PLANNING OF EMERGENCY EVACUATION FOR PERSONS WITH DISABILITY

Prepared by:
MD Jahedul Alam and Muhammad Ahsanul Habib

Prepared for:
MacEachen Institute for Public Policy and Governance, Dalhousie University

Research Report 2022-03

2022

Dalhousie Transportation Collaboratory (DalTRAC)
Rm B105, Dalhousie University, PO Box: 15000
1360 Barrington Street, Halifax, NS Canada, B3H 4R2

Contents

List of Tables

List of Figures

1. Introduction

A mass evacuation plan is one of the most vital elements of emergency planning to guide thousands of people onto safe routes and relocate them to designated safe shelters during an evacuation due to natural hazards. Extreme weather and catastrophic events, be it natural or human-made, pose an increasing and ever-present risk to many urban centers worldwide. Cities subjected to natural disasters, such as hurricanes and flooding, understand the urgency of an efficient evacuation plan, which ensures the supply of transportation and implements traffic management strategies to respond to the mobility needs of the population at risk during an emergency. Nonetheless, a comprehensive plan takes into account vulnerable populations, as their evacuation is more challenging and entails multiple types of risks and factors, which are often overlooked in emergency planning and evacuation literature. For example, a national survey of hurricane evacuation revealed that low mobility and special needs groups are underrepresented in evacuation plans *(Wolshon et al., 2001)*. As *Renne et al. (2011)* posit, evacuation procedures often omit targeted responses for the preparedness of carless and mobility-limited residents, including a disproportionate share of persons with disability (PWDs). The overarching problem with the evacuation of persons with mobility needs is the lack of suitable planning that ascertains the appropriate shelter allocation, optimal emergency vehicle, and evacuation route utilization to avoid any unprecedented traffic congestion in the network *(Ebrahimnejad et al., 2021)*.

A dedicated evacuation route is critical to provide a least-interrupted gateway for the evacuation of PWDs using emergency vehicles. However, a major challenge when determining an evacuation route is to identify its planning elements and to understand the route effectiveness in responding to different evacuation traffic conditions. Another major concern is that the majority of studies *(Zou et al., 2005; Dow and Cutter, 2002; Madireddy et al., 2011)* discussed and analyzed highway evacuation routes; however, there is an urgent need to understand the process of evacuating people from an urban environment, including downtowns through a dedicated evacuation route, as most urban centers have narrow roads and lower road capacity. Several studies *(Cova and Johnson, 2003; Heydar et al., 2016)* performed evacuation routing based on traffic assignment and travel time optimization. However, they present limited content on the interaction between traffic flows and the evacuation route selection process. *Alam et al. (2018)* developed a combined flood risk and traffic microsimulation model to determine network disruptions and resulting traffic congestion during an evacuation in the network. Still, there is a gap in understanding what evacuation routes may work best in a vulnerable transport network considering flood risk, traffic flow outcomes, and the mobility needs of person with disability. Even so, modelling evacuations by automobiles and buses using different optimization and simulation techniques *(Abdelgawad and Abdulhai, 2009; Alam and Habib, 2021a; Naghawi and Wolshon, 2011)* provide valuable insights into evacuation time and traffic congestion. However, robust modelling research is limited in addressing the challenges and complexities in the evacuations of PWDs from the endangered areas to designated shelters. To date, the majority of studies for PWDs focuses on localized, small-scale approaches, including buildings or small facilities evacuation. Therefore, there is a gap in knowledge and practical application considering the mass evacuation of this vulnerable population at a city or regional scale.

Therefore, the objectives of this study are: (1) to determine a dedicated evacuation route following a Strength, Weakness, Opportunity, and Threat (SWOT) analysis for the evacuation of PWDs, and (2) to develop an integrated evacuation modelling framework following a combined optimization and traffic simulation approach to test and evaluate the evacuation of PWDs. First, the study takes into account microsimulation results and field observations in a systematic assessment of evacuation routes for densely populated urban cities to lead evacuees to existing highway evacuation routes for a safe arrival at shelters. By building a traffic evacuation microsimulation model that considers flooding damages to the network, the study produces spatial and temporal traffic congestion data to assist in the evaluation of candidate routes. A 'strength, weakness, opportunities and threats analysis (SWOT) is conducted to determine the optimum evacuation route. Finally, the selected evacuation route is provided with traffic operation recommendations to further optimize evacuation traffic flows. Second, it develops an integrated modelling approach that is demonstrably critical in accounting for resource constraints and traffic operation issues to assess the evacuation of persons with disability holistically. The study applies a simulation model to implement two scenarios: (1) evacuation without any dedicated evacuation route, and (2) evacuation through a dedicated evacuation route. This study provides a benchmark for the measurement of network performances during the evacuation. The baseline understanding of evacuation trip time, zonal clearance time and emergency vehicle 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, emergency management professionals have repeatedly referenced significant shortfalls in the accommodation of vulnerable populations, including PWDs during evacuations. *Bloodworth et al. (2007)* argued that the City of New Orleans was not equipped with the knowledge and preparation to meet the needs of vulnerable populations during the active evacuation and sheltering from Hurricane Katrina. 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 (2015)* 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 is limited. In other literature, such as *Apte et al. (2015)*, it is suggested 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 *(Wolshon et al., 2001)*, in the content analysis of evacuation policies, *Wolshon (2009)* found that only 23 out of 150 policies 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. (2020)* found that elderly persons are more vulnerable due to residing within hospitals and long-term care facilities, which are not often co-located within existing evacuation routes. On the other hand, *Nakanishi et al's (2019)* study in the context of flood evacuation behaviour found that vulnerable and slow-moving elderly people pose a significant increase in projected 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 of or inability to use personal motor vehicle options. Adding to this, *Yazdani et al's (2021)* study reveals a particular vulnerability of residential healthcare infrastructure on evacuation-inducing disasters or climate events that further compound 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 *(Kako et al., 2020)*. *Renne et al. (2011)* 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. In large, the current academic evacuation modelling literature focuses on indoor egress *(Habib et al., 2020)* and small-scale simulation *(Egodage et al., 2020)*. However, many of these methodologies may expand to a larger, city or regional mass evacuation scale. In other evacuation modelling scenarios, such as that performed by *Noh et al. (2016)*, 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.

Although a small amount, there does exist some evacuation research that demonstrates computational modelling methodologies for persons with mobility needs. For example, *Kaiser et al. (2012)* examines urban evacuation using public transit for special needs residents using a linear programming optimization model to determine optimum locations for stops. Through this research, *Kaiser et al. (2012)* determine that between a mathematical and simulation model, the former yielded the best results in terms of effectiveness and speed using 20, 30, 40, 50, and 60 bus stop allocations. In another study, *Dulebnets et al. (2020)* introduced a multi-objective optimization model to minimize negative factors such as total evacuation time and mental and physical demand. Unlike other similar studies, *Dulebnets et al. (2020)* especially accounts for critical social characteristics and the demands placed on evacuees. Finally, *Ebrahimnejah et al. (2021)* applied optimization techniques to retrieve and transfer PWDs from designated locations to previously identified shelters. In this study, *Ebrahimnejah et al. (2021)* utilized small-sized cars and medium-sized vans to the fleet of evacuation vehicles, which significantly reduced the time for tours travelled. These studies assume that all PWDs move to pick-up locations and public transportation take them to shelters, co-sharing the road network with other traffic. However, persons who are immobile may require a curbside pick-up using special vehicles, including ambulances. In addition, it demands a dedicated evacuation route to ensure that the emergency vehicles are not immobile due to traffic congestion in the city center.

Literature *(Urbina, 2002; Wolshon, 2002)* suggests that using an evacuation route paired with contraflow countermeasures is found the most efficient and expedient way to evacuate individuals. Particularly, a dedicated route can be modified to provide ambulances a traffic stream with no hindrance from opposing traffic ensuring an efficient emergency vehicle operation. In evacuation research, contraflow is a countermeasure that involves turning one or more inbound road links outward of the city under risk to increase the road capacity *(Fries et. al. 2011; Wolshon et al., 2005)*. However, in relation to the route evaluation process, there are still several other limiting factors present in existing literature. The first is that earlier studies focus on identification of evacuation routes through only highways and major arterial streets. Particularly, limited research contributions are made for identifying evacuation routes through a congested urban core. The proposed modeling framework in this study fills this gap by focusing on lower capacity roads in high density areas. Second, the studies and articles utilized case studies that have direct highway connections to the inner city, which eliminates two restricting factors in evacuation planning, route capacity and ease of access. This convenience is absent in the context of many coastal cities such as Halifax, Canada. Moreover, the inner-city network in the coastal region has a greater chance to be inundated by flooding as reported by *Alam et. al. (2018)*.

This study contributes to the gaps in existing literature by exploring evacuation of PWDs through a dedicated evacuation route accounting for multiple risk and factors within the proposed integrated evacuation modelling framework. The study utilizes a traffic evacuation microsimulation model and a flood risk model to predict network disruptions and traffic congestions that inform the evacuation route selection process. Furthermore, this study 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 utilizing the evacuation route identified. 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 with information regarding the emergency vehicle activity schedule to relocate PWDs from the Halifax Peninsula to Hospitals (Hs) and Nursing Homes (NHs).

3. Methodology

4.1 Evacuation Route Determination Framework

This study follows a three-stage approach to determine a dedicated evacuation route: (1) selection of candidate routes following a flood risk and traffic evacuation microsimulation modeling approach (2) evaluation of candidate routes by conducting a 'strength, weakness, opportunities, and threats (SWOT)' analysis and implementing a point system, and (3) development of planning recommendations for the final evacuation route. Each stage is described sequentially in the following sections.

4.1.1 Candidate Route Selection Process

A combined flood risk and traffic microsimulation model is utilized to produce three sets of data including the average speed of vehicles on street segments, maximum queue length and traffic volume that certain intersections experience during the evacuation period. Analyzing and visualizing the data produced by the traffic evacuation microsimulation model has been instrumental in developing recommended evacuation routes by identifying specific street segments or traffic movements that experience congestion. Moreover, the number of vehicles on the street segments of the simulation suggests which routes are most heavily used to evacuate the Halifax Peninsula. A Geographic Information System (GIS) is used, in this case ArcGIS and ArcScene, to map the cases and routes, and the traffic simulation result is analyzed through GIS to ascertain where the congestion points are within the Halifax Peninsula. A brief description of the traffic simulation model is presented below.

4.1.2 Traffic Microsimulation Modelling

The traffic evacuation microsimulation model used in this study follows three steps: (1) data processing, (2) network coding, and (3) calibration and validation of the model. To develop the model, various data types are utilized, for example road geometry information from the Halifax Geodatabase 2012 is used for network coding within VISSIM platform. Travel demand data obtained from the Halifax transport network model *(Bela and Habib, 2018)* informs the development of origin-destination trip matrices. Traffic count and signal timing data are collected from the Halifax Regional Municipality Public Work Traffic Study 2014. The traffic simulation model contains all the elements of an actual network including links, intersections, traffic analysis zones, and traffic controls. This model built upon a dynamic traffic assignment procedure to replicate heavily congested transport network operations. A brief overview of the model is provided in the following Table 1. Figure 1a and 1b provide a representation of the transport network and traffic movements within the traffic microsimulation model respectively.

Table 1. Traffic microsimulation model overview

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; PWDs shelter#: 12; General shelter#: 2
Traffic 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 respectively for two morning peak periods

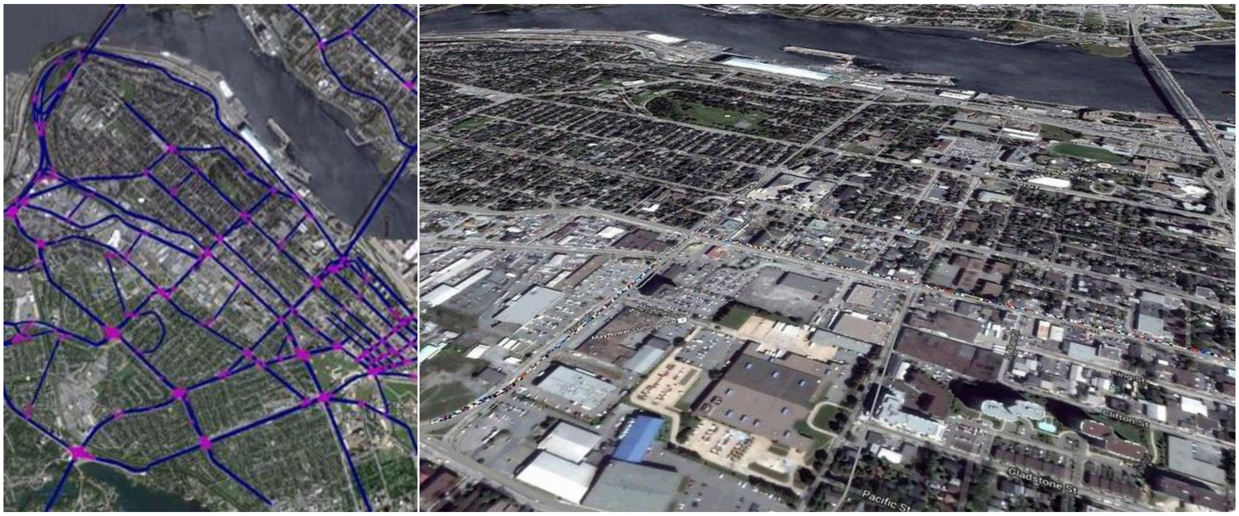

Figure 1: Representation of (a) transport network, and (b) traffic movements within traffic microsimulation model

A flood risk model, which identifies the network links that are prone to inundation during floods of different extremes is combined with the traffic simulation model. To address the flood related damages to the network, the anticipated links for floods of 2.9m and 3.9m are made inactive during the evacuation simulation within the simulation model. The model also reports other flood scenarios including 7.9m, 15m and 30m. Details of the flood risk model and traffic microsimulation model can be found in *Alam et al. (2018)*. This study also develops easy to interpret visualization maps from the results of the microsimulation model. For instance, Figure 2 shows key intersections in the Halifax transport network with traffic queue lengths to better understand network congestion and traffic movements during an evacuation.

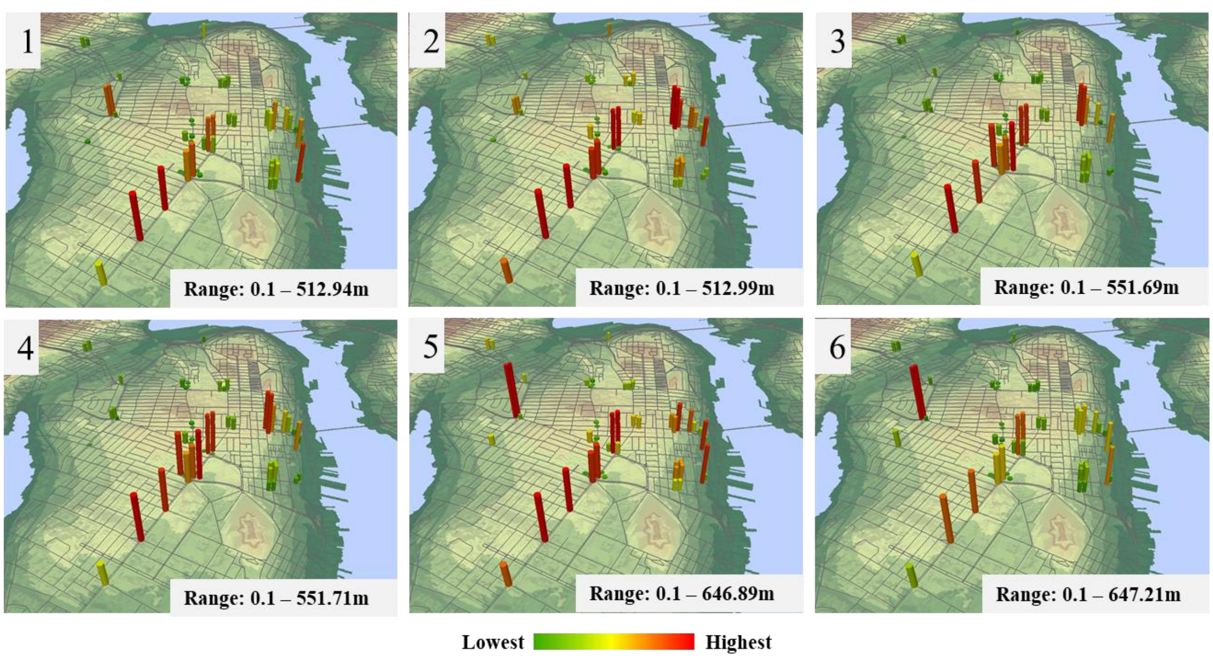

Figure 2: Congestion points at intersections measured by queue length during the congested evacuation hours.

Congestion points are measured using queue lengths at intersections. The results from congestion points identify specific intersections that experience long queues of vehicles, which can specifically identify where congestion is originating in the transportation network. The visualization assists in the qualitative assessment of the evacuation routes, including the SWOT analysis.

4.1.3 Candidate Route Prospects: A SWOT Analysis and Point System

This study performs a link-by-link SWOT analysis to examine the prospect of each candidate evacuation route and a point system is implemented to score the routes for comparison. The point system is implemented for the evaluation of the roadway elements of the candidate routes. Each phase of the processes is described below.

4.1.4 SWOT Analysis of Candidate Evacuation Routes

To determine the final evacuation route, the arterial roads were connected to the most natural exit point. Each candidate route is then evaluated in relation to its strength, weakness, opportunities, and threats. An overall discussion of these four aspects is presented below.

Strengths - The evaluation consists of ease of connectivity, traffic flow efficiency, and route flexibility. The strength of a route is measured in relation to identified criteria, for example, greater arterial road connections, a consistent number of lanes along the entirety of the route and having room to accommodate emergency responders. These strengths in turn allow the study to grade the routes based on aspects that would provide the most flexibility and efficiency during the evacuation of Halifax such as the ability to use the road as a constant communication and command link and the ability to accommodate large volumes of traffic. This assessment of the route's strengths will also provide the basis for understanding which routes to use in alternate situations.

Weaknesses - The evaluation consists of examining the weak aspects of a route that would hinder the evacuation efforts, such as lane number alterations, and creating bottlenecks. The bottlenecks in the transportation network can be caused by the fluctuation of lane numbers whereby multiple lanes would have to merge limiting throughput such as on/off ramps, narrow roads, and the presence of turning lanes. These bottlenecks are then combined with the possibility of unusual road configurations such as the presence of side roads entering the route at odd angles to round out the weaknesses.

Opportunities - The opportunities examined allow the study to determine where possible improvements could be made and what aspects of each route could be used by emergency managers and emergency crews to provide an advantage during evacuations. These opportunities are comprised of whether the route is suitable for staggered zonal evacuations, has an active transit priority lane or one yet to be constructed, and whether the route is a suitable backup route. These aspects could in turn provide the ability to expand the amount of traffic throughput or ability to provide a consistent emergency response route and have ready backup routes in case the primary route is impassable.

Threats - Threats in the context of this study are comprised of examining the routes for aspects that could hinder the evacuation and that were beyond the structural limitations of the route. These threats could be related to inter-agency communication and coordination, or more surrounding structural issues. The communication threats primarily stem from the possibility of coordination issues while undertaking the evacuation such as between the emergency management teams of the HRM and the

Halifax Bridge Commission. The structural issues are related to the city surrounding the route, such as gas stations or redevelopments, that slow traffic and are a potential hazard.

4.1.5 Quantitative Evaluation of Candidate Evacuation Routes

This study conducts a roadway element criteria evaluation in order to compare the candidate evacuation routes. These roadway elements have been noted during field visits and supplemented by aerial map analysis. The elements considered in this study are listed in Table 2.

Each of the criteria listed in Table 2 are divided into three score categories. The highest score category is 2, the middle category is 1, and the lowest is 0. Two different scoring methods are assigned to the criteria based on how they are measured (either number or percentage). The first scoring method uses the range of values of a criterion and divides the difference of this range by three to end up with the three score categories. The number of four-way intersections, number of three-way intersections and number of signalized intersections use this scoring method. Table 2 lists the roadway element evaluation criteria and their scoring categories. The purpose of counting the number of intersections and signalized intersections is to get an idea of how many times vehicles may have to slow down or stop along the potential evacuation routes.

Table 2. Roadway Element Evaluation Criteria and Scoring Categories

Roadway element evaluation criteria	Score		
	Zero	One	Two
# of 4-way intersections	16-20	10-15	3-9
# of 3-way intersections	24-31	16-23	8-15
# of signalized intersections	13-16	9-12	4-8
# of inbound lanes	1.00-1.33	1.34-1.66	1.67-2.00
# of outbound lanes	1.00-1.33	1.34-1.66	1.67-2.00
# of inbound transit lanes	0	0.01-0.49	0.50-1.00
# of outbound transit lanes	0	0.01-0.49	0.50-1.00
Flood risk	2.9m & 3.9m	>=7.9m	-
Wind i.e., possibility of closure/restrictions	Yes	No	-

For flood risk, the two lowest flood scenarios, i.e., 2.9m and 3.9m, resulted in a score of 0. If a route was affected by flooding from a 7.9m flood, it receives a 1. If there was no risk or only risk for tsunami flood values of 15m and 30m, it scores a 2. The flood risk scores were assigned this way because the 2.9m and 3.9m flood risks are the most likely to occur and have previously occurred. 7.9m flood would be from an unprecedented storm. The tsunami flood is more unlikely and would only cause flooding after the impact of the tsunami, and not during the evacuation process. Other storms, such as hurricanes, may bring storm surges causing flooding before the landfall of the storm. The risk of restrictions to or closures of major links due to wind are assigned a 0 if there is a possibility of restrictions or closures, and a 1 if there are no possibilities of restrictions or closures. Although an evacuation would see drivers using the outbound lanes, inbound lanes are included in the evaluation with the possibility of reorganizing lane configurations or traffic flow directions during an evacuation. Although the framework developed is flexible to test different weighting schemes, this study utilizes the weighting scenario presented in Table 2. Following the combined qualitative and quantitative approach mentioned above, a final evacuation route is selected and utilized within the traffic simulation model for the evacuation of PWDs.

4.2 Evacuation of Persons with Disability (PWD)

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 a dedicated and efficient route leading to destinations. Hence, the methodology of PWD evacuation in 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 destination allocation to emergency vehicle tours, and (3) traffic microsimulation modelling of an evacuation of persons with mobility needs through evacuation route. Note that the dwelling time is a part of the total emergency vehicle tour time. This study updates relevant parameters associated with optimization modelling, 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. Figure 3 presents an overall framework illustrating all components required to evacuate persons with mobility needs from Hs and NHs.

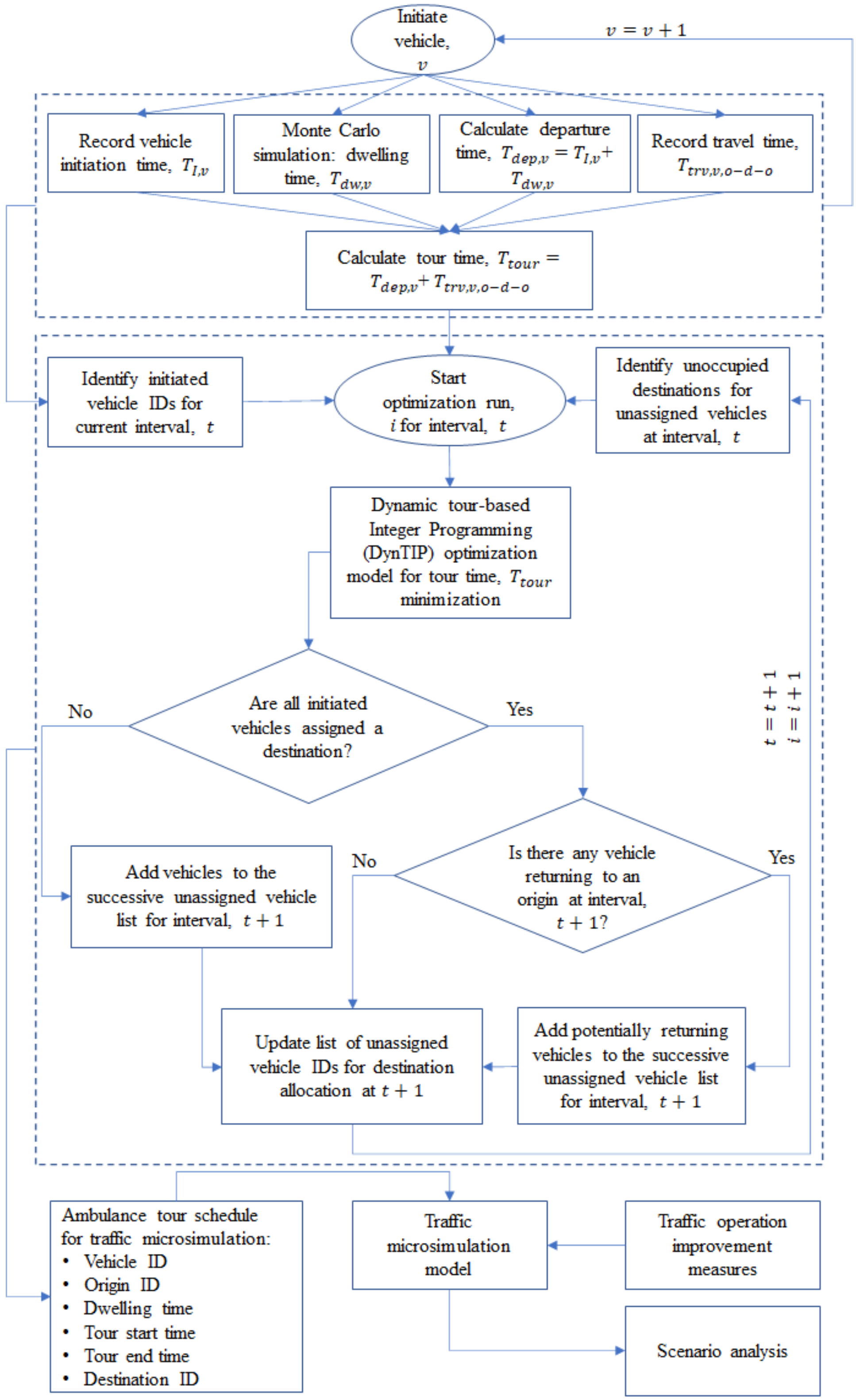

Figure 3: Conceptual framework to optimize and simulate an evacuation operation for the persons with mobility needs using emergency vehicles

4.2.1 Emergency Vehicle Dwelling Time Distribution Model

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 comprised a total of 24,403 instances of emergency transportation to hospitals in Halifax. This total represents approximately 40% of total emergency vehicle demand 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. A tour time of a vehicle thereby 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 minimized within the optimization model when determine 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 determine 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 inter quartile range. IQR can be calculated using the following equations

$$IQR = Q_3 - Q_1,$$

where $Q_1$and Q_3represent the first and third quartile values of the entire data, respectively

- Step 3: Initiate the Monte Carlo simulation, r
- Step 4: Determine the $ADT$and IQR using 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 $r + 1$

It takes 685 Monte Carlo simulation runs to achieve a distribution deviated by only 1% than the observed distribution of the dwelling time for emergency vehicles. This model helps to develop an emergency vehicle scenario

4.2.2 Optimization of Destination and Emergency Vehicle Allocation

This study develops a dynamic tour-based Integer Programming (IP) optimization model (DynTIP) 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 considering 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.

Hence, the destination allocation is dynamic in this study. The optimization model is run at interval t until the target demand is completely evacuated from all the facilities.

4.2.2.1 Assumptions and DynTIP Formulation

This study identifies all hospitals and nursing homes within 100 kilometres of the Halifax Peninsula to prepare a destination choice set for the optimization model. Figure 4 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.

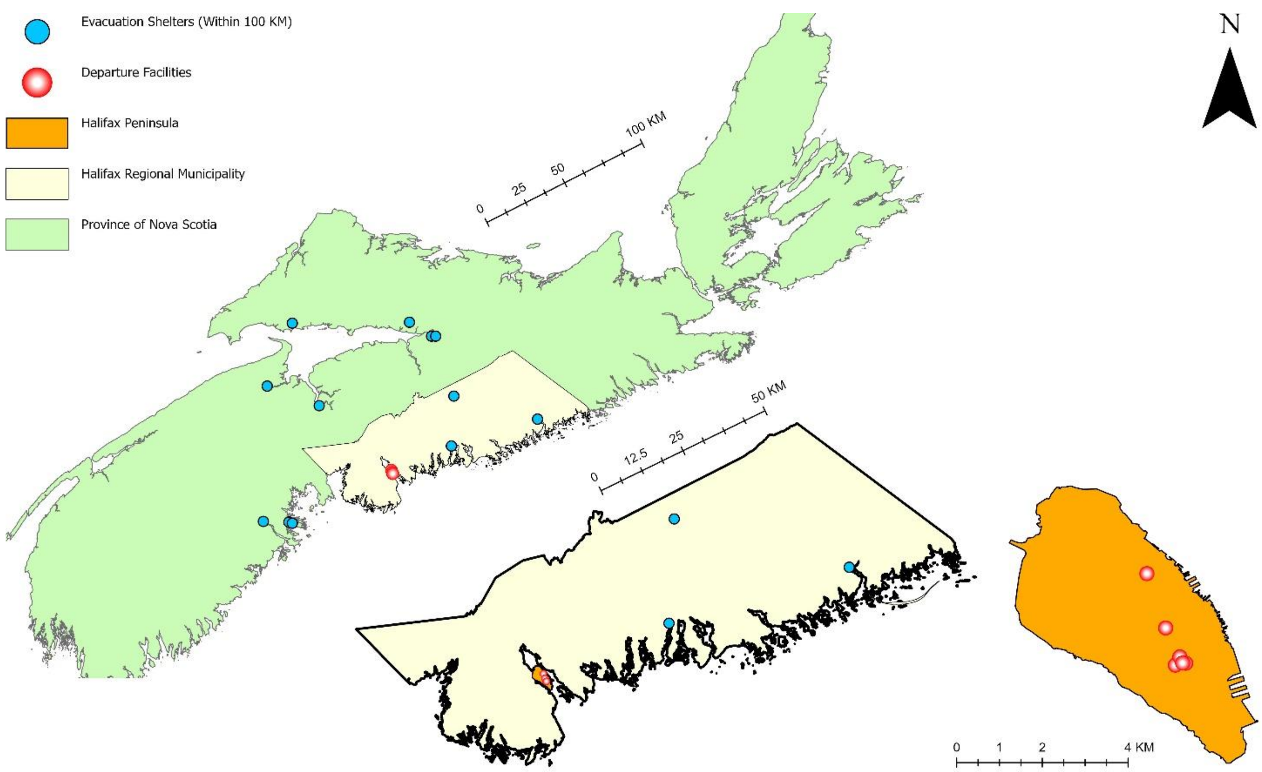

Figure 4: Halifax Peninsula Contextual Geography with Receiving and Departing Locations.

For the optimization model, let $v \in V$ denote an emergency vehicle, where $V = \{v_1, v_2, v_3, \dots\dots\dots\dots v_n\}$ is the set of all emergency vehicles; suppose $f \in F$ denote a facility, where $F = \{f_1, f_2, f_3, \dots\dots\dots\dots f_n\}$ is the set of all facilities; and let $d \in D$ represent a destination, where $D = \{d_1, d_2, d_3, \dots\dots\dots d_n\}$ is the set of all destination locations. Demand at a facility is denoted by Df and each destination has a capacity 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 from the facility f that is shifted 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.

Objectives:

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

Subjected to:

$$\sum_{d \in D} x_{fdt} \geq D_f, \forall f$$

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

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

$$t \leq T, \forall t$$

$$x_{fdt} \geq 0$$

$$y_{vfd} = \{0, 1\}$$

Constraint (i) ensures that all demand of a facility is shifted to a destination, 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 IP model is implemented within a Mathematical Programming Language modelling system platform. The model utilizes several inputs, including vehicle fleet, demand at facilities, travel time, dwell 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 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.

4.2.3 Traffic Microsimulation Modelling of Emergency Vehicle Operations and Evacuation Route

A total of 512 number of persons, requiring mobility assistance are evacuated using ambulances. This study utilized Nova Scotia nursing home and care facility directory and the hospital websites (e.g., https://novascotia.ca/dhw/ccs/documents/nursing-homes-and-residential-care-directories.pdf) to reasonably estimate the demand based on the number of beds. This study assumes that 20% of the persons with disability would need mobility assistance and ambulances for evacuation.

Additionally, 65,000 normal traffic estimated from a Halifax Regional Transport Network Model (Bela and Habib, 2018) are simulated to replicate the traffic congestions due to evacuating and background traffic. The model includes passenger cars, transit buses, and ambulances in evacuation. Traffic microsimulation model is modified to include an emergency vehicle operation, a dedicated emergency route, a countermeasure and collision risks in assessing an evacuation of persons with mobility needs.

Each emergency vehicle is assumed to be single occupancy, and related tour attributes are estimated based on the results from DynTIP. To implement an emergency vehicle tour operation within the traffic simulation model, the following tour attributes are identified, estimated, utilizing the Monte Carlo simulation and DynTIP optimization model.

- Vehicle, and trip ID.
- Tour starts time – Tour starts 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 required for a vehicle to drop a person at a destination facility and come back to the origin facility for the next pick-up. This time is obtained through DynTIP.
- Origin and destination – Origin refers to hospitals and nursing homes 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.

An emergency vehicle performs more than a tour to pick up persons with mobility needs from Hs and NHs and drop them off at other similar service centers. Each vehicle is tracked by locations and IDs, including trip ID, and is analyzed for performance metrics.

This study assumes that all emergency vehicles utilize a dedicated 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 designated 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 emergency vehicle 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 capacity of the network *(Urbina, 2002; Wolshon, 2002)*. These studies illustrated contraflow on a highway. Alternatively, *Habib et al. (2020)* 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 scores. A contraflow traffic operation is implemented along the selected evacuation routes by carrying out the alterations of road network elements suggested by *Habib et al. (2020)*. The traffic simulation model developed in this study offers a flexibility to reverse the road link directions using a command "reverse link direction" and allow to permit specific types of vehicles to use a roadway link. This feature has enabled this study to make the following changes in Figure 5 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 route. In the latter scenario, the traffic network offers a dedicated evacuation route with traffic operation improvement strategy embedded.

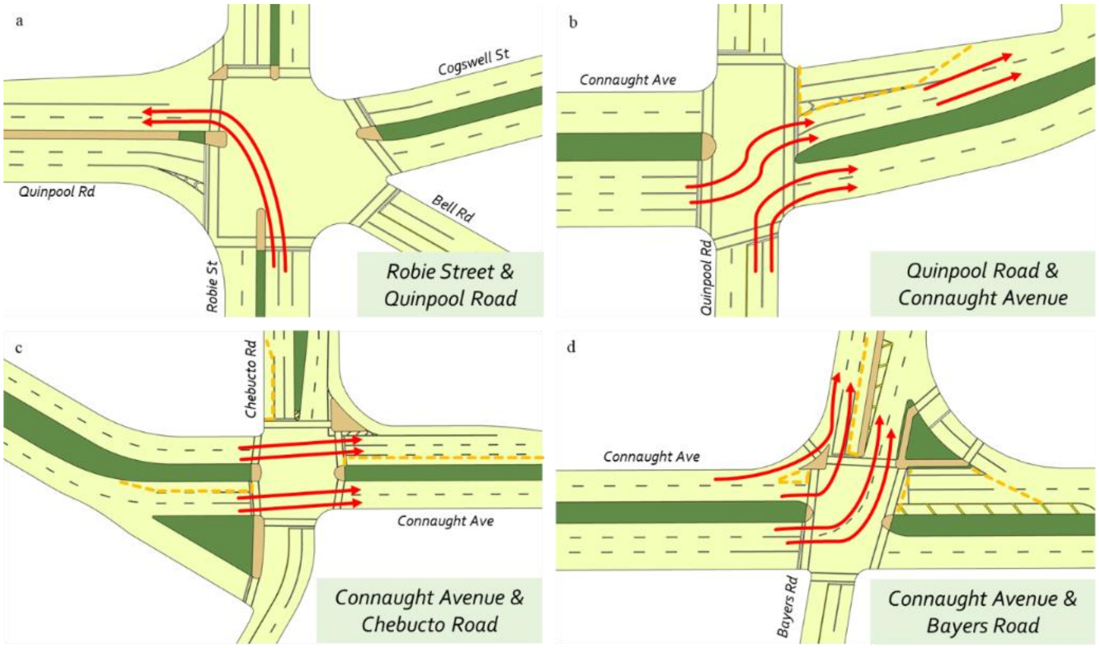

Figure 5: Traffic operation recommendations at intersections (a) Quinpool Road at Robie Street, (b) Quinpool Road at Connaught Avenue, (c) Connaught Avenue at Chebucto Road, and (d) Connaught Avenue at Bayers Road along selected evacuation route being subjected.

5 Results and Discussion

5.1 Evacuation Route Determination Results

5.1.1 Results of SWOT Analysis

Building upon the SWOT analysis, candidate routes (CRs) are evaluated for each criterion considered for route's strength, weakness, opportunities, and threats in Table 3. In Table 3, each CR receives a sign 'x' for all criteria that are true and pertain to that route. For instance, CR8 receives four 'x's' for strength criteria and one for each of the rest, which indicates that the strengths and opportunities pertaining to this route outweigh the weaknesses and threats. CR1 also has a similar number of 'x's' for strength; however, it has two 'x's' for threats. Moreover, CR8 demonstrates strengths for several criteria in addition to the connectivity, which are critical for the selection of an evacuation route.

Table 3. Summary of SWOT Analysis for All Candidate Routes Identified based on a combined Flood Risk and Traffic Microsimulation Model

Analysis Methods	Criteria	CR1	CR2	CR3	CR4	CR5	CR6	CR7	CR8	CR9
Strength	Continuous movement of traffic from zones to exits	x								
	Multiple connection to exits	x	x		x		x			
	Good connection to arterial streets	x			x	x	x	x	x	x
	Passing through the center of city providing an easy access to the route	x	x							x
	Shorter path from downtown to bridge			x						
	Diagonal connection from the center to exits				x					
	Less stopping for vehicles					x				
	Consistent # of outbound lanes i.e., absence of bottleneck							x	x	
	Familiarity of routes and existing signage along the route								x	
	Room for emergency and stopped vehicles								x	
	Good connection to highways							x		x
Weakness	Inconsistent # of lanes	x	x							
	Presence of bottleneck i.e., transition from two to one single outbound lane, like ramp		x			x				
	Limited capacity due to restriction, and unusual road configuration				x					x
	Bottleneck due to turning lanes		x	x			x	x	x	
Opportunities	Suitable for zonal-based evacuation	x								
	Potential transit priority lane		x					x		
	Existing transit lines			x						
	Suitable as back up links					x	x		x	
Threats	Coordinating evacuation effort with Halifax Bridge Commission	x	x	x						
	Coordinating evacuation effort with provincial transportation and NSTIR for highways							x		
	Potential re-development project	x								
	Presence of gas station on the route		x			x		x	x	
	Accident for one-lane route	x	x	x	x					

5.1.2 Selection of Evacuation Routes through a Point System

This study utilizes a point system along with a SWOT analysis to further evaluate the candidate evacuation routes by assigning them numerical scores for comparison. In the point system analysis, CR8 is found to score the highest with a value of twenty-two, shown in Figure 6. Therefore, this study proposes CR8 to be the most optimal evacuation route for Halifax, which consists of multiple road segments including 'Quinpool Street - Connaught Avenue - Bayers Road - Highway 102', as shown in Figure 7.

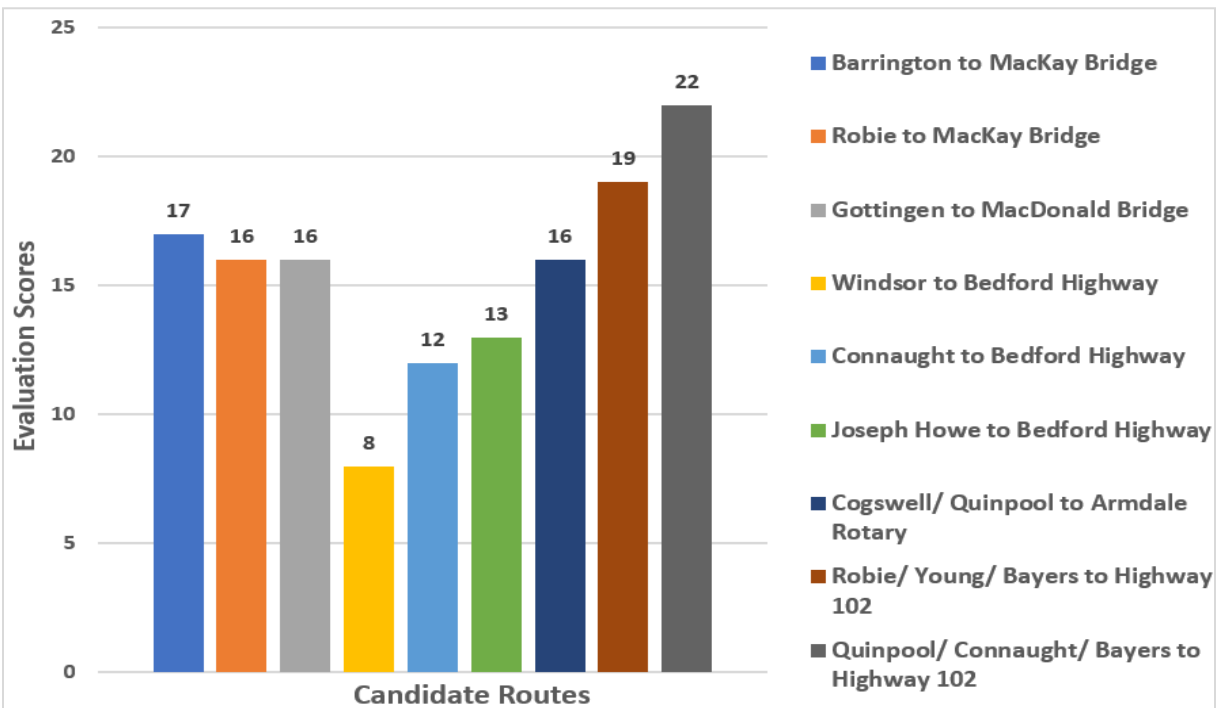

Figure 6: Evaluation scores for all candidate evacuation routes estimated through point system proposed

With this evacuation route being close to hospitals, it will allow for vulnerable populations to be evacuated more quickly and safely. When comparing the evacuation routes and the flood risk map, Connaught Avenue could face increased traffic if the Armdale Rotary is flooded and closed to traffic. Vehicles traveling outbound on Quinpool and Chebucto Roads could be forced to use Connaught Avenue as an alternative route. Additionally, Highway 102 is the only exit point that is not expected to flood or have reduced access due to high winds. This route has the fewest intersections with only five major and twenty-two minor intersections while having four contiguous lanes from the downtown core to Highway 102. It has the lowest possibility of closure due to winds or flood waters. Quinpool Road and Connaught Avenue along the route have the highest number of already existing or planned transit routes making multi modal evacuation possible.

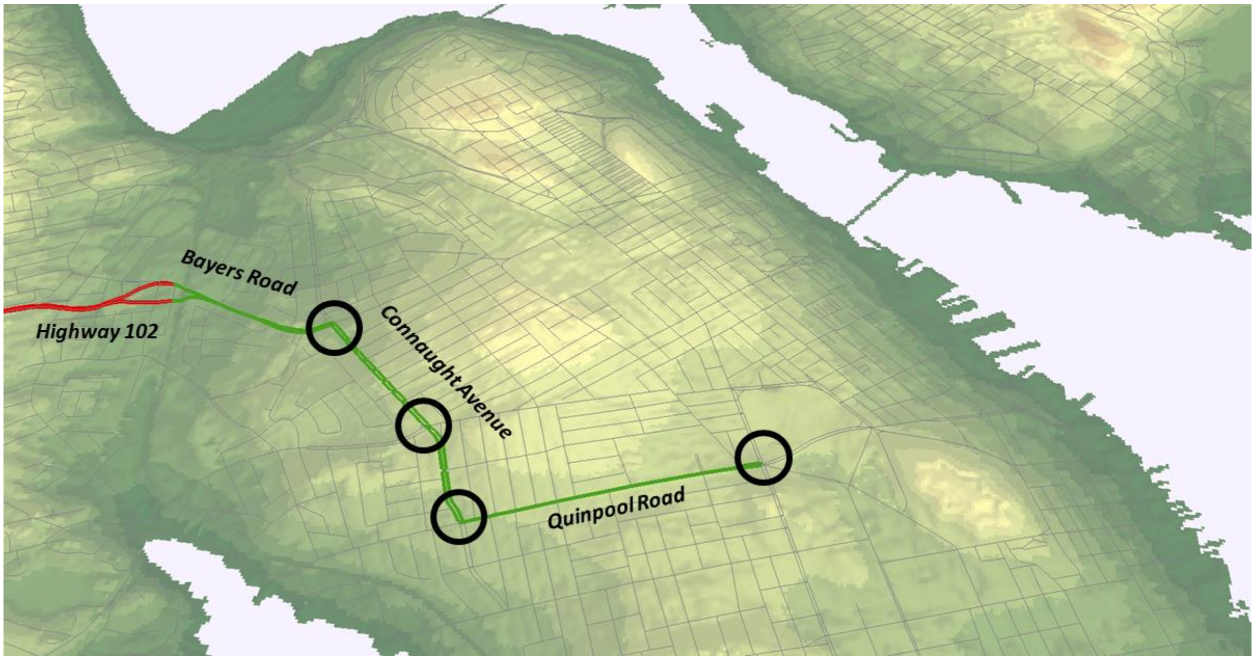

Figure 7: Selected evacuation route for Halifax through SWOT and Point System analysis.

The route is also directly connected to major roads in downtown via Cogswell Street and Barrington Street. This route bypasses many of the historic sectors and funnel points in the network and provides the best possible flexibility with four lanes, i.e., two in each direction from the downtown core to the highway limiting traffic slowdown. In turn, the Quinpool Road forms the missing link between the city road network and the larger highway network. It takes evacuees through the commercial districts of the downtown and then diverts them through a park and residential area en-route to the highway to reduce the likelihood of congestion caused by intersections.

5.2 Evacuation of PWDs: Optimization and Traffic Simulation Results

5.2.1 Optimization Results: Emergency Vehicle and Destination Allocations

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 requiring mobility assistance. Figure 8 illustrates the demand from different facilities evacuated to twelve destinations within a 100 km radius of the peninsula.

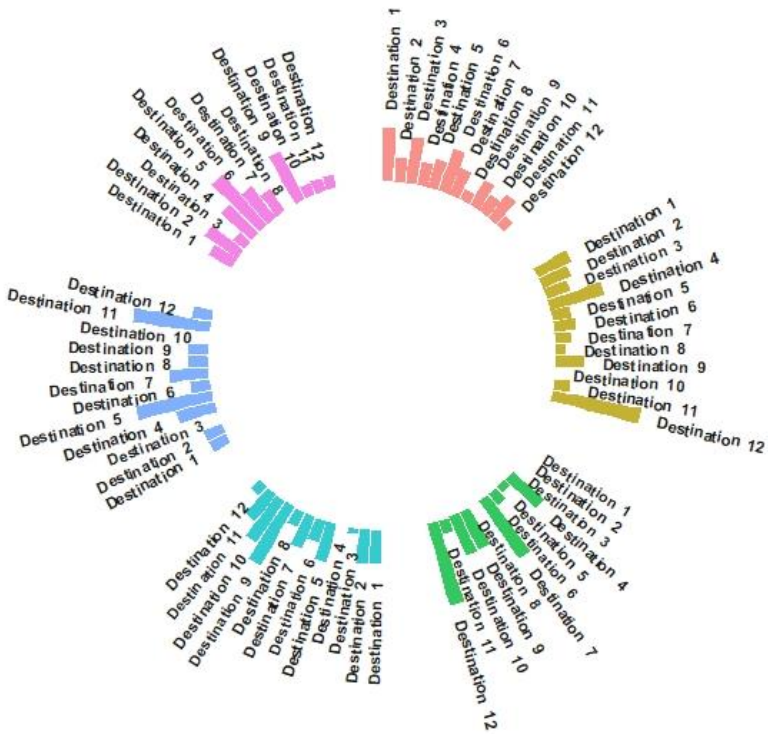

Figure 8: Demand from different Hs and NHs relocated to twelve destinations within a 100 km radius of the peninsula

The 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 this group during evacuation. The optimization results assert that all members with mobility needs are evacuated by ninety emergency vehicles, and it takes 19.5 hours for an optimal allocation of emergency vehicles to all demand at origin locations. 35.6% of the emergency vehicles is 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 Figure 9. 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 can be used by Hs and NHs authorities to develop proactive plans for preparedness purposes.

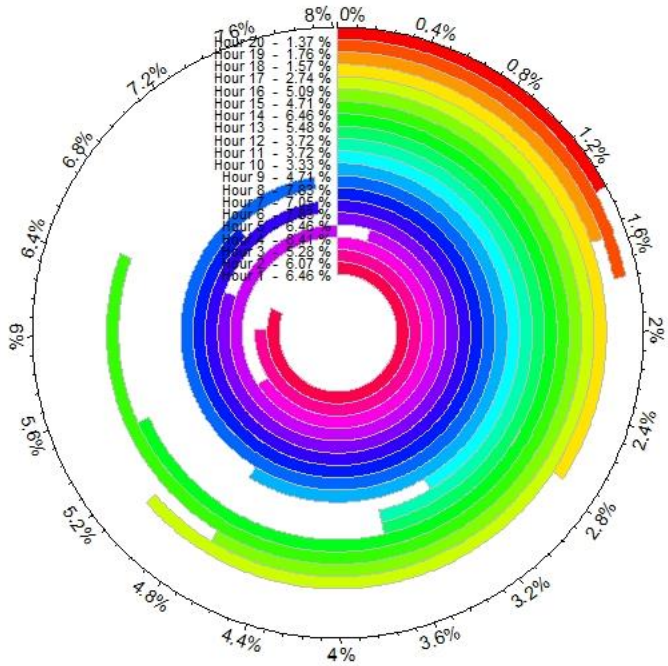

Figure 9: Percent completion of the evacuation of PWDs in different evacuation hours.

5.2.2 Traffic Simulation Results: Evacuation Time Analysis

To have an in-depth understanding of the emergency vehicle operations in the network, this study simulates PWD evacuation scenarios 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. Figure 10 presents a box plot of emergency vehicle tour times in scenarios 1 (evacuation without the dedicated route) and 2 (evacuation with dedicated route). In scenario 2, 75% of tours have an average completion time of 2 hours and 12 minutes. The results suggest that tour time of ambulances reduces in the range of 6 - 25.2 minutes if the emergency evacuation route is in place. Results also reveal that average travel time reduces by 32.31% along the evacuation route. In total, 21 hours is required to evacuate the PWDs demand considered in this study.

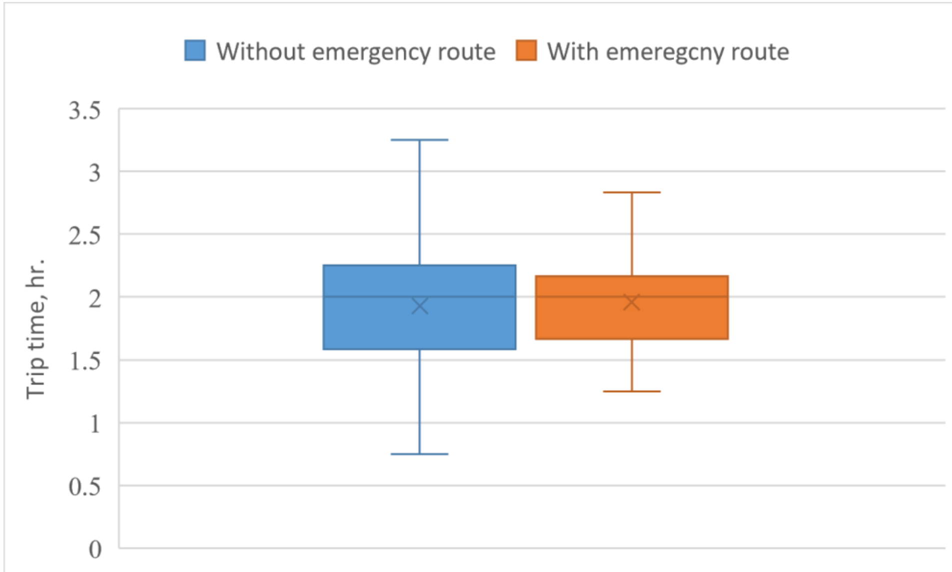

Figure 10: Trip time distribution for the evacuation of persons with mobility needs from facilities located in proximity to the evacuation route.

5.2.3 Traffic Simulation Results: 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. Results show 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. Conclusion

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 predicted growth of vulnerable populations in Nova Scotia, Canada, pragmatic modelling approaches that specifically account for persons with mobility needs are more vital than ever. This research aims to investigate the temporal and logistical requirements for evacuating persons with mobility needs located on the Halifax Peninsula region of the Halifax Regional Municipality. 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 the evacuation of 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. Moreover, it delineates a detailed framework of evacuation route determination with an integration of flood risk and traffic evacuation modeling and roadway assessment. The study optimizes resource allocations and implements a dedicated emergency evacuation route within the traffic simulation modelling framework to improve the evacuations of persons with disabilities. 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.

This paper presents 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 scenarios: emergency vehicle operation with and without the dedicated evacuation route equipped with contraflow. This analysis shows that the mass evacuation of persons with mobility needs using ambulance fleets is a practical and effective method of accounting for special groups, resulting in their continued care in Hs and NHs outside of the evacuation boundary. Ninety emergency vehicles are allocated to evacuate all mobility assistance-seeking individuals in 21 hours. When dedicated evacuation route is in place, trips are reduced by 6 minutes – 25.2 minutes and travel time along the route is reduced by 32.31%. The route used in this study forms a direct connection from the downtown core to the highway via the inner-city road network, and conveniently passes near most Hs and NHs, making it perfectly situated to move people, particularly mobility-limited persons, out of the downtown core to shelter locations. The traffic operation recommendations propose achieving better traffic flows, while restricting turns and other directional traffic flows that hinder traffic movements and prolong the evacuation. Signal priorities, signage, and personnel were also recommended at key intersections to ensure that the contraflow on the selected links is maintained. This study considers the person with disability that require mobility assistance and ambulances for a curbside pick-up for evacuation. The study assumes that 20% of the total estimated demand at Hs, and NHs will be evacuated by ambulances. This research utilizes a single occupant ambulance and does not explicitly accommodate the types of disability within the model. It will be interesting to consider different types of disabilities and utilize various types of ambulances for evacuating the persons with disabilities using the developed model. For example, it is critical to consider the use of specialized emergency vehicles that are designed to accommodate people that use life-saving or large-scale mobility aids. Further investigation is also required for a better understanding of the logistical requirements and the time needed to move patients from their bed to a curbside ambulance. Furthermore, it will also be interesting to explore how socioeconomic characteristics, family compositions, different levels of disability, and peer- communication may affect the process of evacuating PWDs.

Concisely, the study contributes to developing an operational evacuation modelling framework for assessing the evacuation of persons with disability using a dedicated evacuation route. However, future efforts in evacuation simulation modelling should incorporate more planning considerations that other researchers are exploring in this project of "Evacuation of Persons with Disability", e.g., shelter accessibility. The research will help emergency management professionals develop policies to tackle challenges and risks associated with the evacuation of persons with disability by implementing suitable preventive measures, as well as will be useful to inform operational planning for mass evacuations in coastal regions.

REFERENCES

Abdelgawad H, and Abdulhai B. Emergency evacuation planning as a network design problem: a critical review. Transportation Letters. 2009 Jan 1;1(1):41-58.

Alam MJ, Habib MA. A dynamic programming optimization for traffic microsimulation modelling of a mass evacuation. Transportation Research Part D: Transport and Environment. 2021a Aug1; 97: 102946.

Alam, M. J., Habib, M. A., Quigley, K., and Webster, T. L. Evaluation of the Traffic Impacts of Mass Evacuation of Halifax: Flood Risk and Dynamic Traffic Microsimulation Modeling. Transportation Research Record: Journal of the Transportation Research Board, 2018. 2672(1): 148-160. doi: 0361198118799169.

Apte A, Heath SK, Pico A, Ronny Tan YH. Evacuating people with mobility-challenges in a short-notice disaster. Decision Sciences. 2015 Aug;46(4):731-54.

Bela, P. L., and Habib, M. A. Urban Freight Network and Emission Modeling for Port City Halifax, Canada: A Spatial and Temporal Evaluation of Commercial Vehicles Movement. Proceedings of the 97th Annual Meeting of Transportation Research Board, Washington D. C., 2018, January 7-11.

Bloodworth DM, Kevorkian CG, Rumbaut E, Chiou-Tan FY. Impairment and disability in the astrodome after Hurricane Katrina: Lessons learned about the needs of the disabled after large population movements. American J of Physical Medicine & Rehabilitation. 2007 Sep 1;86(9):770-5.

Cova, T. J., and Johnson, J. P. A Network Flow Model for Lane-Based Evacuation Routing. Transportation Research Part A, 2003. 37: 579-604.

Dow, K., and Cutter, S. L. Emerging Hurricane Evacuation Issues: Hurricane Floyd and South Carolina. Natural Hazards Review, 2002. 3(1): 12-18.

Dulebenets MA, Pasha J, Kavoosi M, Abioye OF, Ozguven EE, Moses R, Boot WR, Sando T. Multiobjective optimization model for emergency evacuation planning in geographical locations with vulnerable population groups. J of Management in Engineering. 2020 Mar 1;36(2):04019043.

Ebrahimnejad S, Villeneuve M, Tavakkoli-Moghaddam R. An optimization model for evacuating people with disability in extreme disaster conditions: A case study. Scientia Iranica. 2021 May 3.

Egodage N, Abdeen FN, Sridarran P. Fire emergency evacuation procedures for differently-abled community in high-rise buildings. J of Facilities Management. 2020 Sep 4. evacuation shelters

Transactions in GIS. 2008 Apr;12(2):227-48. evacuation. The Island Packet [Internet]. 2018 Sept [cited 2020 May 15].

Fries, R., Chowdhury, M., Ma, Y., and Stephen, L. Evaluation of Different Contraflow Strategies for Hurricane Evacuation in Charleston, South Carolina. Transportation Planning and Technology, 2011. 2(34): 139-154. doi:10.1080/03081060.2011.554706

Habib MA, Alam MJ, Lacroix J, Morganthaler A. Mass evacuation planning: determination of evacuation routes through traffic microsimulations. Paper presented at: the 99th Annual Transportation Research Board Meeting, Washington, D.C; 2020 Jan 12-16 (No. 20-05786).

Habib, M. A., Alam, M. J., Lacroix, J., and Morgenthaler, L. A. Mass Evacuation Planning: Determination of Evacuation Routes through Traffic Microsimulations. Presented in the 99th Annual Meeting of Transportation Research Board, Washington D. C., 2020, January 12-16.

Heydar, M., Yu, J., Liu, Y., and Petering, M. E. Strategic Evacuation Planning with Pedestrian Guidance and Bus Routing: a Mixed Integer Programming Model and Heuristic Solution. Journal of Advanced Transportation, 2016. 1314-1335.

Kaisar EI, Hess L, Portal Palomo AB. An emergency evacuation planning model for special needs populations using public transit systems. J of Public Transportation. 2012;15(2):3.

Kako M, Steenkamp M, Ryan B, Arbon P, Takada Y. Best practice for evacuation centres accommodating vulnerable populations: a literature review. International journal of disaster risk reduction. 2020 Jun 1;46:101497.

Li, J., Wang, J., Jin, B., Wang, Y., Zhi, Y., and Wang, Z. Evacuation of nursing home based on massmotion: effect of the distribution of dependent elderly. KSCE Journal of Civil Engineering, 2020; 24(4):1330-1337.

Madireddy, M., Medeiros, D. J., and Kumara, S. An Agent Based Model for Evacuation Traffic Management. Winter Simulation Conference, Pennsylvania, 2011. 222-223).

Naghawi H, Wolshon B. Performance of multi-modal evacuation traffic networks: a simulation-based assessment. Paper Presented at: The 90th Annual Meeting of the Transportation Research Board, Washington, D.C; 2011 Jan 23-27 (No. 11-1802).

Nakanishi, H., Black, J., and Suenaga, Y. Investigating the flood evacuation behaviour of older people: A case study of a rural town in Japan. Research in Transportation Business & Management, 2019; 30:100376.

Noh DJ, Koo J, Kim BI. An efficient partially dedicated strategy for evacuation of a heterogeneous population. Simulation Modelling Practice and Theory. 2016 Mar 1;62:157-65.

Nova Scotia, Province of. Access by design 2030. Nova Scotia: Department of Justice; 2018.

Renne JL, Sanchez TW, Litman T. Carless and special needs evacuation planning: a literature review. J of Planning Literature. 2011 Nov;26(4):420-31.

Stough LM, Kang D. The Sendai framework for disaster risk reduction and persons with disabilities. International Journal of Disaster Risk Science. 2015 Jun;6(2):140-9.

Urbina EA. A state-of-the-practice review of hurricane evacuation plans and policies [Master's Thesis]. Baton Rouge, LA: Louisiana State University; 2002.

Wolshon B. Planning for the evacuation of New Orleans. Institute of Transportation Engineers (ITE) J. 2002 Feb 1; 72(2):44.

Wolshon PB, Urbina EA, Levitan M. National review of hurricane evacuation plans and policies. Baton Rouge, LA: Louisiana State University Hurricane Center; 2001.

Wolshon, B., Urbina, E., Wilmot, C., and Levitan, M. Review of policies and practices for hurricane evacuation. I: Transportation planning, preparedness, and response. Natural Hazards Review, 2005. 6(3): 129-142.

Yazdani, M., Mojtahedi, M., Loosemore, M., Sanderson, D., and Dixit, V. Hospital evacuation modelling: A critical literature review on current knowledge and research gaps. International Journal of Disaster Risk Reduction, 2021; 66:102627.

Zou, N., Yeh, S.-T., Chang, G.-L., and Alvin Marquess, A. M. Simulation-Based Emergency Evacuation System for Ocean City, Maryland, During Hurricanes. Journal of the Transportation Research Board, 2005. 1922(1): 138-148. doi:https://doi.org/10.1177/0361198105192200118