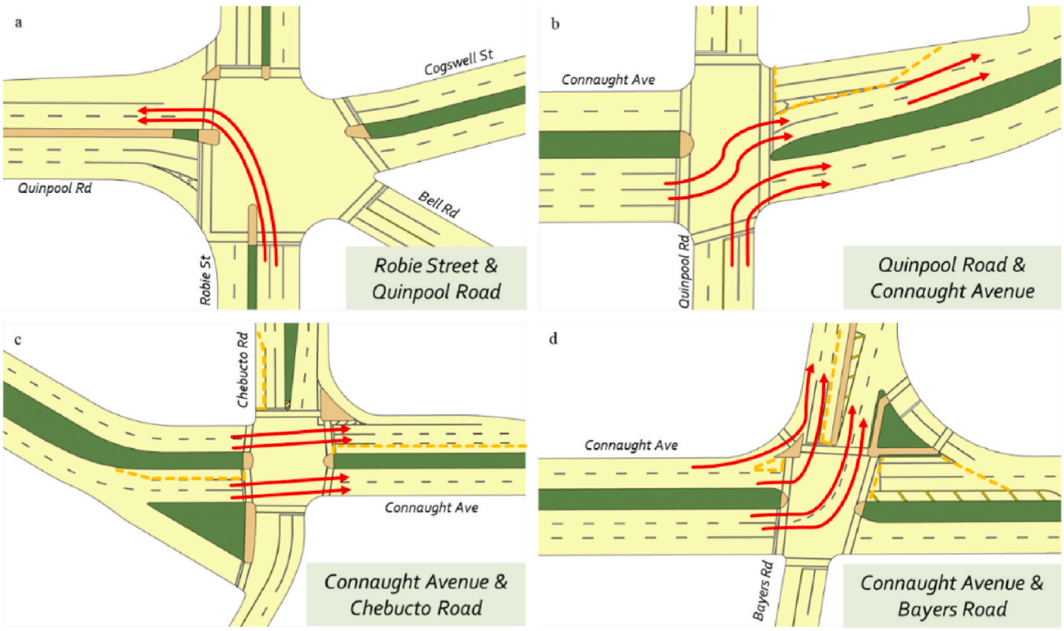

Fig. 3. Traffic operation recommendations at intersections (a) Quinpool Road at Robie Street, (b) Quinpool Road at Connaught Avenue, (c) Connaught Avenue at Chebucto Road, and (d) Connaught Avenue at Bayers Road along selected evacuation route being subjected to contraflow operations.

in this study offers the flexibility to reverse the road link directions using a command "reverse link direction" and allows specific types of vehicles to use a roadway link. This feature has enabled this study to make the following changes in Fig. 3 to the evacuation route and create a one-way traffic flow restricting the shadow and background traffic. This research tests two evacuation scenarios within the traffic microsimulation model: (1) emergency vehicle operation without a dedicated evacuation route, and (2) emergency vehicle operations through a dedicated evacuation route.

Collision risk during evacuation – This study considers further complexity in assessing evacuation scenarios by incorporating collision risks within the developed traffic evacuation microsimulation model. The study utilizes a collision prediction model [38] that implements a combined Bayes theory and Monte Carlo simulation techniques to identify collision hotspots and determine the spatial and temporal distribution of collision occurrence in the network. This research has adopted a worst-case scenario from *Alam and Habib* [38] demonstrating concurrent collision events at five key locations, including exit, arterial streets and downtown roads of the city. A red-green signal phase concept is utilized to generate collisions within the traffic microsimulation model dynamically. This technique enables the generation of a collision during an ongoing evacuation where a red light indicates a disruption by collisions.

5. Results and discussions

5.1. Optimization results

This study optimizes the destination allocation and emergency vehicle assignment for evacuating persons with mobility needs from different hospitals and nursing homes on the Halifax Peninsula. A total of six Hs and NHs are identified within the study area that require special transportation assistance to evacuate persons with disability. Fig. 4 illustrates the demand evacuated from different facilities to twelve destinations within a 100 km radius of the peninsula.

Results show that destinations 3, 4, 5, 11, and 12 share the major portion of the PWDs relocated due to their proximity to the peninsula, which can be quickly reached using the highways. It is observed that these destinations share 43% of PWDs during evacuation. The optimization results assert that all members with mobility needs are evacuated by ninety emergency vehicles, and it takes 19.5 h for an optimal allocation of emergency vehicles to all demand at origin locations. 35.6% of the emergency vehicles are allocated to a facility that has a maximum demand comprising 36% of the total. Moreover, this study examines the emergency vehicle service at a temporal scale, revealing that the evacuation of this group of vulnerable population peaks between the 4th and 9th evacuation hours in the network, as shown in Fig. 5. Within this period, all vehicles are already assigned in the network, which perform multiple tours between origin and destinations. These results provide insights into the peak vehicle mobilization time, which will help Hs and NHs authorities to develop proactive plans for preparedness purposes.

5.2. Traffic microsimulation results

5.2.1. Emergency vehicle operation through dedicated evacuation route

To have an in-depth understanding of the emergency vehicle operations in the network, this study simulates PWD evacuation with and without the implementation of emergency evacuation route. The scenario demonstrating the emergency vehicle operation through a dedicated evacuation route with countermeasure applied presents promising results, particularly for evacuating the facilities closest to the route. Fig. 6 presents a box plot of emergency vehicle tour times in scenarios 1 (evacuation without the dedicated route) and 2 (evacuation with dedicated route). The results suggest that 75% of tours have an average completion time of 2 h and 12 min with the emergency route in place. In contrast, in the absence of a special route, a tour is completed in an average time of 2 h and 18 min. The

Fig. 4. Demand evacuated from different Hs and NHs to twelve destinations within a 100 km radius of the peninsula.

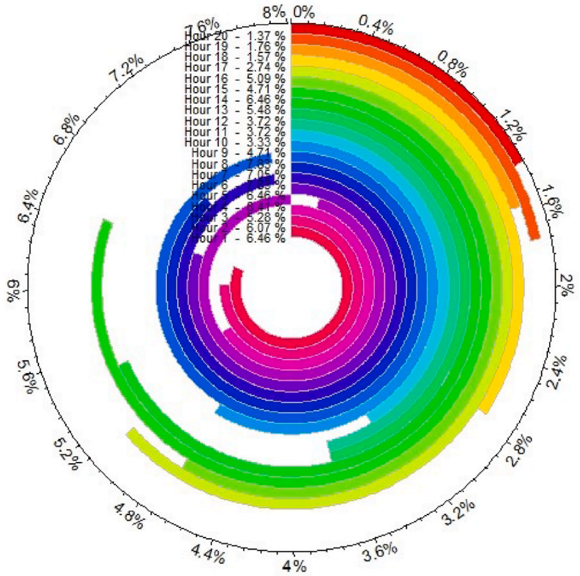

Fig. 5. Percent completion of the PWD evacuation in different evacuation hours.

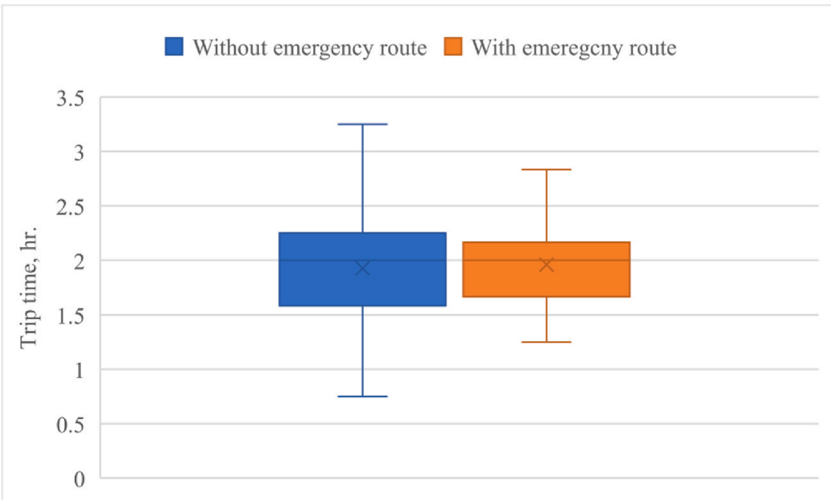

Fig. 6. Ambulance tour time distribution for the evacuation of persons with mobility needs from facilities located in proximity to the evacuation route.

maximum time to complete a tour in scenario 2 is 25.2 min less than in scenario 1. The results also suggest that it takes 21 h to evacuate all PWDs through optimal utilization of emergency vehicles while it takes 23.9 h to evacuate the entire peninsula.

In the case of a hospital located farther from the access points of the evacuation route and requires travelling several blocks to access the route, it is observed that it takes a higher average time to complete a tour. Fig. 7 illustrates that the average tour time for an emergency vehicle is less in the scenario without the dedicated route as the corresponding care facility is closely located to an exit (i.e., one block farther) which is a faster approach for evacuating the peninsula.

Although a dedicated route with special traffic operation measures benefits most Hs and NHs, ambulance from a care facility mentioned above anticipate an average travel time of 1.92 h in scenario 1 while it is 2.08 h in scenario 2. The results highlight the importance of the dedicated emergency evacuation routes, possibly in combination with countermeasure application to ascertain that the emergency vehicles are not rendered immobile; however, the emergency traffic operation planning should address the operational requirements for evacuation of the vulnerable population from different facilities sparsely located in the network.

5.2.2. Emergency vehicle operation with collision risks

This study explores the evacuation process for persons with mobility needs accounting for uncertain collision risks in the network. Results reveal that any threat has the potential to significantly impact the overall evacuation process, particularly, it may increase the

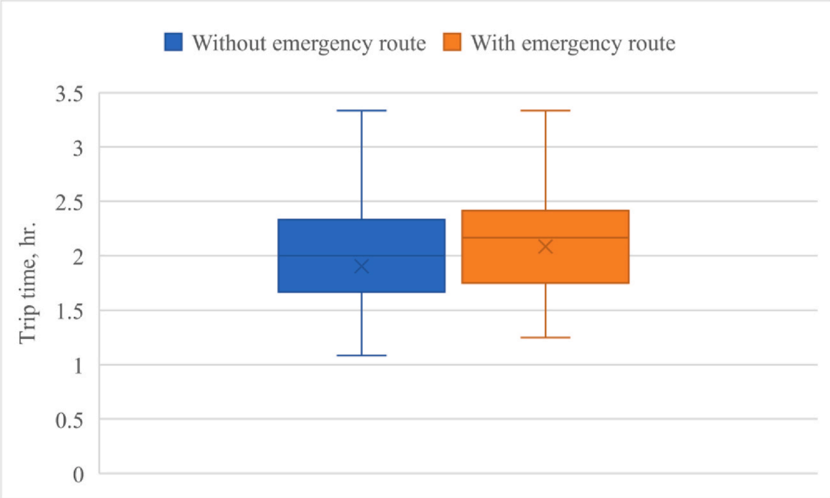

Fig. 7. Ambulance tour time distribution for the evacuation of persons with mobility needs from facilities located farther from the evacuation route.

evacuation time and lead to an incomplete evacuation. Simulation results suggest that collisions in the network may yield an evacuation time of 31 h for 65,000 traffic that demonstrate an increase of 29.7% in evacuation time with respect to the evacuation time under a no-collision scenario. However, evacuation of persons with mobility needs can not be completed due to an increase in tour time of the ambulance. Results show that only 72.3% evacuation of persons with mobility needs can be accomplished within this timeframe. The reason is that 68% of ambulances complete 0.5–3.5 fewer tours compared to the number of tours made in a scenario without collision. This result warrants a special attention to emergency evacuation planning for persons with mobility needs as this group of people is impacted the most by any natural hazards, and uncertain threats.

5.2.3. *Overall evacuation performances*

This study explores the potential impacts on the overall evacuation performances that may result from emergency vehicle operations under different network conditions. Fig. 8 demonstrates zonal clearance time for two scenarios mentioned earlier. Fig. 8 shows that in scenario 2 with the dedicated evacuation route, 41% of zones anticipate a reduction of 15min - 4.75 h in clearance time with respect to scenario 1. Although, travel times of several zones increase, it does not affect the overall evacuation time, which indicates the possibility of accommodating the requirements of diverse groups within the evacuation plan to make the evacuation equitable and beneficial to all.

6. Conclusions

Accommodating persons with disabilities, particularly those requiring mobility assistance during a mass evacuation, is a critical consideration for emergency planners and engineers. Combined with the persistent and ever-growing threat of climate change, which predicts an increase in natural hazards, the potential need for evacuation, and the growth in the composition of vulnerable populations, pragmatic modelling approaches that specifically account for persons with mobility needs is more vital than ever. Primarily, this research aims to investigate the resources and traffic operation requirements for evacuating persons with mobility needs located on the Halifax Peninsula region of the Halifax Regional Municipality, Nova Scotia, Canada. Given its inherent vulnerable proximity to the surrounding coastline and limited routes for evacuation, this focused investigation seeks to provide policymakers with insights into challenges associated with evacuating persons with mobility needs and help develop strategies to account for often overlooked community members. The novelty of this study is that it combines optimization and traffic simulation modelling to account for multiple risks and factors in developing and testing an evacuation process for persons with mobility needs. Furthermore, the study optimizes resource allocations and implements a designated emergency evacuation route within the traffic simulation modelling framework to improve the evacuations of this group of vulnerable populations.

The study tests a case study of Halifax, Canada, involving the evacuation of five hundred and twelve persons with mobility needs using the emergency vehicles owned by the Nova Scotia Emergency Health Services. The evacuation is evaluated by two operational conditions: emergency vehicle operation with and without the dedicated evacuation route equipped with contraflow. The results from this analysis show that the mass evacuation of persons with mobility needs using provincial ambulance fleets is a practical and effective method of accounting for special groups, resulting in their continued care in Hs and Ns outside the evacuation boundary. The optimization process allocates ninety ambulances to evacuate all mobility assistance-seeking individuals in 21 h. On the other hand, the entire peninsula is evacuated in 23.9 h. This study concludes that, travel time along the evacuation route reduces by 32.31%. Moreover, the maximum tour time also decreases by 25.2 min if evacuation is carried out through the implemented dedicated evacuation route. On the other hand, the study finds that if collision risk is considered within the evacuation simulation modelling, it takes 31 h to evacuate the peninsula. However, only 72.3% of persons, needing mobility assistance are evacuated within the same time

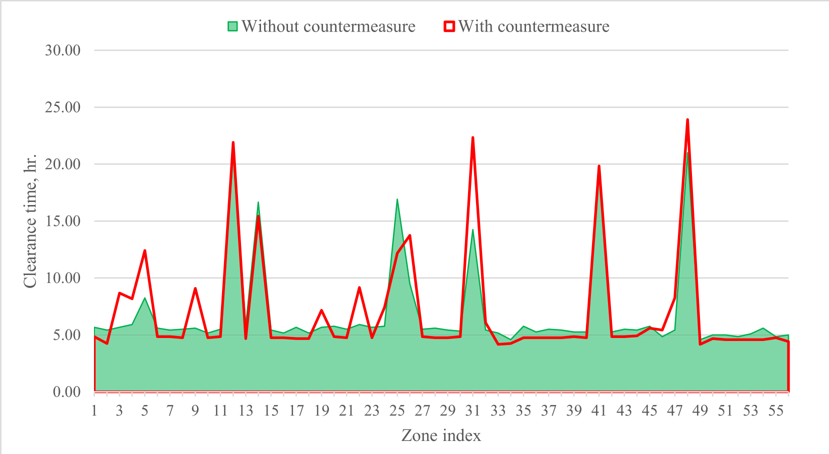

Fig. 8. Zonal evacuation time in Halifax with and without a dedicated evacuation route.

frame. The method developed in this study is applicable to other geographies and the developed optimization model can be expanded to allocate the required resources for evacuation, particularly, when there exist equity issues, for instance, those who have personal vehicles are in an advantageous position during a resource scarcity.

The study has some limitations. For example, it assumes that all persons, needing mobility assistance, need an ambulance for their evacuations. It would be interesting to explore an allocation of different types of emergency vehicles based on the levels of disability and evaluate the role of transit in this context within the modelling framework. Moreover, it is important to conduct a finer estimation of the mobilization time in relation to levels of disability, and develop a prioritization process accordingly, which warrant the collection of the observed data. Observed data would also help future research to incorporate evacuation behaviour within the traffic evacuation microsimulation model.

Nevertheless, the study fills the gap in the evacuation literature by developing an operational evacuation modelling framework for vulnerable populations, particularly focusing on the persons with mobility needs. It advances traffic evacuation microsimulation by incorporating special vehicle fleets i.e., ambulance for curb-side pick-up of persons with mobility needs from hospitals and nursing homes and evacuating them to designated destinations. The modelling framework developed incorporates uncertain risks to explore the subsequent impacts on the evacuation of the vulnerable population. Further, it evaluates traffic operation improvement measures to ascertain an efficient evacuation. The methodology developed in this model is generic. The model can be applied to other jurisdictions using a similar set of information, including network topography, demand, hospitals and nursing home facility, and emergency vehicle fleet data. The research will help emergency management professionals develop policies to tackle challenges and risks associated with evacuating persons with disability and mobility needs and implement suitable preventive measures.

Author contribution statement

The authors confirm contribution to the paper as follows: study conception and design: **MD Jahedul Alam**, **Muhammad Ahsanul Habib**; data collection: **MD Jahedul Alam**, **Muhammad Ahsanul Habib**, **Devin Husk**; analysis and interpretation of results: **MD Jahedul Alam**, **Muhammad Ahsanul Habib, Devin Husk**; draft manuscript preparation: **MD Jahedul Alam, Devin Husk, Muhammad Ahsanul Habib**. All authors reviewed the results and approved the final version of the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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