THE USE OF HUMAN BEHAVIOUR IN FIRE TO INFORM CANADIAN WILDLAND URBAN INTERFACE EVACUATIONS

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Abstract

Wildland urban interface (WUI) communities are generally the most at risk of being impacted by wildfires. In order to assess the vulnerability of these communities, it is important to understand the impact that human behaviour in fire (HBiF) can have on wildfire evacuations, specifically in Canada where such data is lacking. To lay the groundwork for a comprehensive vulnerability assessment of a Canadian case study community, a conceptual model of protective action decision-making during WUI fires was created. This was used to develop a survey to understand the WUI fire awareness and experience as well as the anticipated protective actions of the case study community residents. The microsimulation software PTV VISSIM was used to model 10 evacuation scenarios to identify key evacuation modelling considerations and potential evacuation challenges faced by the community. In doing so, a framework for using HBiF to inform WUI vulnerability assessments and evacuations was developed.

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Statement of Co-Authorship

The work herein this thesis has been completed by Lauren Folk under the supervision of Dr. John Gales at York University. Sections of this thesis have been influenced by two publications written over the duration of the author's graduate degree. The author was the lead author of both of these publications.

Portions of Chapter 2 have been modified from the following journal paper (included in Appendix D):

- Folk, L H.., Kuligowski, E. D., Gwynne, S., Gales, J (2019). A Provisional Conceptual Model of Human Behaviour in Response to Wildland-Urban Interface Fires, *Fire Technology*, Springer

Portions of Chapter 4 have been modified from the following conference paper (included in Appendix E):

- Folk, L. H., Gales, J (2019). Approach to Using Human Behaviour in Fire to Inform WUI Community Evacuations, *Proceedings for the 15th International Wildland Fire Safety Summit & 5th Human Dimensions of Wildland Fire Conference*, Asheville, North Carolina

In addition to these works, a third article was written during the time of this thesis as part of a secondary project undertaken by the author which built upon research conducted during the author's undergraduate degree. This paper has been included in Appendix F.

- Folk, L. H., Gonzales, K., Gales, J., Kinsey, M., Carattin, E (submitted). Emergency Egress for the Elderly in Care Home Fire Situations. FAM-18-0144, *Fire and Materials*, Wiley.

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Chapter 1: Introduction

1.1 Wildfires and the Canadian Wildland Urban Interface

Wildfires are an integral part of the Canadian ecosystem and are common occurrences, specifically during the summer months [1]. Over the last 20 years, an average of over 2800 wildfires burned over 1.1 million ha of land each year [2]. In the last two years, this average was over 6000 fires and over 2800 ha burned. It is anticipated that in the coming years, the number of wildfires occurring in Canada will continue to increase in much of the country as a result of climate change [3], [4] and the increasing interaction between people and the wildland [5]–[7]. While the challenges resulting from this are increasing, Canadian wildland fire science and technology are struggling to keep pace [8].

Interactions between people and the wildland generally occur in what is known as the wildland urban interface (WUI). The WUI is identified as places "where humans and their development meet or intermix with wildland fuel" [9]. The WUI includes both intermix and interface communities, with varying densities, levels of remoteness, and interaction with the wildland [10]. Intermix communities include areas where wildland vegetation and housing intermingle, and interface communities are those that are in close vicinity to areas of large, dense wildland vegetation [5]. Given their proximity to the wildland, WUI communities are generally the most vulnerable to wildfires and the subsequent property damage and physical, social, environmental, and psychological impacts [5]. In addition, other vulnerabilities such as fewer and more dangerous egress routes and a lack of easily accessible firefighting resources contribute to the additional challenges faced by WUI communities [11].

While Canada continues to become increasingly urban, there are important growth trends that may correlate with the growth of the Canadian WUI. In an analysis of fire risk and population trends in the Canadian WUI, the Canadian Council of Forest Ministers identified that while the number of rural farming residents has declined over the past few decades, the number of non-farming rural residents has increased [7]. The analysis identified three trends that are contributing to this. These include urban sprawl, demand for recreational property, and some growth in isolated communities [7]. Urban sprawl has resulted in an increase in people living in urban fringe areas (small urban areas close to but not part of the urban core). This can influence WUI risk when such areas are located in rural or semi-rural areas next to cities. Increases in demand for second homes or recreational properties which are often located in the WUI also contributes to growth in these areas. As the Canadian population ages, and retirees (and those planning for retirement) look to cabin and cottage country, this could be an increasingly important contributor to this growth [12]. Finally, the Canadian Council of Forest Ministers' report noted that growth in some isolated rural areas, located primarily in the Canadian north, is also playing a role. Many of these communities have a strong Aboriginal presence, and as the Aboriginal population continues to grow, these communities may continue to do so as well [13].

In the first national study of its kind, Johnston and Flannigan 2018 created a map of the Canadian WUI [14]. The study found that the WUI covered 32.3 million ha, corresponding to 3.8% of the country's land area and 5.8% of the country's wildland fuel area. Most of the interface areas were found to be located in the southern portions of Canada, with Quebec, Alberta, Ontario and British Columbia having the largest areas. Very limited interface areas were identified in the northern regions of the country, in part due to the location of human settlements and the nature/type of wildland fuel in these areas. While 3.8% may seem like a small percentage of the country as a whole, given the size and the distribution of people within the country it is important to consider this area in relation to human settlements (cities, towns, reservations, etc.). Of the 544 ‘Populated Places’ mapped in the study, 96% of them had at least some WUI within 5-km and 60% had more than 500 ha of WUI within 5-km. Figure 1.1 below shows the location of the Canadian WUI and Figure 1.2 shows the Canadian WUI in relation to populated areas.

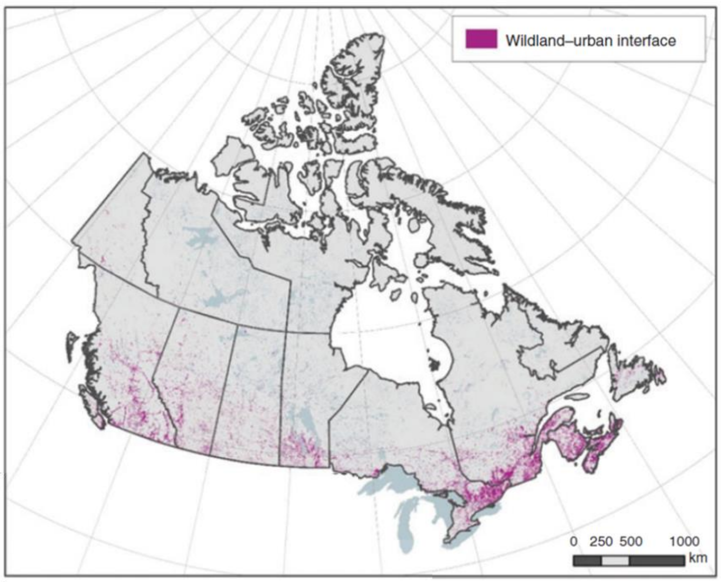

Figure 1.1: Canadian wildland urban interface [14]

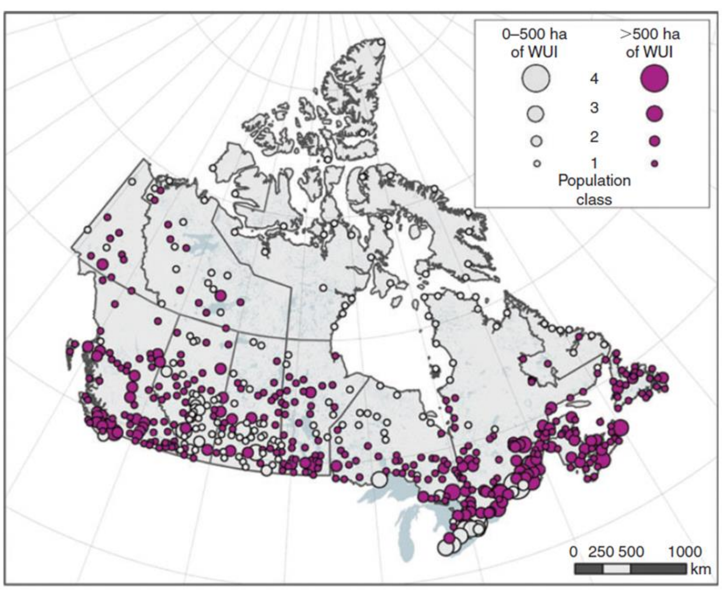

Figure 1.2: Interaction between ‘populated places’ and the Canadian wildland urban interface where Population Class 4 = more than 1,000,000 people, Population Class 3 = 100,000 – 999,999 people, Population Class 2 = 10,000 – 99,999 people, and Population Class 1 = 1 – 9999 people [14]

It is important to note that the relationship between 'populated places' and the WUI does not necessarily correlate to the fire risk of these places (where risk is a defined as the product of potential exposure and vulnerability). A community's vulnerability and therefore risk is influenced by many interconnected factors, such as social factors (resource dependence, social capital, attitudes toward and perceptions about fire, etc.) [15] and environmental factors (climate/weather, topography, ecology/fuels, etc.) [16]. Johnston and Flannigan 2018 cross-referenced the number of fires and area burned with interface areas, though this again only looks at the potential exposure portion of risk and not vulnerability (Figure 1.3a and b).

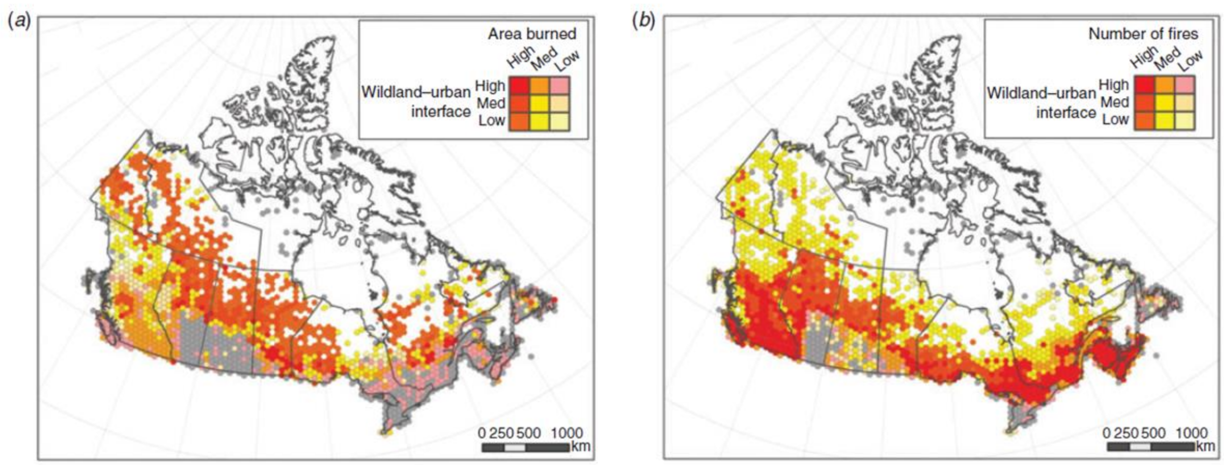

Figure 1.3: Maps of relationship between percentage of interface area in each cell and either burned area (as a percentage of land area in cell (a)) or number of fires (total number of fires in each cell (b)). Categories for interface areas are high (>6%), medium (<1-6%), and low (≤1%). Categories for fire area burned include high (>30%), medium (>2%-30%) and low (≤2%). Categories for number of fires are high (>100), medium (6-100), and low (≤5). Grey cells indicate cells with zero burned area or zero fires [14]. *Fire data is from the NFDB for the years 1980-2014).*

1.2 Canadian Wildfire Evacuations

1.2.1 Emergency Management and Wildfire Evacuations

In every jurisdiction, Canada has taken an "all hazards" approach to emergency management [17]. Within the system, vulnerabilities to both natural disasters and hazards (tornados, floods, wildfires, etc.) and human-made disasters and hazards (such as chemical, urban fires, terrorism, etc.) are addressed [17], [18]. In addition to the *Emergency Management Act* [19], Canada created *An Emergency Management Framework for Canada* in 2007 (revised in 2011, 2017) which "establishes a common approach for a range of collaborative emergency management initiative in support of safe and resilient communities" [17].

In looking at wildfires and WUI fire evacuations specifically, many different agencies are involved in the process of administering and executing an evacuation. The variation in the nature and frequency of WUI fire evacuations across the country (and within provinces) as a result of different patterns in wildfire activity, vegetation type and population density add to the complexity of WUI fire and evacuation management. Evacuation decisions are based on information about the fire, fire suppression capabilities, egress routes and the community threatened. The number and type of agencies involved in carrying out an evacuation can vary depending on the characteristics of the population in need of evacuation (location, size, etc.) [20]. Generally, civil authorities must work in collaboration with provincial/territorial fire management agencies when WUI fire evacuations are necessary. There are some areas where provincial/territorial agencies do not have the legislative authority to order evacuations, including on federal lands, Department of National Defense reserves, and Indian reserves [21].[1] If local capacity is not sufficient to manage evacuations, civil authorities can ask for assistance from mutual aid organizations or provincial emergency measures organizations [20]. A state of emergency can also be declared, giving the declaring agency wide-ranging powers under the *Emergency Program Act*, including requesting assistance from the Department of National Defense [21]. When WUI fires cross regional, provincial or even federal boundaries, agencies and authorities within each must also work

[1] Provincial/territorial agencies can advise people living on these lands to evacuate and police series can help promote this message, but an official evacuation order cannot be given [21].

together. Organizations such as the Canadian Interagency Forest Fire Centre (CIFFC) and agreements such as the Canada/United States Reciprocal Forest Fire Fighting Arrangement (CANUS) can aid in this collaboration, as can having a standardized command-and-control structure (or incident command system (ICS)) [21].

1.2.2 Characteristics of Canadian WUI Evacuations

As in any country with frequent and intense wildfires, evacuations in the Canadian WUI are to be expected. However, there are several factors which have, historically, differentiated Canadian WUI fire evacuations from those in other fire-prone places such as the United States and Australia, specifically when it comes to life and property loss. In their study of WUI fire evacuations in Canada between 1980 – 2007, Beverly and Bothwell identified several key characteristics and trends that characterized such evacuations during this time [20]. A few of these are summarized below:

- Despite the prevalence of WUI fires, relatively few people were impacted each year. The greatest number of evacuations occurred in the boreal ecozones which see some of the highest percentages of area burned each year but have relatively low population densities. While fires in the southern parts of the country were less common, wildfires in these areas impacted large numbers of people resulting in larger evacuations (low probability, high-consequence locations).
- The number of evacuees varied greatly from year to year, ranging from 40 people to over 50,000, with 70% of evacuations involving less than 300 people. The annual average was over 7400 people and the median was over 3500 people. Nearly one third of evacuees were in British Columbia.

- Similarly, the number of wildfire evacuations varied greatly each year, ranging from one to 53 (median: 13, average: 20). Most of these evacuations occurred in the provinces of Ontario, British Columbia, Manitoba and Alberta.
- Most WUI fire evacuations were in response to direct fire threat (not smoke) and were prompted by fires less than 10km from the evacuation site and over 1000 ha in size.
- During this timespan, only one civilian casualty was documented in direct relation to a wildfire.

1.2.3 Recent Changes in Canadian WUI Evacuations

Since Beverly and Bothwell's study of 28 years of Canadian wildfire evacuations, the number of people evacuated annually due to WUI fires has increased. Between 1980 and 2007, the total number of evacuees per year surpassed 10,000 evacuees six times, generally as a result of evacuations in multiple provinces and/or fires threatening densely populated areas [20]. In looking at the 10 years since 2007, seven years surpassed 10,000 annual wildfire evacuees [22], [23].[2] Figure 1.4 shows the number of wildfire evacuations between 1980-2015, and Figure 1.5 shows the number of evacuees from 1980-2017 as recorded in the Canadian Forest Service Wildfire Evacuation Database [22], [23].

[2] It is important to note that collecting information about the number of evacuees during WUI fire events is challenging, and it is likely that this, combined with changes in information medium and accessibility will have an effect on the accuracy of exact evacuee numbers.

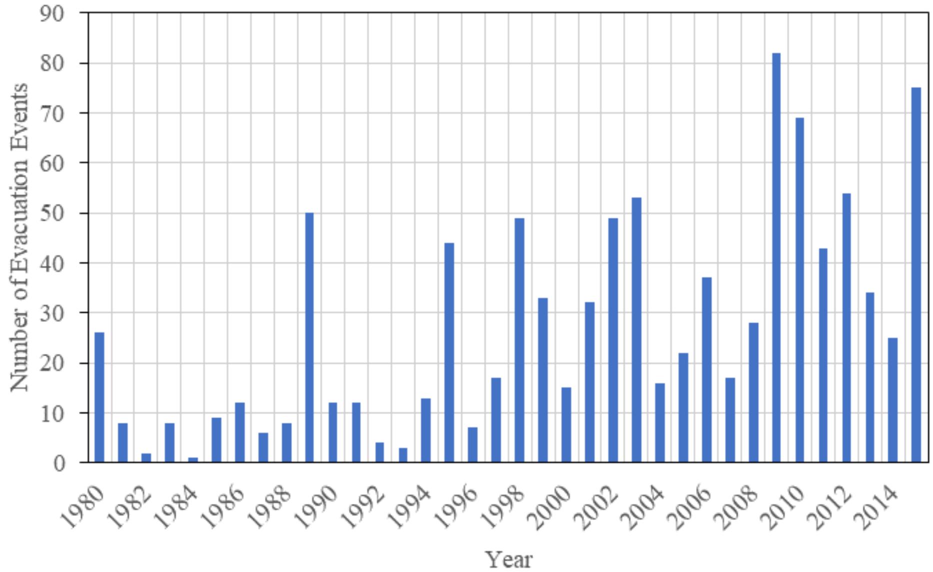

Figure 1.4: Number of wildfire evacuations in Canada between 1980-2015 [22], [23]

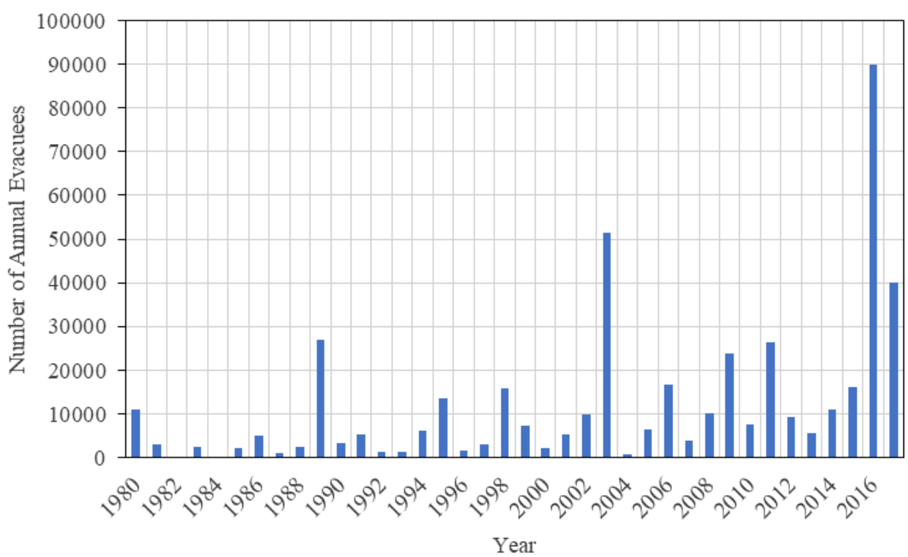

Figure 1.5: Number of wildfire evacuees in Canada between 1980-2017 [22], [23]

Given the relatively short period of time that these evacuation and evacuee numbers were determined for (35-37 years), and the fact that evacuations of largely populated areas can cause spikes in the number of people evacuated, it is important that assumptions not be made about changes in the underlying mechanisms influencing wildfires (and therefore evacuations).

However, as was discussed in Section 1.1, the number of fires and the number of people in the WUI does appear to be increasing and this could be contributing to the increased number of annual evacuees. It is also possible that more fires are occurring in and around the low-risk, high-consequence areas that are more densely populated as compared to in previous decades. A better understanding of the reasoning behind the increased number of WUI fire evacuees in the past decade will be important in moving forward with assessing the vulnerability of different WUI areas and communities.

1.3 Summary of Important WUI Fires

In recent years there have been several significant and in some cases deadly wildfires that have impacted communities around the world. A select number of these fires are detailed below. If possible, official reports and investigations were sourced, however, in the cases of the most recent fires, information was obtained from news reports alone.[3]

1.3.1 North America

Wood Buffalo Wildfire (Fort McMurry Fire), Alberta, Canada, May 2016

On May 1, 2016, a small wildfire was noticed seven kilometres outside of the Urban Area of Fort McMurray [24]. The fire growth was prompted by a dry winter season, strong winds and high temperatures [25]. Evacuation warnings were issued to nearby campgrounds and a state of emergency was declared in the area [26]. The warning levels were reduced the following day after wind conditions changed and were blowing away from the city of Fort McMurray. However, the conditions changed again on May 3rd, pushing the fire into the community and prompting the

[3] Only official and news reports written in English were referenced for this summary.

evacuation of tens of thousands of people. The changing conditions led to some evacuation shelters set up during the initial stages of the fire to be also evacuated, and by the end of the day, over 60,000 people had been evacuated (including over 100 patients at the local health centre). The one road leading in and out of the community experienced extensive congestion during the evacuation, with some vehicles being abandoned after running out of fuel after sitting in traffic for hours [27]. A provincial state of emergency was declared the following day, with 1600 structures destroyed, 10,000 ha burning, and evacuation orders issued for 80,000 people. On May 5th, 4000 people were airlifted from work camps north of the city and on May 6th, an additional 8000 oilsands workers were evacuated. A number of First Nations communities were also evacuated during this time [26]. While there were no fatalities directly associated with the wildfire, two people were killed as a result of a car accident during the evacuation. By the end of the fire event, over 88,000 people had been evacuated [24]. It is estimated that the response and recovery costs from the fire exceeded 740 million Canadian dollars [24].

The Camp Fire, California, USA, November 2018

Early in the morning on November 8th, around 6:30 am, a wildfire was reported in Northern California near the towns of Pulga and Paradise. The Butte County Sheriff issued evacuation orders for Pulga half an hour after the fire was reported and for Paradise one hour later [28]. Strong winds and dry conditions aided in the fire’s propagation, with the fire moving through Paradise quickly, making evacuation difficult and destroying most of the town [29]. The fire, which burned for over two weeks, destroyed nearly 14,000 homes, burnt over 62,000 ha and forced the evacuation an estimated 52,000 people [30]–[32]. The fire was the deadliest and most expensive in the state’s history, resulting in the deaths of at least 85 people and an estimated 16.5 billion US dollars in total losses [32], [33].

1.3.2 Australia

Victoria Bushfires (Black Saturday Bushfires), Victoria, February 2008

On February 7, 2009, after a severe and prolonged heat wave the month before, wildfires broke out across the state of Victoria, Australia [34]. Leading up to the day of the fires, severe bushfire warnings had been issued, with residents of high-danger areas being advised to evacuate pre-emptively. With temperatures above 40^{o}C on the day of the fire, strong winds and very dry fuels fed over 300 rapidly burning fires (15 of which were significantly damaging). Winds carried firebrands for kilometers, resulting in spot fire burning far from the main fire fronts. Five of the fires were fatal, resulting in 173 fatalities, making it the deadliest fire in the country's history. In addition to the devastating loss of life, hundreds of people were injured, around 3500 structures were destroyed, 450,000 ha of land was burned, and it is estimated that the fire had an economic cost of 4.4 billion Australian Dollars [25].

1.3.3 Europe

Pedrógão Grande, Portugal, June 2017

On June 17th and 18th, during a severe heatwave, over 50 wildfires broke out across the country [35]. Several fires occurred in central Portugal near the Pedrógão Grande area. Here, fires burned quickly and resulted in 66 fatalities, making them the deadliest fires in the country's history [36]. Most of the casualties occurred on a rural road while people were trying to evacuate [37]. Hundreds more people were injured, with numerous small communities in the area being affected. The fires in Pedrógão Grande burned over 53,000 ha of land (20,000 ha of forest), cost farmer and businesses tens of millions of Euros, and destroyed nearly 500 houses [36]. Problems with communication during the fire have been noted as contributing to the high death toll, with the fire destroying phone lines and communication towers thwarting early efforts to notify the public [38], [39].

Attica Wildfires, Greece, July 2018

On July 23rd and 24th, 2018, numerous wildfires broke out along the coast in the Attica region of Greece, northeast of Athens. The fires occurred during a summer heatwave impacting much of Europe, with high temperatures, strong winds and dry conditions [40]. Driven by the wind, the fires burned quickly and impacted the areas around Kineta, Penteli, Neos Voutzas, and Rafina among others, with the greatest loss occurring in the village of Mati [40], [41]. A popular tourist area, the fires forced thousands of tourists and locals alike to evacuate with little to no warning, with many fleeing to the sea [42]. The fire was the country's deadliest in decades and resulted in the death of around 100 people, most of whom died while trying to evacuate on foot or in cars [43]. Hundreds more people were injured and more than 2000 homes were destroyed [41], [42].

1.4 Tools for Improving WUI Evacuations

Fires such as those summarized above highlight the growing need to better prepare for and manage WUI fire evacuations. WUI evacuations are complex, requiring the collaboration of numerous agencies and adaptability to the nature of the fire and the environment, as well as the characteristics and number of people who need to evacuate [20]. Given this complexity, it is necessary for all the influential elements to be understood, and for people from various disciplines (engineering, urban planning, policy, social science, fire science, emergency management and fire services, etc.) to work together to tackle the challenges posed by such evacuations.

Researchers and practitioners in many different fields are looking to develop new and innovative ways to tackle the challenges posed by wildfires and wildfire evacuations, seeking to design better systems, tools and methods to plan for and manage these events. One of the key outcomes of the 2017 workshop sponsored by the International Association for Fire Safety Science (IAFSS) was the identification of the need to have an IAFSS working group dedicated specifically to looking at Large Outdoor Fires and the Built Environment [44]. The National Fire Protection Association (NFPA) is currently in the midst of a multi-stage project to develop a comprehensive WUI evacuation model that would take into account pedestrian behaviour, traffic movement and wildfire dynamics [25]. In support of the creation of standardized guidelines for more effective alerting systems, researchers in the Fire Research Division (FRD) at the National Institute of Standards and Technology (NIST) recently conducted a review of short message alerts and public responses [45]. These are just a few examples of work being done to improve WUI fire safety and evacuations.

One technical tool that can be used to help improve WUI fire evacuations is traffic simulation models. Traffic models are commonly used in fields such as traffic engineering and transportation planning, and have also been used to help improve emergency evacuations. Such models can simulate different evacuation procedures and strategies or specific evacuation scenarios, and the subsequent outcomes can be analyzed to better plan for and manage evacuations [46]. By conducting such analyzes, these tools can also aid in assessing the vulnerability of WUI communities. Given that conducting community fire evacuation drills is not as simple (or practical) as conducting evacuation drills in buildings, and that analyzing egress routes and traffic congestion during or after actual community evacuations is challenging if not impossible, modelling provides an alternative evaluation and analysis method. There are important considerations that need to be made when modelling evacuations, as such scenarios differ from standard traffic modelling. Evacuation models need to consider how travel demand, trip distribution, traffic assignment and the behaviour of travellers will differ under abnormal conditions (such as in the case where a wildfire is threatening a community). As such, whether using a standard traffic model or one developed specifically for evacuations, it is important that the nuances of an evacuation be represented, and the limitations of the model be understood and explained.

1.5 Human Dimensions of WUI Fire Evacuations

One important component that can be overlooked when striving to improve WUI fire evacuations is the role and impact that human behaviour can have on the success of an evacuation. Human behaviour in fire (HBiF) is a multidisciplinary field of study that looks at human response to fire events [47], [48]. Though historically undervalued, the acceptance of HBiF as one of the key pillars of fire safety engineering has grown in recent years [49]. While typically associated with fires in the built environment (office buildings, apartments, houses, etc.), the study of HBiF is closely related to the field of disaster research, where researchers have sought to understand the ways people respond to natural and technological disasters such as tornados, volcanos, hurricanes, floods and more recently, wildfires. The way that people respond to these events will impact their evacuation decisions. With a more thorough understanding of the decision-making process and the factors that impact how people behave and act, researchers and practitioners can design and assess systems, messages, procedures and communities to support safer and more effective WUI evacuations.

The study of human response and decision-making during wildfires has grown over the past few decades, primarily in the United States and Australia [50]. Despite this growing momentum, there are few Canadian studies looking at the impact of human behaviour on WUI fire evacuations and the studies that do exist are focused primarily on aboriginal communities [51]–[53]. While many similarities do exist between countries with respect to people's response to fire, and applicable insights can be gained from international research, it is also important that the nuances of each country (or region or community) be understood. Differences in population density, demographics and in historic evacuation and fire management practices and policies can impact the way WUI evacuations are conducted and how people respond. Given the diversity of the Canadian WUI, it is important to look at different types of communities such as seasonal communities located in Canadian cabin and cottage country, growing urban centres such as Fort McMurry that develop around natural resource extraction, and tourist communities such as those in the Rocky Mountains.

1.6 Motivation and Research Objectives

Given the importance of understanding human responses to WUI fires and the current lack of diverse, Canadian-specific research in this area, this research is a first step in moving towards a more comprehensive understanding of this discipline in Canada. The research seeks to answer the following question: *How can human behaviour in fire be used to inform Canadian WUI evacuations?*

More specifically, the research investigates:

- *How can HBiF help predict when/if people decide to evacuate?*
- *How can HBiF help improve notification and communication during WUI fire evacuations?*
- *How can an understanding of the factors that influence protective action decision-making improve the accuracy of evacuation traffic simulations?*

These questions are investigated generally and in the specific context of a Canadian case study community: a small, seasonal WUI community located in the Canadian Interior. Given the variable Canadian climate, seasonal communities are generally comprised of cabins and cottages where people spend time during the warmer summer months, which corresponds to the Canadian fire season [54]. These communities are popular with local and foreign tourists alike and generally see large population fluctuations over the course of the year. As the Canadian fire season is changing and more of these communities become at risk of being impacted by a wildfire threat [14], there is a growing need to understand the many factors that contribute to communities' vulnerability so that their WUI fire vulnerability can be assessed and reduced. HBiF is one such factor and it will be the focus of this thesis, which will lay the groundwork for the implementation of a vulnerability study for the case study community.

1.7 Research Focus and Scope

The research conducted as part of this thesis comprises the beginning stages of a larger vulnerability assessment that will be conducted in the case study community over the coming years. These stages involve the creation of a conceptual model of protective action decision-making during WUI fires, the creation of a survey to be distributed to the case study community to understand the WUI fire awareness and the expected protective actions of residents, and the modelling of an evacuation of part of the community. It was the initial intention that the survey would be distributed, and the results analyzed as part of this stage of the project, however, due to time constraints (particularly from the required timeframe for highly complicated ethical clearances with the university and community agency partner) this was not possible. Assessing other factors that contribute to the case study community's vulnerability such as those that contribute to wildfire dynamics (weather, topography, and fuel – moisture, physical properties and arrangement) or the type and layout of the structures within the community were outside the scope of this current thesis. These will, however, be important to consider in the next stages of the project as it continues. A summary of the chapters within this thesis are provided below:

1.7.1 Chapter 1: Introduction

The introduction provides an overview of the Canadian wildland urban interface, and the state of wildfires and WUI evacuations in Canada. It summarizes key global WUI fire events and provides context as to the need for a more comprehensive approach to WUI fire evacuations. It will identify new trends as well as gaps in WUI fire evacuation research and discusses the important role that HBiF plays in the development of comprehensive and effective tools to aid in improving wildfire evacuations.

1.7.2 Chapter 2: Human Behaviour and Protective Action Decision-Making During Wildfires and Hurricanes

Chapter 2 provides a comprehensive literature review of wildfire and hurricane evacuation literature looking at the factors that affect the decision to evacuate. Given that the body of related literature is very small in Canada, the review focuses on wildfire literature from the United States and Australia. Hurricane literature from the United States is also reviewed to supplement the wildfire findings given that the field is more developed. The factors identified in the literature review were used to create a first-stage conceptual model for evacuation decision-making during wildfires using the Protective Action Decision Model (PADM) as a framework [55]. This conceptual model is a first-step in improving the fire safety engineering community's understanding of the factors that have the greatest impact on the different stages of the decision-making process: pre-decision, credible threat and risk assessment, and protective action decision.

For completeness, a summary of the few Canadian studies is also given, however, they were not used in the creation of the conceptual model.

1.7.3 Chapter 3: Communication and Notification During Hazards – Considerations for Canadian WUI Fire Evacuations

Chapter 3 focuses on an important element identified by the conceptual model, namely, notification and communication. It explores the current Canadian public alerting system, with a focus on its new wireless alert component that allows messages to be sent to cellular devices. An exploratory case study analysis of the wireless system's first official use in 2018 for an Amber Alert and the corresponding public response was conducted using Google Trends data. The implications of the findings from this case study are also discussed in the context of WUI fire evacuations.

1.7.4 Chapter 4: Canadian Case Study

Chapter 4 applies and further develops the insights gained in the previous two chapters to a Canadian WUI case study community. The chapter is broken into two main parts: the creation of a quantitative survey and an evacuation traffic simulation of the case study community.

Part 1: Survey Creation and Data Collection Preparation

The aim of the survey is to collect information about the factors influencing protective action decision-making within the context of a seasonal Canadian WUI community that does not have a recent history of a wildfire evacuation. As such, it is written to collect information about *expected* actions and behaviours, and how long people *anticipate* spending on specific pre-evacuation tasks. Given that Canadian policy and practice heavily favours evacuation over staying and defending (and this is the most common practice seen in past Canadian WUI evacuations), the survey questions primarily relate to evacuation and less so to staying and defending during a fire. The survey is based on the findings from Chapters 2 and 3, and incorporates questions looking at elements common to most of the literature reviewed as well as questions aiming to fill some of the current knowledge gaps.

Part 2: Traffic Simulation

The traffic microsimulation software PTV Vissim was used to model an evacuation of part of the case study community. This software allows for dynamic traffic assessment, thereby enabling interactions between evacuees and the traffic environment, such as making enroute travel decisions, to be modelled. As microsimulation models are computationally more demanding given their level of detail, a specifically vulnerable area of the case study community was modelled (as opposed to the entire community) at this stage. Several simulations were run to see the impact that the number of evacuees and the speed of the evacuation had on the nature of the overall evacuation (total and individual evacuation times, location and degree of congestion).

1.7.5 Chapter 5: Conclusions and Recommendations

Chapter 5 summarizes the findings of the previous chapters and discusses their impact on WUI fire safety and evacuations in Canada. It will discuss the limitations of the work along with recommendations for undertaking similar work in the future. Future work necessary for the continued advancement of the study of HBiF within a Canadian WUI fire context is addressed, including the next stages of the Canadian case study vulnerability assessment project.

Chapter 2: A First-Stage Conceptual Model of Human Behaviour in Response to Wildland Urban Interface Fires

Research relating to WUI fire evacuations was collected to identify the factors that influence protective action decision-making and responses during these events, specifically whether someone chooses to evacuate or not. To supplement the findings, related hurricane evacuation literature was also reviewed for such factors. These factors were organized according to the Protective Action Decision Model (PADM) and form a first-stage conceptual model of human behaviour during the initial stages of WUI fire evacuations. The goal of this chapter is to understand the factors that can affect protective action decision-making and their corresponding impact on public responses such that they can be accounted for in the creation of comprehensive evacuation strategies and modelling tools.

2.1 Introduction and Purpose

With more frequent and destructive wildfires occurring in the growing WUI as discussed in Chapter 1, the ability to ensure the safe evacuation of potentially large groups of people is of increasing importance. This is a challenging task made only more difficult by the fact that there is often little warning and that evacuations often need to take place in a short period of time. The creation of credible and effective evacuation models is needed within the fire safety engineering community to help address this challenge and has been called for by organizations such as the NFPA and IAFSS. Although potentially difficult to represent, a critical component in developing such models is the consideration of what people will do in response to a WUI fire.

Modelling tools are available to simulate components of evacuations; however, some gaps in capabilities exist. Current modelling tools are either statistical or empirical in nature and/or feature only one aspect of the incident; e.g. the fire development, the emergency response, the evacuation response, etc. [25]. As such, these models are incapable of explicitly representing the temporal and the highly coupled nature of an incident. Having a type of time-based, inclusive simulation approach would better enable the vulnerability of communities to be assessed. This would not only be beneficial for WUI evacuations, but for other types of community evacuations as well.

Additionally, current evacuation simulation tools focus primarily on people or traffic movement, and in turn, neglect to simulate evacuation decision-making and behaviour that would prompt or prohibit evacuation movement to take place. Instead, a model often represents the probability of a particular response rather than representing the decision-making process through which an individual passes before selecting a response. In order to create such comprehensive evacuation tools, it is necessary to understand what factors affect evacuation decision-making and what information is necessary for evacuation models to be useful and effective. This understanding of evacuee decision-making comes from exploring existing research on public response to WUI fires and other disasters.

The majority of current and past research on the factors that affect WUI fire protective action decision-making – sociodemographic factors, social and environmental cues, preparation and experience, risk assessment, etc. – available in English originates from the United States and Australia. There currently exists only a small body of such literature in Canada. Behavioural research on WUI fires is relatively new compared to research looking at other disaster types, and therefore a smaller amount of data has been collected. Fortunately, despite the differences among disaster types, there are several similarities which enable our understanding of WUI fire evacuations to be enhanced through an understanding of public responses to other disaster types.

For example, with respect to evacuations, there are similar challenges among longer-duration (or slow-onset) disasters regarding notification, timing, ingress and egress decisions and actions [56]. There is a substantial body of research that looks at such challenges and the factors that affect them with respect to disasters in general [57]–[61]. Additionally, the overall process that one goes through to make decisions and respond to natural or technological disasters is ultimately the same [55]. As such, looking at research relating to other disasters can further our understanding of how people will act and behave during WUI fires.

While looking in detail at research from all disaster types (floods, earthquakes, man-made disasters, etc.) would provide the most comprehensive understanding of evacuation factors, it was within the scope of this thesis to compare two disaster types. Relevant U.S. and Australian WUI fire[4] research was identified and reviewed along with hurricane research from the United States to determine potential environmental and social factors that affect protective action decision-making and response. Hurricane evacuations were chosen to maximize the amount of information available for comparison given the wealth of United States' hurricane literature (available in English). Focusing on American studies also meant that additional cultural and political influences would not need to be considered (within this study). Although there are differences between wildfires and hurricanes, there are many similarities that make their focus in this review a reasonable exercise, e.g.:

- the movement of wildfires and the track of hurricanes are dependent on many factors, making prediction difficult;

[4] WUI fire research include that which referred to wildfires, bushfires and forest fires.

- both hazards provide similar timeframes for notification – including public alerts and warnings, in that they begin in one location and have the potential (over time) to negatively impact communities in its path;
- both hazards have the capacity to displace large groups of people; and
- both hurricanes and wildfires have the potential to change course or direction without warning, therefore potentially decreasing the time available to make protective action decisions.

The factors identified by this review are organized according to the Protective Action Decision Model (PADM) to better understand what factors affect the different stages of the decision-making process [55]. From these factors, and their organization in the PADM, a first-stage conceptual model of protective action decision-making for WUI fires has been developed. It is the intent that the collection and analysis of this information, and the development of a first-stage conceptual model, will help to inform the development of broad and all-inclusive WUI fire evacuation models.

2.2 Background

2.2.1 Evacuation Modelling

In any WUI evacuation model, certain key components need to be addressed in order to simulate WUI fire scenarios to an acceptable degree of detail. In reference to the evacuation model, vehicle evacuation – including both private vehicles and public transportation – is the primary transport mode for affected populations during WUI fire incidents. This reliance on vehicles is often due to the scale of these incidents, the distances that need to be covered, the trend in household units to evacuate together, and the fact that the transport of goods/provisions (in addition to the evacuees) are often required during evacuations. Therefore, WUI evacuation models should be capable of simulating the movement, route choice, and route destination of vehicles of varying capacities, which is covered in depth by the field of traffic modelling (see [25] for more details).

It is important to understand that traffic performance (and modelling) is not independent of the actions of individuals (referred to here as pedestrians). Pedestrian decision-making and preparation will determine the time at which household units decide to initiate their evacuation as well as the time that they move from their starting location (e.g., home, business, hospital, care homes, school, etc.) and eventually enter the traffic system. For more information about pedestrian decision-making and evacuations in long term care and retirement homes, see Appendix F. This aspect of individual/household decision-making in WUI fire events is less developed, and in turn, not well represented in current disaster-based evacuation models. What is required are large-scale evacuation models that account for individual/household protective action decision-making before vehicular evacuation begins. Protective action decision-making is defined here as the process by which people make decisions based on the cues/information available (i.e., threat conditions) to protect themselves, others, and/or their property in the event of a WUI fire. Furthermore, current evacuation and traffic models could be improved if they were better able to account for behavioural choices of individuals/households based not only on threat conditions, but the interactions between individuals as well. A number of studies have previously explored the benefits of including such components into existing models [61]–[66].

The first step in accounting for individual/household decision-making during WUI fires is made in this chapter. From a review of WUI fire and hurricane literature, a first-stage conceptual model of decision-making for WUI fires has been developed. The PADM is used as the foundation for the development of this model and is discussed in the following section.

2.2.2 Behavioural Modelling

Over the last 50 years, numerous empirical studies have sought to systematically chart the social processes involved in human responses to emergency incidents [67]–[69]. Of these, the Protective Action Decision Model (PADM) is selected here as it provides a framework to understand how people protect themselves and one another in response to cues from a disaster event [55], [70]. This model was deemed most appropriate for the task of categorizing the factors affecting the different stages of the decision-making process to create a behavioural conceptual model for WUI fire evacuations.

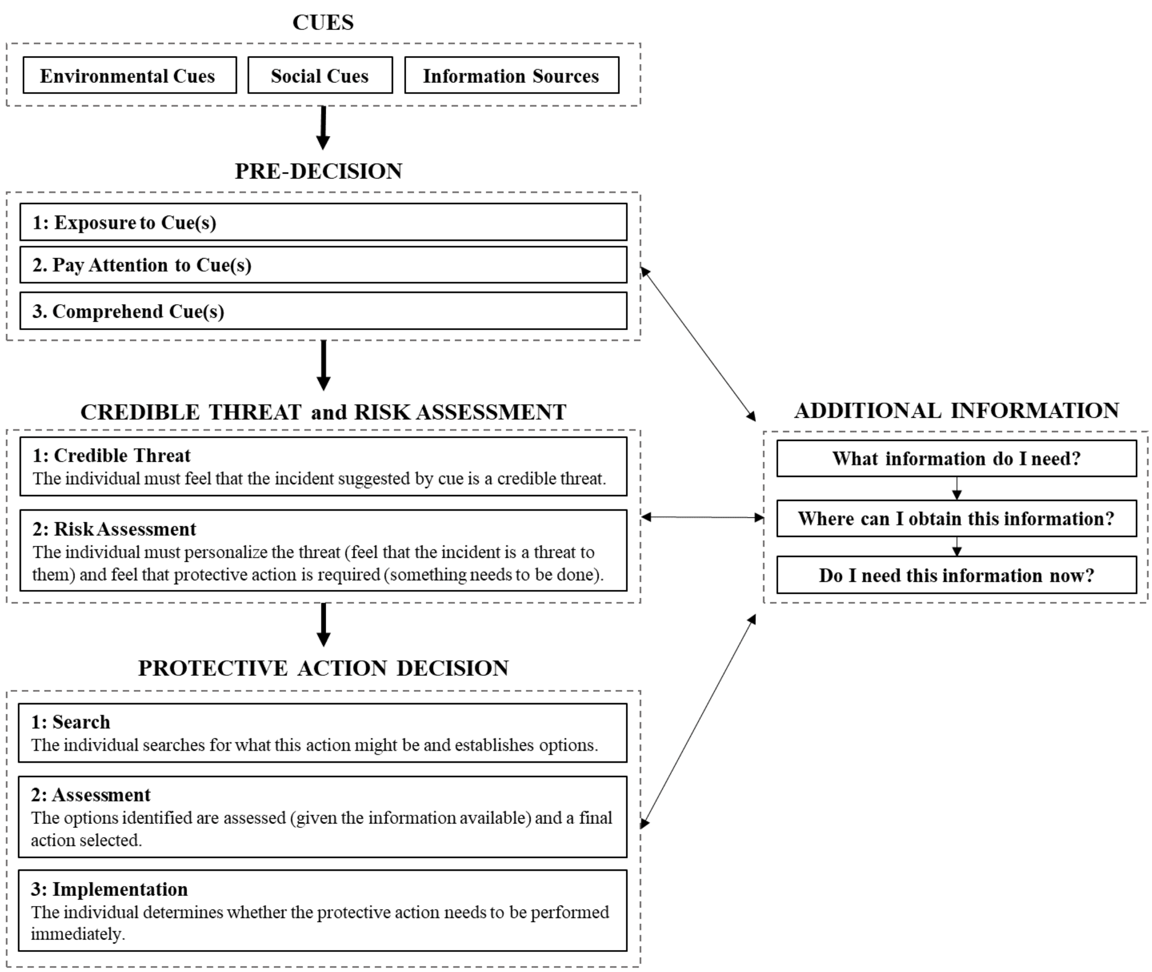

Figure 2.1: Protective Action Decision Model Framework (adapted from [55]*)*

The PADM asserts that the process of protective action decision-making begins when people are first presented with any kind of environmental cue, including physical and social cues and information. The introduction of these cues initiates a series of stages through which an individual passes prior to performing protective actions; e.g., initiating evacuation or deciding to stay and protect one's home. These stages are split into pre-decisional processes, which determine whether a decision-making process commences (*Pre-Decision* in Figure 2.1), and into the key components of the decision-making process itself (*Credible Threat, Risk Assessment and Protective Action Decision* in Figure 2.1).

Initially, the individual needs to receive a cue, pay attention to it, and comprehend the meaning associated with the cue (e.g., hearing an alerting signal, seeing flames, or smelling smoke). These represent the three pre-decisional stages of the PADM (*Pre-Decision* 1-3 in Figure 2.1), the stages that determine whether external information is processed such that it can inform the decision-making process [55]. Given that this information is processed, it then needs to be assessed to determine whether the information provided is credible (*Credible Threat* in Figure 2.1). At this stage, the individual decides if there is actually something occurring that may require action.

If the individual considers there to be a threat, they next determine whether the threat is relevant to themselves (*Risk Assessment* in Figure 2.1), known as personalizing the threat (or risk). Research has shown that a person's perception of personal risk, or "the individual's expectation of personal exposure to death, injury, or property damage" is highly correlated with taking protective action [55], [68], [71], [72]. The individual tries to gain insight into the potential outcomes of the disaster and what those potential outcomes mean to his or her safety. If the cues are deemed to relate to them, the individual then determines whether it is relevant and pressing. This then requires the individual to determine the nature of the response required at that point in time.

At this stage (*Protective Action Decision* in Figure 2.1), the individual engages in a decision-making process to identify a set of possible protective actions from which to choose. When it comes to taking protective actions in response to a WUI fire threat, there are ultimately two choices, to stay or to leave. Within the option of staying, households may choose to actively defend their home and property, or passively shelter in place (SIP), i.e., in their home, another location on their property or in their community. After establishing at least one protective action option, an individual engages in protective action assessment of these options and their current action.

If at any stage the individual is uncertain about the situation, the individual engages in additional information-seeking actions or they simply wait until additional information is provided to them. If seeking information, they may search for other sources (e.g., websites, media, etc.) and/or reach out to other people to discuss the situation and what to do (also known as the milling process) [73], [74]. The greater the ambiguity involved in the situation, the more likely that individuals will search for additional information that can guide their actions [75], [76]. Information seeking is especially likely to occur when individuals think that time is available to gain additional insight. The individual continues in this action until sufficient information is available or time runs out [55]. During an incident, information received can be incomplete, ambiguous, or contradictory, causing uncertainty in understanding the nature of the event and the actions necessary [77], [78]. In these cases, progress in the stages of the PADM can be significantly delayed and/or promote inefficient or unsafe protective action behaviour.

2.3 Methodology

The first-stage conceptual model discussed in this chapter was created by reviewing literature related to evacuation decision-making during WUI fires and hurricanes. This includes literature from various databases including Web of Science, Google Scholar, the NIST Research Library, and the York and Carleton University Libraries. The literature was obtained from peer-reviewed journal articles, conference proceedings, book chapters, government agency and university reports. The literature includes both qualitative and quantitative studies, as well as related literature reviews and compendiums. A set of key search terms was identified, and additional terms were added as the research progressed. These terms included: *Wildfire, Bushfire, Forest Fire, Wildland Urban Interface, WUI, Hurricane, Evacuation Behaviour/Decision/ Actions/Alternatives, Decision-Making, Evacuation Modelling, Shelter-In-Place, Protective Actions, Affecting/Influencing, and Risk Perception*. The review includes primarily post-2000 literature as the majority of related research for WUI fires and hurricanes was conducted during this time, however, a small number of commonly referenced hurricane research papers from the 1990s were also included. The selected studies were reviewed to identify the factors deemed influential in the protective action decision-making process. The factors included in this chapter are those that were found by the authors of the reviewed literature to be significant based on each study's own criteria. In the case of quantitative studies, these include factors that were deemed statistically significant. For the qualitative studies, these factors included those that were deemed notable by the researchers, based on the analysis methods employed.

WUI fire literature from both the United States and Australia has been included, while the hurricane literature was limited to the United States. Given the limited and narrow nature of the research relating to the factors affecting protective action decision-making in a Canadian WUI fire context, the few identified studies are not included in the creation of this first-stage conceptual model. However, Canadian-context considerations are discussed in Section 2.6.3. It is important to note that Australia and the United States have historically had very different approaches to wildfire policy. Australia's policy of "prepare, stay and defend or leave early" and later "Prepare. Act. Survive," allows for the practice of staying and defending one's home. Conversely, in the United States, evacuating all people threatened by wildfires has been the long-accepted practice. Given these differences between Australian and U.S. wildfire policies, it is acknowledged that the findings given in the respective literature would have been influenced by the varying perspectives about wildfire safety and the role of evacuations. It is also understood that additional factors, both technical and non-technical, may exist that have an impact on the protective action decision-making process. This is beyond the scope of this chapter.

The methodologies employed in the reviewed material differed, as some studies collected purely qualitative data, quantitative data, or a combination of both. Within these studies, some conducted correlation analysis, while others also utilized regression analysis. Varying sampling techniques and strategies were used, including surveys, questionnaires, interviews and focus groups. The size and nature of the samples also varied, with some sample groups having a greater awareness and interest in the risk posed to them by the hazard in question. Some studies collected post-disaster data, whereas others looked at intended actions. The definition of terms such as evacuation, as well as other aspects of the process, may have been different and in turn, measured differently between the studies. In addition, each paper discussed its own limitations within the context of the individual study. Commonly mentioned limitations included the accurate representation of a target population, survey response rate, hindsight bias, and issues related to the reliability of behavioural intention studies.

2.4 Factors Influencing Protective Action Decision-Making During WUI Fires

This section details the factors identified in the literature relating to protective action decision-making during WUI fire events. A summary of the identified factors can be seen in Section 2.6.1, Table 2.1. Section 2.4.1 focuses solely on the factors affecting threat identification and risk assessment, since minimal to no data was found relating to the pre-decisional phases of the PADM (i.e., perception, attention, and comprehension). Next, Section 2.4.2 addresses factors affecting the decision to evacuate or not. Finally, Section 2.4.3 details additional factors relevant to delay, delay time and the specific types of actions undertaken.

2.4.1 Credible Threat and Risk Assessment

WUI fire literature was identified that discussed factors that affect the following PADM processes: identification of a credible threat and risk assessment. A few studies identified sociodemographic and cue-related factors, but the majority of factors were related to location, preparation and experience.

One WUI fire study identified sociodemographic factors and their impact on threat and risk identification. Mozumder et al. [79] found that having a higher income or level of education was related to an increased level of concern that one's home may be threatened by a wildfire. Additional studies explored the role of environmental and social cues in decision-making. In several studies, a fire cue was often noted to be a trigger that indicated a credible threat and a high level of risk inciting evacuation. This trigger could be the sight of others leaving [80]; sensory cues such as visible smoke, embers or flames; or information from trusted sources about the location and intensity of the fire [80], [81].

Studies also identified residence, location, knowledge and experience with WUI fires as influential to threat identification and risk assessment. First, the length of time a household lived in the area; i.e., residence time, was found to relate to the level of perceived wildfire risk. Newer residents were more likely to be concerned that their home was endangered, whereas long-term residents were more likely to feel that their property was safe [79], [82]. However, if a household had experienced previous property damage due to a wildfire, they were more likely to be concerned that their home would be endangered again [79]. Similarly, a household's knowledge of previous fires in their community and area led to greater concern that wildfire may endanger their own home, impacting their assessment of risk and leading to a higher likelihood of evacuation [79], [83]. In a study looking at Australia's 2009 Black Saturday Fires, it was also found that one's location had an impact on their risk perception, as many people living in suburban locations had not considered themselves at risk to wildfire [84].

2.4.2 Protective Action Decision

The vast majority of WUI fire literature focused on identifying the factors that influence the protective action decision itself; i.e., the decision to stay or go. These factors were grouped into categories relating to sociodemographic factors, environmental and social cues, experience and preparation, familial and societal responsibilities, place/location, and credible threat and risk assessment.

Sociodemographic Factors

One of the most commonly cited demographic factors affecting the likelihood of evacuation was gender. Numerous pre- and post-disaster studies indicated that women were more likely than men to decide to evacuate, and that men were more likely than women to stay in place [79], [84]–[90]. On a similar note, Proudley [91] found that the roles people play within a family had a large role in how people respond and behave during a WUI fire event. Among those who chose to stay, women were found more likely to report that they thought it was too dangerous to leave or that their attempt to leave had been unsuccessful [87]. The study found that protecting property was more often cited by men as their reason for staying, however, this was also a major reason for women as well.

Additional sociodemographic factors that influenced evacuation decisions included political leaning, age, income and occupation. Mozumder et al. [79] found that in the United States, Democrats were more likely than Republicans to evacuate under both voluntary and mandatory evacuation orders. The average age of those who chose to stay and defend during the 2009 Black Saturday Fires was slightly higher than those who evacuated (51.5 years vs. 48.4 years), suggesting that age could be a potential factor [90]. One study found that people with a higher income were more likely to evacuate, and those employed by the wood products and insurance industries were more likely to stay and defend (implied by the authors as being potentially a result of having greater knowledge or skills related to wildfire management or danger) [89].

Environmental and Social Cues

The nature and number of cues received about a wildfire threat have been found to influence the protective action decision made. Rates of evacuation have been found to be higher when people receive multiple warnings from more than one source [83], and receiving advice to leave from friends, family, neighbours and emergency services was also found to influence evacuation (more so for women than men) [87]. However, Strawderman et al. [83] found that these sources had less impact than a more formal warning from authorities. McLennan et al. [90] found that a greater percentage of those who chose to evacuate had received information about the fire from neighbours or emergency personnel in a face-to-face setting. Similarly, receiving a voluntary or mandatory evacuation order was found to increase the likelihood of evacuating, with the latter having a greater effect [79]; however, this may not always be the case [92].

Preparation and Experience

Preparation for WUI fires and experience with these events can also influence protective action decisions. Commitment to a previously developed plan to stay and defend, coupled with a belief that preparations taken were sufficient to meet the perceived level of risk, was a principal factor in staying and defending [80], [81], [90], [93]. Similarly, a lack of preparedness and planning to stay has been found as influential on evacuation decisions, showing that levels of wildfire preparedness and knowledge were higher among those who chose to stay and defend versus those who evacuated [90]. Having a plan to evacuate made people less likely to consider staying and defending and more likely to evacuate [89], [94]. Additionally, studies found that those who intended to stay and defend had greater confidence in their perceived physical readiness and ability to successfully defend their homes than did those who intended to evacuate [90], [95], [96].

In reference to previous experience, Whittaker and Handmer [84] found that previous false alarms – i.e., evacuations or evacuation orders later deemed unnecessary – led people to be less likely to evacuate in the future, while Benight et al. [82] found that such experience did not have a negative impact on future evacuation intentions. Other studies found that those who had evacuated in previous WUI fire events were more likely than those without such experience to evacuate in the future [83]. This variation in the influence of previous evacuations was also noted by Cohn et al. [85], who found that for some, previous experience motivated immediate evacuation; for others, it resulted in evacuation after a longer period of time, and for others still, it made them less inclined to evacuate at all as they deemed it unnecessary.

Familial and Social Responsibilities

Various studies show that there are several factors related to familial and social roles and responsibilities that influence protective action decisions. It was found that having children in a household not only influenced evacuation behaviour, but it also prompted a quicker response – either immediately upon threat awareness or under a voluntary evacuation order [90], [96]. Conversely, those with pets or livestock were more likely to wait and see or stay and defend than those without [79], [90], [96]. The impact that having livestock had on decisions to stay was found to be stronger than the impact of pets [79]. As noted by Tibbits and Whittaker [93], focus groups revealed that for many farmers and people whose livelihoods depend on their livestock, there was a feeling that they had no choice but to stay and defend, for economic reasons as well as for the welfare of their animals.

For those who choose to stay and defend, connections to their community and emotional attachment to their property were found to be motivating factors [81], [90], [94]. Studies found that concerns about personal and family safety were motivating factors for people intending to evacuate [94], [96], whereas a desire to protect property with the acceptance of some personal risk was found to motivate those intending to stay and defend [85]. Another reason Cohn et al. [85] identified for staying was the concern about an inability to return for an extended period of time. According to Tibbits and Whittaker [93], people's confidence in their own ability to defend their property was influenced by active emergency and firefighting officials in the area, as well as by having more than one able-bodied person in the home to help defend; however, other studies found no such evidence [90]. Paveglio et al. [89] found that the belief that residents who live near forests should accept the likelihood of some level of potential property damage was found more commonly among those who choose to stay and defend [89]. Similarly, McLennan et al. [81] found that some of those who chose to stay and defend during the Black Saturday Fires of 2009 were more likely to believe that they were to some extent responsible for protecting their own property, as opposed to relying entirely on emergency personnel.

Place and Location

The decision to evacuate has been shown to be influenced by the location and length/frequency of residence. Some residents of rural areas have been found to decide to stay in place as they deem it impractical given the time and distance required to reach a safe area [89], [93]; however, other studies found no effect of property location on protective action decision-making [90]. In a more general sense, the belief that evacuation was no longer safe was found by McLennan et al. [80] to be a factor contributing to the decision to stay and defend in some cases. Conversely, Strawderman et al. [83] found that those living in a rural area or on a farm were more likely to evacuate than those living in subdivisions or urban areas. Paveglio et al. [89] noted that full-time residents were less likely to evacuate than part-time residents.

Credible Threat and Risk Assessment

The assessment of risk was identified by various studies as being an important factor in the decision to evacuate [79], [83], [94], though not universally across all studies [89], [95]. For those who intended to evacuate, "risk" could be defined as a concern that one's life and home would be endangered [79], [94]; for those who intended to wait and see or stay and defend, "risk" corresponded to danger associated with leaving unnecessarily and having to drive through hazardous conditions [94], [97]. McLennan et al. [94] noted that while those intending to leave were more likely to report higher levels of concern about wildfire danger, they were no more likely than those intending to stay to believe that they were at greater risk than others.

Delay and Actions

A number of factors have been identified which affect the time it takes to make a decision. The decision to ‘wait and see’ has been shown to be influenced by people’s perception of their capability of successfully defending their home/property against spot fires [98]. It has been indicated by Paveglio et al. [89] that in the United States, those planning on employing shelter in place are likely to ‘wait and see’ how bad the fire gets, and potentially evacuate if conditions degrade. McNeill et al. [99] found that the biggest cause for decision delay is a lack of distinct attractiveness of one option over another. That is, both the option of evacuating or staying and defending are similarly appealing. They found this to have more of an impact on decision delay than a lack of perceived risk, sociodemographic or responsibility avoidance. Additionally, Rhodes [97] notes that ‘waiting and then leaving when threatened’ is seen by some to be an acceptable strategy that allows for the increased chances of protecting property and life safety. Individuals who ‘wait and see’ do not necessarily see their actions as being risky [98]. In their review of literature from the United States, Canada and Australia, McLennan et al. [50] found that many people are likely to delay leaving (because they want to protect their property or avoid the costs of evacuating – financial burden, dangers during evacuation) and therefore it should not be assumed that all those threatened by a WUI fire will evacuate immediately upon receiving an evacuation order or warning.

There are also a number of factors that influence the actions people take once they have decided to evacuate. Often times, people prepare, including collecting their belongings and packing vehicles, before evacuating; especially in cases where pre-fire preparations are lacking [82], [83] and even among those who originally chose to stay and defend, but considered evacuation as a last-minute possibility [93]. Also, families tend to leave together as a group, sometimes with neighbours and extended family as well [85]. Evacuees will often search for others and inquire about what they have heard about the event before packing up and leaving [85]. These actions have the potential to increase the time it takes to evacuate.

2.5 Factors Influencing Protective Action Decision-Making During Hurricanes

This section details factors influencing protective action decision-making during hurricanes as found in the related literature. Table 2.1 is Section 2.6.1 provides a summary of these factors in comparison to those identified in the WUI fire literature. As with the WUI fire data discussed in Section 4, there was no discussion of factors affecting the pre-decisional phases of the PADM, and because of this, only those factors that influence threat identification and risk assessment are discussed (Section 2.5.1). Additionally, Section 2.5.2 discusses factors that influence the decision to act, i.e., stay or go. Finally, factors relating to delay, delay time, and specific types of actions taken are discussed in Section 2.5.3.

2.5.1 Credible Threat and Risk Assessment

Literature was found that identified factors that influence threat identification and risk assessment. These factors include sociodemographic factors, as well as those relating to environmental and social cues, place/location, and experience.

First, sociodemographic factors were identified as influential to threat identification and risk assessment. In their analysis of gender roles in hurricane evacuations, Bateman and Edwards [100] found that women were more likely than men to perceive higher levels of risk. Even more complicated is that studies have found the perception of risk to be a mediating variable between gender and evacuation behaviour – in that while men were less likely to perceive risk, men who did perceive risk were more likely than women (with comparable levels of risk) to evacuate.

Environmental and social cues have been identified by several studies as playing a role in the identification of a credible threat and assessment of risk. Storm intensity and severity were found to be of primary concern and were seen as key indicators of personal risk [101], [102]. Additionally, the perceived potential for flooding was found to influence the perception of risk more than forecasts for high winds [102] or the risk of storm surge [103]. Huang et al. [104] found that in addition to environmental cues, social cues also had an impact on risk assessment. Official warnings were determined to have a positive effect on both the identification of a credible threat and risk assessment.

Studies also identified location and experience in hurricanes as influential to threat identification and risk assessment. Surprisingly, it was found that those farther from the coast perceive more severe storm characteristics, potentially as a result of the types of environmental cues faced by residents in different locations [104]. For example, Stein et al. [103] found that there was a heightened perception of risk due to the wind rather than flooding or storm surge for residents outside of the evacuation zone. Additionally, having previous hurricane experience has been shown to increase the perception of credible threat and risk [104]. However, experience with unnecessary evacuation was found to have an impact on lowered risk levels, leading to the belief that previous positive outcomes indicated positive outcomes in the future.

2.5.2 Protective Action Decision

As was found when looking at the WUI fire literature, most of the factors discussed in the hurricane literature were found to influence the actual protective action decision. These included sociodemographic factors, and those relating to environmental and social cues, experience and preparation, familial and societal responsibilities, place/location, and credible threat and risk assessment.

Sociodemographic Factors

It was noted by a number of researchers that females were more likely than males to evacuate [105]–[108]. However, other studies found that when other factors, such as roles and responsibilities within the family and location within the risk areas were taken into account, the effect of gender on evacuation decision was insignificant [100], [104]. In general, the likelihood of evacuating has been found to be higher among younger individuals [100], [106], with the exception of those who classified themselves as retirees who have been found to be more likely to evacuate [100], [109] (even more so with women than with men [100]). It should be noted that other studies found no significant association between age and evacuation [109], [110]. Conflicting results have been found for other socio-demographic factors such as income, education, marital status, and race. Some studies have found these factors to have a significant influence on evacuation [102], [105], [110]–[113], while other studies have found that these factors do not play a significant role [100], [109], [114].

Environmental and Social Cues

Receiving information about a hurricane threat or an evacuation notice from a trusted source, particularly from family, peers or authorities, tended to lead to a higher likelihood of evacuation [106], [112]. Other sources of information such as national television stations, were also identified as influential and, depending on the situation, could have a greater impact on evacuation decisions than other information sources [114]. One of the most influential social cues on the decision to evacuate was receiving an official evacuation order or warning [104], [106], [109]. Both voluntary and mandatory evacuation orders have been found to increase the likelihood of evacuation, with the latter having a greater effect [102], [111], [112], [115], [116].

It has been found that one's location inside or outside of an evacuation zone can impact the outcome of such evacuation orders. For example, those located outside of the evacuation zone were less likely to evacuate, unless they received information about the evacuation order from the media, which then prompted them to evacuate unnecessarily [103]. The effect of the news media was found to have a minimal impact on those inside evacuation zones. Conversely, Lazo et al. [107] noted that perceived evacuation zone did not have a significant impact on evacuation behaviour.

The type of information disseminated about the storm was also found to play an important role in the decision to evacuate. Dow and Cutter [115] noted that the probability and location of hurricane landfall were important factors affecting evacuation decisions. Information on wind speeds [116], storm strength [108], [111], [114] and storm severity [109], [115] were also identified as influential to the decision to evacuate. However, location, such as coastal proximity, and the fact that public officials tend to disseminate stronger messages during stronger storms, can mediate the influence of such storm indicators [106], [109]. The mediation effect caused by other factors was also noted when it came to the effect of observing others. Observing neighbours and peers leaving, or the absence of neighbours who have already left, has been shown to increase the likelihood of evacuating [100], [106], particularly in the case of residents in non-evacuation zones [103]. However, other research found that neighbourhood evacuation was strongly related to high-risk areas and with actions taken by officials, therefore making it difficult to identify the independent strength of this factor [109].

Preparation and Experience

Previous experience with hurricanes and hurricane evacuations is a potentially influential factor in hurricane evacuation decisions [105]. Numerous studies have found such experience to lead to increased likelihood of evacuation [101], [107], [110], [113], [114]. Petrolia and Bhattacharjee [116] found that past storm experience had a significant impact on future evacuation intention; however, the nature of the experience determined whether the person was inclined to stay or go. For example, past experience has been found to negatively impact evacuation in instances where past evacuations were viewed as unnecessary [104], [112]. It should be noted that other studies have found the impact of past experience to be insignificant [106], though others point out that it can contribute to awareness of the hazard and potentially produce a greater appreciation for the danger it may pose [109]. Murray-Tuite et al. [110] noted a level of consistency between previous evacuation actions, with 70% of study respondents making the same protective action decisions for both Hurricane Katrina and Hurricane Ivan.

People who had created a household evacuation plan were more likely to evacuate [100], [107] and those who had spent more money on household storm preparation and planning were less likely to evacuate [114]. Increased knowledge about hurricanes was not found to impact evacuation decisions [109].

Familial and Social Responsibilities

The strength and viability of one's social network have been found to have an impact on evacuation decisions, with those who have stronger social support being more likely and able to evacuate [113], [117]. Riad et al. [113] noted that it was a weaker social network, and not poverty, that was the greatest obstacle to evacuation for those with fewer resources.

The desire to keep one's family safe was identified as being one of the strongest influences on evacuation intention [107]. In line with this, research has found family size and the presence of children to impact the decision to evacuate. However, this impact varies. Studies have found that having children in the household can positively impact evacuation [106], [108], [112], [114], negatively impact evacuation [110], or have no effect at all [100], [109]. Similarly, the impact of family size is unclear [100], [110], [114].

Work responsibilities and the potential loss of income due to evacuating have been found to significantly impact the decision to stay [112], [115]. Additionally, wanting to protect property from the storm and/or from looters [109], [111] and having pets or livestock decreased the likelihood of evacuation [102], [111], [114]. Concerns regarding perceived evacuation impediments, including traffic congestion, reduced the likelihood of evacuation [104], [115]. In line with this, people tended to consider a wide variety of indirect costs associated with evacuation such as travel costs, care for pets, and potential difficulties with re-entering the evacuation zone [115].

Place and Location

The vulnerability of one's home to hurricanes has been shown to impact the likelihood of evacuation, though the strength of this factor varies depending on the study. In the case of hurricanes, vulnerability is most often classified as living in a mobile home, and for those who do, studies show that they are more likely to evacuate [100], [108]–[110], [114], [116]. Conversely, some research indicated an insignificant correlation between evacuation and mobile home residence [106].

Other research on place and location has found that living in multi-family dwellings can increase the likelihood of evacuation [110]; however, not all studies agree [111]. Homeownership, compared with renting, is also identified as an influential factor for non-evacuation in some studies [108], [112], [114], with longer-term residents being less likely to evacuate than shorter-term residents [113]. However, not all studies found significant results [109]. The belief that one's home was a safe place was identified by Dow and Cutter [115] as being the first consideration in deciding to stay, followed by traffic, work responsibilities and the likelihood that landfall would be nearby. In line with this, living near the coast or bodies of inland water, or in flood areas has been shown to lead to increased levels of evacuation [100], [104], [106], [109], [114]. However, context matters here. The factors of the population within the coastal communities, e.g., income and other demographics, should also be taken into account [110].

Credible Threat and Risk Assessment

As the PADM model shows, risk perception is a critical factor that influences protective action decisions. Those who felt safe in their home were more likely to stay, and those who felt unsafe were more likely to leave [101], [109], [113]. Individuals who were concerned about costly damages favoured evacuation [109], [111], as did those who perceived personal vulnerability to wind and storm surge [107].

Delay and Actions

Some research found that those living farther from the coast were more likely to wait before making their decision to evacuate compared to those closer to the coast [116]; however, they were more likely to take less time to prepare – i.e., spending less time protecting their property, packing and securing their home [106], [118]. Not having an evacuation destination identified ahead of time (pre-storm) was identified as contributing to added confusion and subsequently delay as a result of not knowing what protective action decision to make [116]. Additionally, large households tended to evacuate later and took more vehicles, whereas older adults tended to evacuate earlier [118].

2.6 Discussion

2.6.1 Similarities and Differences Between WUI Fire and Hurricane Factors

For this chapter, the factors mentioned in Section 2.4 and 2.5 above, for WUI fire and hurricane events respectively, are structured according to the PADM framework. This allows for a more comprehensive understanding of how a given factor will affect the evacuee decision-making process and how this effect might propagate through this process, potentially affecting the time it takes to respond and the outcome of the response. As will be shown in the discussion below, it was often found that a particular factor influenced more than one part of this process. A summary of the identified factors is presented below in Table 2.1. Factors that were identified solely in qualitative studies are denoted with an asterisk (*), all other factors were found in quantitative studies or in both qualitative and quantitative studies.

For both hurricanes and WUI fires, very little research was found that identified the factors affecting the pre-decisional phases (i.e., receipt of, attention paid to, and comprehension of cues and information). The only study identified discussed how hot weather may have prevented awareness of the Black Saturday Fires as the heat prompted people to stay indoors [86]. Identifying additional factors that affect the pre-decisional phases will enable WUI evacuation models to more effectively and comprehensively represent potential obstacles to resident fire threat awareness.

Table 2.1: Hurricane and WUI Fire PADM Factors

<table>
<tr><th>PADM Stage</th><th>Wildfire</th><th>Hurricane</th></tr>
<tr><td>Pre-Decision</td><td>Weather [86]*</td><td>Not Applicable</td></tr>
<tr><td>Credible Threat and Risk Assessment</td><td>Income/Education [79]
Trusted sources [80], [81]*
Length of time lived in area [79], [82]
Location [84]*
Observe others [80]*
Previous experience with wildfires, knowledge of other fires [79], [83]
Sensory – environmental [80], [81]*</td><td>Coastal proximity [103], [104]
Environmental cues [101]–[103]
Gender [100]
Previous hurricane experience, unnecessary evacuations [104]
Social cues [104]
Trusted sources [104]</td></tr>
<tr><td rowspan="5">Protective Action Decision</td><td>Sociodemographic Factors
[79], [82], [84]–[91]
• Age
• Gender
• Income
• Occupation
• Political leaning</td><td>Sociodemographic Factors
[100], [102], [104]–[114]
• Education
• Gender
• Income
• Marital status
• Race
• Retired</td></tr>
<tr><td>Environmental/Social Cues
[79], [83], [87], [90], [92]
• Evacuation order
• Multiple sources
• Telling other people
• Trusted source
• Wait and see</td><td>Environmental/Social Cues
[100], [102]–[104], [106]–[109], [111], [112], [114]–[116]
• Environmental cues
• Evacuation order
• Observing neighbours
• Trusted source</td></tr>
<tr><td>Preparation/Experience
[80]–[85], [89], [90], [93]–[96]
• Belief in capacity/survivability
• Commitment to plan
• Preparation and knowledge
• Previous evacuation/fire experience</td><td>Preparation/Experience
[100], [101], [104]–[107], [109], [110], [112]–[114], [116]
• Plan
• Previous experience (hurricane and/or evacuations)</td></tr>
<tr><td>Familial and Societal Responsibilities
[79], [81], [85], [89], [90], [93], [94], [96]
• Attachment to home/community/ desire to protect property
• Children
• Pets/livestock</td><td>Familial and Societal Responsibilities
[100], [102], [104], [106]–[115], [117]
• Protect property (from storm and looters)
• Keep family safe (children, family size)
• Pets/livestock
• Social network
• Work responsibilities</td></tr>
<tr><td>Place/Location
[80], [83], [89], [90], [93]
• Distance to neighbours
• Full time vs. part time residents
• Rural vs. suburban</td><td>Place/Location
[100], [104], [106], [108]–[116]
• Dwelling type (mobile home, multi-family)
• Coastal/water proximity
• Home as a safe place
• Home ownership and length of residence</td></tr>
</table>

Table 2.1: Hurricane and WUI Fire PADM Factors (continued)

PADM Stage	Wildfire	Hurricane
Protective Action Decision (cont.)	Risk Assessment/Credible Threat [79], [83], [89], [94], [95], [97] ● Assessment of effectiveness ● Concern ● Risk/danger (staying or leaving)	Risk Assessment/Credible Threat [101], [107], [109], [111], [113] ● Risk of flooding, high cost damages
Delay and Actions	Families stay together [85]* Gathering physical possessions [82], [93] Indecision [99] Wait and see [50], [89], [97], [98]	Age [118] Evacuation destination [116] Household size [118] Location [106], [116], [118]

With respect to the threat identification and risk assessment stages of the PADM, similar factors were identified in the hurricane and WUI fire case studies. Within the sociodemographic factor category, income, education and gender were identified as having potential impacts on the assessment of threat and risk in both the WUI fire and hurricane literature. Similarly, within the environmental and social cue category, triggers were important factors identified for both hazards. For instance, for WUI fires, environmental cues consisted of smelling or seeing flames, embers or smoke; and for hurricanes, environmental and social cues consisted of storm intensity and severity, as well as the risk of flooding due to heavy rain or storm surge. Both data sets found that social cues, such as observing others leaving, receiving information from trusted sources, or receiving an evacuation order increased the credibility of a threat and the perception of risk. Place and location, as well as preparation and experience, were also factor categories found to play a role in threat and risk assessment in both hazards. In both cases, it is important to note that previous experience alone was not enough to influence behaviour. This factor is more nuanced in that the type of experience (e.g., positive or negative), is what influenced threat identification and/or risk assessment.

Most of the factors identified in this literature review played a role in the protective action decision-making stage of the PADM. With respect to sociodemographic factors, gender was found to be the most commonly discussed factor for both WUI fires and hurricanes. In both cases, it was predominantly the case that women were identified as being more likely than men to evacuate. These findings must be taken in context, as when other factors associated with gender roles were considered (e.g., roles and responsibilities within the home), the impact of gender became insignificant in some studies. Moving forward, it would be beneficial to delve further into the role of gender in evacuation decision-making and response. Additional sociodemographic factors such as age and income were mentioned in both WUI fire and hurricane research, but they were identified less often, and/or their influence was often contradicted by findings from other studies.

In a general sense, environmental and social factors that influenced evacuation decision-making were similar in both the WUI fire and hurricane literature; i.e., observing others; receiving warnings from multiple sources, especially from trusted sources; and receiving evacuation orders (especially those mandatory in nature) tending to result in a decision to evacuate. Place and location were also identified in both data sets as influential to evacuation decision-making. Influential factors identified were locations (i.e., rural versus suburban), residency, neighbour proximity, home vulnerability, home ownership, length of residence, and proximity to the hazard (i.e., the coast in reference to the hurricane studies and proximity to the fire front in a WUI fire). It is important to note; however, that the findings were not consistent across the studies, making it even more important for additional research to be performed on evacuation behaviour in response to hazards.

Researchers identified that preparation and previous experience influenced protective action decision-making for both WUI fire and hurricanes. Similar to its impact on threat identification and risk assessment, the effect of previous experience is complex, requiring an understanding of the *type* or *nature* of the experience (i.e., positive or negative). Familial and societal responsibilities also affected decision-making in both WUI fires and hurricanes. Having children, a need to protect the family, family size, and owning pets and livestock were found to influence evacuation behaviour. The influence of pets and livestock might be influenced by restrictive shelter policies and/or boarding facilities requiring proof of vaccination (which evacuees are unlikely to have with them). Additionally, having a connection to one's community, wanting to protect property, and believing that one could successfully do so were also factors that were discussed along with the impact of one's social network and work responsibilities. Similarly, factors highlighting the important role of threat credibility and risk perception in evacuation decision-making was found in both data sets. The risk to life versus property, as well as the likelihood of evacuation being the safest option (versus being potentially dangerous), were examples of risk assessment impacts on WUI fire evacuation. The hurricane data showed that the risk of varying types of storm-related impacts such as flooding, storm surge and wind influenced people's likelihood of evacuating.

Lastly, factors influencing delay, delay time, and specific types of actions included confidence in one's capability to defend one's home in the face of a WUI fire, coastal proximity, age, family size and having (or lacking) a destination choice. Post-decision actions were identified by a few WUI fire papers and these included collecting belongings, checking on and waiting for family/friends, and deciding on the evacuation destination and travel routes to get there.

The factors identified in Table 2.1 aid in the development of a conceptual model of protective action decision-making in WUI fires. Factors have been linked with various stages of the PADM, to create the framework for a model that can conceptually explain eventual decisions to evacuate or stay in place (either to defend the home or to shelter in place). The factors identified from the hurricane studies fill in gaps left behind by the WUI fire studies to develop a more comprehensive model. The framework, or conceptual model presented in Table 2.1, can be further developed, quantified, calibrated and validated with actual data on protective action response from a WUI fire event to eventually create a computational simulation of a WUI fire evacuation.

2.6.2 Conceptual Model Considerations

The conceptual model presented here has several limitations. First, individual study conditions can vary by hazard conditions, populations, and community environment, which in turn, can affect the factors identified as influential to evacuation decision-making and response. Also, the WUI fire studies reviewed focused on U.S. and Australian populations, which can differ by evacuation policy, preparedness and experience. Within both Australia's former wildfire evacuation policy and its current one, there is a greater acceptance of staying and defending, while in the U.S., community officials almost exclusively disseminate mandatory (and sometimes voluntary) evacuations to threatened communities[5]. Delays (or "wait and see" behaviours) still occur in U.S. fire evacuations; however, issues of data applicability lie in the final decision to stay or go. Policies in one country may affect evacuee perception of viable evacuation alternatives and/or their experience or knowledge with such evacuation alternatives (which then influences the eventual decision). Very little data (in English) is available on evacuation decision-making and behaviour during WUI fires in countries other than the United States and Australia. Studies of WUI fires in other countries would strengthen and broaden the scope of the conceptual model developed here as would collaboration with researchers from multiple countries so that research in languages other than English could be included.

[5] Despite the practiced policy of evacuation in the United States, a number of studies suggest a growing number of people do not want or intend to evacuate automatically in the event of a wildfire and a small number of communities have looked into implementing a version of evacuation alternatives, primarily shelter in place [79], [92], [135], [181]. With that said, such cases are very rare and such methods are still typically seen as a last resort if evacuation is not a possibility.

2.6.3 A Canadian Context Exploration

As noted earlier, there is little research looking at WUI fire protective action decision-making in Canada. The majority of Canadian wildfire research is focused on wildfire mitigation (e.g., [119]–[121]), wildfire risk management and assessment (e.g., [122]–[124]), and the impact of climate and climate change (e.g., [125]–[127]). As noted in Chapter 1, there has been one study looking at WUI evacuations in Canada between 1980 and 2007 which focused on the number of wildfire events and evacuees, their location, the timing of the evacuations (season and duration), the characteristics of the wildfire, the weather, the vegetation, the spatial variation, the impact of smoke, the loss of structures, the number of fatalities and the quality of the available data [20].

The small body of research that has been conducted about factors influencing WUI fire evacuation decisions in Canada has focused primarily on First Nations and Metis communities [51]–[53]. These identified studies were qualitative and generally had a small sample size. Often the communities studied were very isolated. One study found that residents had to be evacuated via plane or helicopter as there was no direct road access [53]. This increased the complexity and challenges associated with the evacuation, including having to evacuate people in small groups following a "risk triage protocol" (most vulnerable first – those with respiratory issues, the elderly, pregnant women, etc.) and therefore having to separate families or social units. This was identified by the authors as increasing peoples' reluctance to evacuate. In another study looking at a First Nation community that evacuated due to smoke from a nearby wildfire, it was found that over half of those interviewed did not want to evacuate [52]. This included "residents who did not want to leave pictures and other precious belongings behind; perceived the fire risk to be low; wanted to stay home and carry out their usual activities; felt uncomfortable staying in a town or evacuation centre; and wanted to obtain firefighting work" [52]. Of those who did not want to evacuate, a few ended up leaving for the sake of children, at the insistence of a friend or when escorted by the police. In a study that looked at intended and preferred evacuation actions, all participants indicated that they would prefer to stay and defend as opposed to evacuating [51]. It was noted that the perceived safety of the participants' properties contributed to this intention. The participants were concerned about leaving their homes unprotected, about the spoiling of food stocks and what they would do with livestock and dogsled teams if they left. For the majority of the participants, their confidence in their ability to defend their property was found to be dependent on the severity of the fire, with most stating that they might consider leaving their properties if a fire became too extreme. This is reflective of findings from some Australian and American studies discussed earlier in this Chapter. It was also found that participants had little to no wildfire experience and were unsure what to expect should they stay and defend during a wildfire event. All participants felt that sheltering in place seemed counter-intuitive and over half said that they would not feel comfortable passively sheltering in their home during a wildfire. This draws attention to the important distinction between the intention to passively shelter or actively defend one's property.

With respect to Canadian studies looking at more populous and non-Indigenous communities, only one study was found. This study looked at Fort McMurray residents' experiences with the 2016 wildfire evacuation [128]. Through an online survey one month after the fire, it was identified that prior to the fire, most respondents felt that the threat of a wildfire was low. They became aware of the fire through many different means, ranging from seeing the fire to hearing about it on the radio or from a family member.[6] In looking at the time between notification and evacuation, the study found that 11.7% of respondents had to leave immediately,

[6] The paper does not discuss if multiple sources were used to get information about the fire or how different sources impacted evacuation decisions or actions.

while most people (52.7%) spent between 15 and 60 minutes getting ready to leave. It was also noted that over half of respondents had trouble leaving their neighbourhood and the city due to congestion or not knowing which direction to go.

Given the occurrence in recent years of WUI fires that have resulted in multiple and mass evacuations such as those in Alberta [24] and British Columbia [129], it is important that more research into evacuation decision-making in Canada is undertaken. Such research should look at both the general populous and specific groups, and at both small and large communities. This would allow planners, government agencies and emergency management personnel to have a better understanding of Canadians' responses to WUI fire events in different parts of the country and would improve the accuracy of future egress models to represent Canadian WUI fire evacuations as well as the ability to assess WUI community vulnerability.

2.6.4 Future Model Development and Research Needs

As mentioned earlier, Section 2.6.1 and Table 2.1 provide the first-stage conceptual model of protective action decision-making in WUI fire (and hurricane) events. Factors are identified as influential to each step of the PADM (noting that there is little research that identifies influential factors of the pre-decisional phases). The next step in conceptual model development is to identify the ways in which the factors that influence the same decision-making phase interact with one another in a more integrated manner. In reality, many of these factors are highly coupled and this may affect the outcome in complex ways (i.e. additive, counteractive and multiplicative). Reconciling these interactions is not a trivial task (and one that requires additional empirical support), but it is necessary for the continued development of this type of conceptual model. For instance, Dash and Gladwin [105] identified risk perception as having a greater impact on hurricane evacuation than negative past experience such as traffic delays. Similarly, it was found that risk perception could have a bigger impact than evacuation warnings if people believed their homes were safe as they were less likely to interpret such warnings or orders as being directly applicable to them and their situation [109]. This was also shown to apply in the reverse where environmental cues led people to evacuate even when they were not under an evacuation order [103]. For these reasons, understanding factor interactions at each decision-making phase of the PADM will be vital when translating these concepts into a quantitative model.

This work has focused on establishing a qualitative first-stage framework identifying the social and environmental factors to be considered within a WUI evacuation model. For implementation within a computational platform, this framework would need to be quantified. Work is currently underway by researchers to create a quantitative modelling framework (based on the framework adopted and developed here) to simulate householder risk perception given a WUI fire event and to predict householder protective actions [130]. Such predictions could be embedded within a simulation tool to make time-based estimations of the *consequences* of the decisions made by residents in conjunction with the resources available, the fire incident conditions and the existing physical infrastructure. An understanding of such consequences would be of great benefit in planning and design, vulnerability assessment, emergency response, and in post-incident investigations when attempting to assess the effectiveness of the emergency plans enacted. Provided here is a list of research gaps that need to be addressed to facilitate the development and validation of the conceptual model described above and the subsequent implementation within a simulation tool:

1. The factors that influence the three pre-decisional phases, including perception, attention, and comprehension.
2. The relationship between previous experience and PADM processes and mediating factors.

3. A more current representation of the relationship between gender and PADM processes and mediating factors.
4. The factors that influence specific actions taken before evacuation movement begins, as well as the time to complete those actions.
5. The factors that influence evacuation decisions, such as route choice and choice of final evacuation destination.
6. An understanding of the interaction of factors and their resulting outcomes.
7. Data from studies on WUI fires from populations in countries outside of the U.S. and Australia.
8. The influence of changing demographics of people living in the WUI on evacuation decision-making and response (e.g. new WUI residents and long-term aging WUI residents).
9. The influence of a changing WUI landscape (e.g. environmental conditions) on evacuation decision-making and response, especially where communities are now vulnerable to WUI fires for the first time.

2.7 Summary

The increasing prevalence of large and destructive wildfires is an issue of growing concern. With more people living in the wildland urban interface, being able to evacuate potentially large groups of people with little warning and in a short amount of time will continue to become a more pressing and challenging task. One of the ways that the fire protection engineering community is addressing this more credibly and effectively is through the use and development of comprehensive WUI fire evacuation models.

A key component that must be considered in these models is protective action decision-making and behaviour in the WUI; i.e. what people do in response to the fire. Choosing to evacuate or taking another protective action is a complex process influenced by several diverse factors including sociodemographic factors, social and environmental cues, preparation and experience, familial responsibilities, location, and credible threat and risk assessment. Although challenging, it is important to represent these factors within WUI fire evacuation models, as they influence if/when people choose to evacuate and where they will go. At this stage, identifying the factors that influence evacuee decision-making during WUI fire events and characterizing the nature of this impact is a key step – a step that has been addressed in this chapter. The factors identified as influencing evacuee decision-making and response to WUI fires and hurricanes have been collected and categorized according to the PADM framework. The first-stage conceptual model developed represents a qualitative description of the evacuation decision, delay and actions taken before vehicular movement begins. This represents an important foundation on which to build.

Broadening the scope of this conceptual model to include research from WUI fires and hurricanes was necessary given the limited information available; it also generated ideas for future research into the factors influencing the decision to evacuate or not in WUI fires. This approach provided the opportunity to see how factors might vary given different incident scenarios, strengthened the findings that some specific factors were particularly influential, and identified gaps in our current understanding that should be explored in future research.

Chapter 3: Communication and Notification During Hazards – Considerations for Canadian WUI Fire Evacuations

3.1 Communication Systems During WUI Fire Evacuations

Recent Canadian wildfires such as the 2016 Fort McMurray Fire and the British Columbia fires of 2017 resulted in the evacuation of tens of thousands of people. Within the summer months of 2018, wildfires in the western provinces of British Columbia, Alberta, Saskatchewan and Manitoba resulted in numerous communities being evacuated or put on evacuation notice. The deadly November 2018 wildfires in California led to hundreds of thousands of people being evacuated. As more frequent and large-scale wildfires such as these occur in the increasingly populated WUI, it is of growing importance to be able to safely evacuate potentially large groups of people. One key component of this is communication.

When a wildfire threatens populated areas, a lack of useful information can compromise the ability of people to manage, fight and escape from the fire. Information affects the ability of agencies to manage the event and it impacts the ability of those threatened by the fire to adapt to the risk and take the appropriate actions (when to leave, where to go, etc.) [131]. However, given the complexity of wildfires and wildfire management and evacuations, disseminating this information can be challenging. There are multiple agencies involved, fires can occur at night when people are sleeping or during the day when they are at work, and often those who are most at risk may have limited access to information sources (cellular and internet service, radio, television, etc.). The fire itself can also interfere with communication further, disrupting telephone and power lines. In addition, the severity of a WUI fire and the speed at which it can develop and travel not only adds to the importance of prompt evacuation notification but also highlights the challenge of doing this successfully.

Given this complexity, the dissemination of WUI fire information often takes a multipronged approach. Evacuees can be notified in person by police officers going door-to-door in communities under mandatory evacuation orders, television and radio stations can broadcast evacuation orders (along with general coverage of the event) and reverse 911 can be used to make notify people via landline phones. More informally, people may turn to their friends, family and neighbours for information, as well as to social media and internet news sources. A relatively new means of communicating information about hazardous events such as wildfires is through the use of mobile devices and wireless technology. Given the growing prevalence of smartphones, the ability for the government and agencies to officially alert the public about a WUI fire threat via their wireless device provides a new opportunity to reach large groups of people quickly. Several countries, including Canada, are taking note of this.

Wireless components of national hazard and threat notification systems allow governments and approved agencies to send out text-like messages to the public’s wireless cellular devices. These messages are meant to be geographically relevant, using cell towers in the vicinity of the event to notify those in the area under threat. In the United States, a Wireless Emergency Alert (WEA) system has been in place since 2012. Since its installment, WEAs have been used for over 33,000 alerts [132]. During the California Wildfires of 2017, the WEA system was used 20 times, with county governors reporting that the alerts helped move people in their communities to safety [133]. Over the past few years, Canada has also been developing its own wireless alert system, expanding its existing National Public Alerting System to include a wireless device notification component. This will be discussed further in Section 3.3.1. Given its recent implementation, the

Canadian wireless alert system has not been used for wildfire evacuation orders or notification as of the writing of this thesis.

The effectiveness, reliability and success of emergency notification systems are dependent on many factors, including the ability of the system to function properly, the alert to reach its intended audience, the message to convey the necessary information and the public to act accordingly. These factors must be considered and addressed if emergency communication systems are to be effective. This chapter will focus on the new wireless component of Canada's emergency alert system and how these factors and challenges can manifest within it. Given that the Canadian wireless alerting system is still in its infancy, a number of these challenges have been made apparent by the few system tests and recent official uses over the past year. One specific incident, an Amber Alert in May 2018, will be discussed in detail in Section 3.3.2, as will the lessons that can be learned and their implications for WUI fire notification.

3.2 The Role of Human Behaviour in Fire in Emergency Communication

As discussed in Chapter 2, the first step in protective action decision-making is receiving, perceiving and comprehending a cue about the hazard. Not only this, but the literature reviewed prior by the author, showed that information seeking occurs at each stage of the decision-making process and that the nature of the source and whether it was trusted or not could affect its impact (with information coming from trusted sources, especially in the form of evacuation orders, having the strongest impact). Additionally, receiver characteristics such as prior experience, pre-existing beliefs, cost of compliance and demographic variables can also play a role in how people react to information about a hazard [134]. Given that information and information seeking plays such an important role in the decision-making process and therefore in the potential outcome of an event, the timeliness and accuracy of the available information are critical. One study comparing the nature of evacuation communication during two different wildfires noted that people felt safer and had greater trust in the fire management agencies when communication was frequent, detailed, and open during wildfire evacuations [135]. When communication was limited between the community and the fire management agencies, residents turned to the media for information (which was often conflicting or inaccurate) and years after the fire expressed fear about wildfires and distrust in the fire management agencies. Other studies have found that one of the most significant challenges noted by wildfire evacuees is a lack of up to date information about the fire activity and impacts [135].

One of the reasons officials are sometimes hesitant to issue multiple, detailed alerts is the perception that people will panic if they have too much information. Panic, or the loss of social order and selfish competition [136], is a phenomenon often noted by media and public officials, as well as by the people involved in a stressful incident such as a wildfire evacuation itself. However, as noted by Kuligowski in her discussion of "discarded theories" in human behaviour in fire, research does not support the idea that people respond to fire stimuli by behaving in self-destructive or "animalistic panic-type" ways [47]. When people report having experienced or witnessed panic, they are often referring to emotions such as fear or anxiety, emotions which are natural in threatening situations. These emotions, however, do not equate to the behaviours associated with panic. In contrast to behaving irrationally, research has shown that in many disaster situations people tend to first assume that nothing is wrong, a concept referred to as normalcy bias. Particularly when faced with ambiguous or contradictory information, people have a tendency to believe the less distressing option [137]. This reinforces the importance of accurate and detailed information about a fire event given that people are unlikely to act in the desired, self-protecting way unless they believe that they are truly in danger.

Alarm fatigue, or desensitization, is another element that can impact the effectiveness of notification systems and messages as a result of human behaviour. It is a phenomenon initially observed in medical care, where numerous and repetitive loud alerts or notifications from medical monitoring devices overwhelm and desensitize the staff to these alerts. Staff members experiencing alarm fatigue may then miss, ignore or disable alarms, particularly if the alarm in question has a high false positive rate [138]. Alarm fatigue is not limited to the medical profession; it has played a role in rail, aviation and industrial accidents as well [139]. Studies have shown that a common problem leading to alarm fatigue is that people learn to distrust the alarm systems set up to assist them due to their high frequency of activation and/or high false positive rates [138]. In the context of disaster alerts, a high frequency could mean that the public is receiving multiple messages from multiple sources, potentially with little to no new or helpful information. A false positive in this case would not only include the reporting of a false event (false alarm), it could also be the reporting of events that seem irrelevant to the recipient due to their proximity to the threat. It should be noted that there is a limited body of research looking at alarm or warning fatigue in the context of disaster research specifically and that it has shown the concept to be nuanced, a function of the disaster type and the frequency and timing of the warnings [140]. One study looking at warning fatigue in the context of Australian bushfires found that warning fatigue was influenced by five aspects – trust and credibility, over-warning, false alarms, skepticism and helplessness [140]. This study also noted that unofficial warnings including media stories also influenced alarm fatigue responses (not just official warnings). Alarm or warning fatigue is therefore something that should be studied further to better understand its role in the response to WUI fire alerts and should be considered when developing an approach to WUI fire notifications.

3.3 National Public Alerting in Canada

As discussed in Chapter 1, the Canadian WUI is somewhat different from other countries. While the density of the Canadian WUI is less than places such as California [20], the isolation and often small size of WUI communities can pose unique challenges when looking to notify people about an impending wildfire and when trying to evacuate these communities. This makes having a multipronged notification approach all the more important as not all methods will be useful for all WUI communities. In some of the larger WUI communities such as Fort McMurray, Alberta, the potential of wireless alert systems for wildfire notification and evacuation has great potential. This is also true for smaller, more isolated WUI communities provided that there is adequate cellular service, a complementary component to this system that needs to be better understood.

The following sub-sections will look at the history of public alerting systems in Canada, including the birth of its new wireless alert component, and will discuss a case study looking at one of the first official uses of the wireless system, the lessons learned from this use and how these lessons can help inform the system's continued improvement and use for WUI fire alerts.

3.3.1 History

In 2007, Canada initiated its National Public Alerting System (NPAS) [141]. The purpose of the system is to enable emergency management organizations in all provinces and territories to promptly warn the public of "imminent or unfolding hazards to life" [142]. Such hazards include fire events, natural disasters, terrorist threat, civil emergencies or biological, explosive, and environmental threats [18]. As noted in Chapter 1, emergency management functions are shared between the Federal-Provincial-Territorial (FPT) governments and industry partners, and this applies to the NPAS as well. The former includes the Government of Canada, federal agencies, provincial and territorial governments, and authorized municipal agencies. These institutions are responsible for creating and issuing the alerts. The latter includes companies such as Pelmorex Corp which owns and operates the National Alert Aggregation and Dissemination (NAAD) System that provides the central technical infrastructure necessary for collecting and validating the alerts and disseminating them to the public [142]. Figure 3.1 below shows the timeline of a NAPS alert.

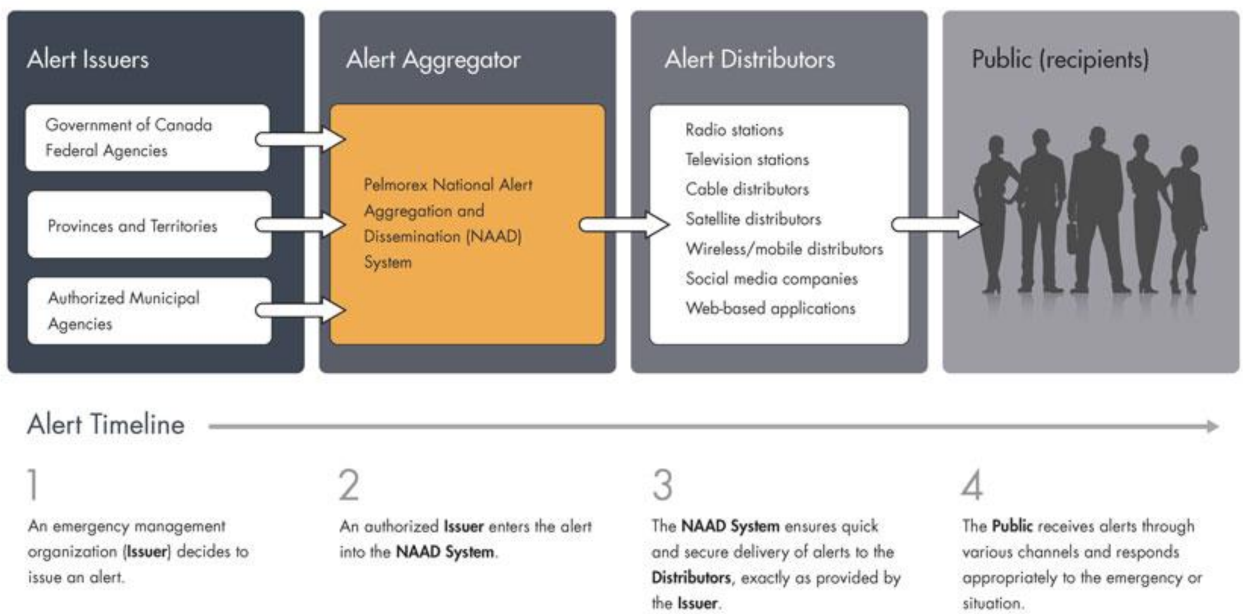

Figure 3.1: National Public Alerting System (NPAS) alert timeline [142]

Over the past decade, FPT governments have been working together as part of the Senior Officials Responsible for Emergency Management (SOREM) forum to improve and expand the NPAS. A summary of key events as detailed by Public Safety Canada [141] can be seen below:

- **2007** – The Canadian Radio-television and Telecommunications Commission (CRTC) agrees to remove regulatory barriers to alert services. Radio and television broadcasters can volunteer to take part in the distribution of public alerts.

- **2009** – Pelmorex Corp (owners of the Weather Network / MétéoMédia television channels) is approved by the CRTC to launch the NAAD System. FPT governments begin working with Pelmorex and private sector broadcasters to make the NAAD System operational.
- **2010** – The NAAD System is officially launched, providing the technical infrastructure of Canada's NPAS. All provinces and territories agree to issue and accept emergency alerts via their Emergency Management Systems through the NAAD system. Environment and Climate Change Canada also agree.
- **2014** – The CRTC requires television and radio broadcasters, cable and satellite companies to distribute NPAS emergency alerts. The Wireless Public Alerting System (WPAS) begins as a three-year pilot project, seeking to create and showcase effective solutions for emergency public alerting using Long-Term Evolution (LTE) based technology
- **2015** – Alert Ready is launched as a public awareness and education campaign about NPAS (becoming the public-facing brand name for the NPAS initiative).
- **2017** – WPAS pilot study is successfully completed. After consultation with key stakeholders and the public, the CRTC mandates that wireless service providers implement the NPAS into their LTE wireless networks by April 2018.
- **2018** – FPT governments, Pelmorex and wireless service providers work to meet the requirements of the CRTC mandate to enable authorized government agencies to alert Canadians on compatible wireless devices. Each alerting authority begins using this new method as it builds the capacity to do so. Building the success of the ongoing Alert Ready campaign, Pelmorex and Public Safety Canada work with provinces and territories to launch a wireless public alerting campaign to inform the public about the new wireless alerts.

Thus far, there have been two official tests of the wireless alerting system, one in May 2018 and one in November 2018. Previous tests of the non-wireless elements of the system have also taken place in some provinces [143]. As a whole, the system has only been used a few times for official alerts, including tornado warnings in Manitoba (2015) and Ontario (2018) [144], [145] and several Amber Alerts [146]–[148], one of which will be discussed in greater detail as a case study below. It should be noted that there is not an easily accessible or publicly available list of the system's history of use (when, where and why it was used). As such, most of the information about specific incidences where it has been used comes from media coverage of the events.

Given that alerts issued via the Alert Ready system have the potential to reach large groups of people and deliver critical and time-sensitive information, it is important that these alerts are clear and effective. As discussed in Section 3.2, human behaviour is one of the things that must be considered when implementing such a system as it can influence people's responses to an alert and therefore the outcome of the event. Though not a wildfire incident, the case study of the May 2018 Amber Alert issued in Ontario provides an opportunity to identify factors that should be considered in the endeavor to successfully notify people using this alerting system and therefore improve the system for all future alerts, including those relating to wildfires.

3.3.2 Alert Ready Case Study: Thunder Bay Amber Alert

Introduction

On May 14, 2018, an 8-year-old boy was reported missing near Thunder Bay, Ontario. At 11:35 AM, a subsequent Amber Alert was issued. Amber Alerts are a critical and important method of communication that is used to notify the public of missing children. Normally in Canada Amber Alerts are broadcast on TV, radio, and/or billboards. However, this Amber Alert was different, as it was also sent using the new wireless component of the Alert Ready system. The system had been tested nationwide for the first time less than a week prior. The system sends emergency text-based messages accompanied by a loud siren-sounding alarm tone which overrides device volume settings to the loudest setting to better attract people's attention. The wireless system is cell tower based, allowing alerts to be sent out to devices connected to towers in the areas affected by the emergency or hazard. This means that any compatible cell phone, regardless of number, area code or service provider, will receive the alert if it is within the designated area [149].

The emergency alert on May 14th was sent out across Ontario, reaching as far as the cities of Ottawa and Toronto, nearly 1500 km away from Thunder Bay. The Amber Alert consisted of a total of three messages sent out through the Alert Ready wireless system over the course of two hours (see Figure 3.2). As each of the alerts was sent, the effect that they had on Google-search behaviour could be seen via the internet communication tracking software Google Trends. Google Trends allows the popularity of certain search terms to be examined and compared over a selected time period. This provides insight into the relative popularity of specific search terms and when people are searching for a specific term. In the context of the Amber Alert, the data generated can provide insight into how the Alert Ready wireless system was being perceived during this event and how effectively it communicated its message. Through conducting a small, exploratory study of specific search terms, a general understanding of people's reaction to the alert and new wireless alerting system could be gained.

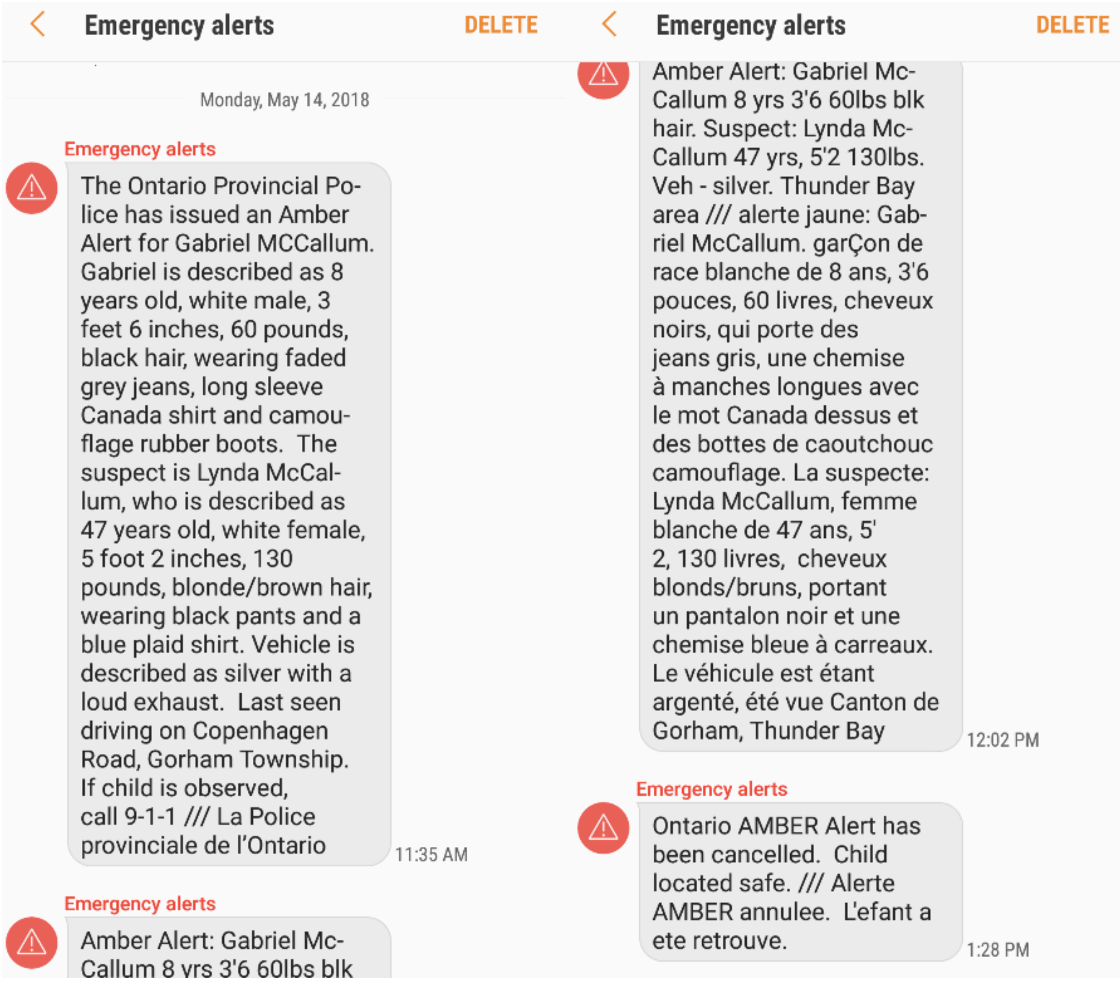

Figure 3.2: Three Alert Ready messages sent on May 14, 2018

Methodology

Data was gathered for three search terms over the 24 hours following the alert (11:30 am on May 14th to 11:30 am the following day). The terms included "Disable Amber Alerts", "Disable Emergency Alerts", and "Amber Alert Ontario" [150]. The three terms were specifically chosen to represent three different levels of response to the alerts, namely: "Amber Alert Ontario" to observe general information seeking about the Amber Alert; "Disable Amber Alert" to see potentially negative responses to the use of the system for Amber Alerts; and "Disable Emergency Alerts" to gauge the popularity of negative responses to the system as a whole. Bearing in mind the concept of alarm fatigue discussed above, this brief and exploratory study was conducted to see if indications of a trend existed between the number of alerts and the popularity of search terms related to the type of information being sought. It was hypothesized that the popularity of each search term would change over the course of the three alerts, that the number of searches would increase each time for the search terms related to disabling the alert, and that the searches would spike each time an alert was received.

Limitations of Google Trends

The data provided by Google Trends shows the relative popularity of search terms for the time period over which the data set was taken. For example, a value of 100 would be the most popular search time for a term in that 24-hour period, corresponding with the highest volume of search traffic, whereas 50 would be half as popular, at half the volume. The data is aggregated over 8-minute periods (for a 24-hour time period) and as such times shown may be ± 4 minutes. It is important to recognize that Google Trends does not display the volume of searches, and that the use of the popularity scale means it is not possible to compare data taken on different days or times outside of the 24-hour period (while retaining the 8-minute time resolution). Google's popularity scale sets the highest search volume to 100, regardless of whether the highest search volume for the time was 10 or 10,000 searches. In this case, all data was recorded and visualized on comparison graphs generated by Google Trends, all within the same 24-hour period, thus keeping the data on the same scale. As no count was provided, a traditional baseline could not be used. For the purposes of this analysis, it was assumed that because the event and subsequent reactions were covered by several reputable national media agencies, there were enough people searching for these terms to make this exploratory study worthwhile.

Another limitation of using Google Trends is that the popularity of each search term is represented individually, and it is impossible to amalgamate multiple similar terms into a group.

This means that similar terms such as ‘Disable Emergency *Alerts*’ and ‘Disable Emergency *Alert*’ are considered two separate terms and are shown independent of each other. If undertaking a more comprehensive study using Google Trends, one would need to look at a greater number of search terms, including slight variations of the same term. In order to compare search volumes, a different toolkit would need to be used. This toolkit would need to monitor and convert the normalized data back into search volumes and amalgamate similar terms, allowing improved comparison over multiple days, events or time periods. Given that this study was small, and its intent was to investigate if a potential trend existed within a single 24-hour period following an unanticipated event, it was deemed that the selected open-source tool was sufficient for this purpose.

Findings

Figure 3.3 displays the relative search popularity for “Amber Alert Ontario” over a three-and-a-half-hour period encompassing the time during which the alerts were issued. The search for information regarding the Amber Alert itself was by and large the most popular of the three terms, with three sharp peaks corresponding to the time of the alerts being sent out. The high popularity of this search term seems to indicate that the message largely had the desired effect as it prompted people to seek more information about the alert. There is also a small increase in the popularity of the search terms observed around 1:00 PM, which may correspond to lunch hour for those working.

The data regarding “Disable Amber Alerts” and “Disable Emergency Alerts” is too close to the axis to be shown on the same graph as “Amber Alert Ontario” as their relative popularity was much lower, but the timing of the spikes indicate people did react to the system similarly each time an alert was issued (see Figure 3.4). Much like Figure 3.3, there are three peaks, each corresponding to an alert being received. However, in this case, the highest peak corresponds not to the first, but to the second alert. The first alert triggered the lowest peak in popularity for disabling the alerts (both Amber and Emergency), whereas the second and third messages sparked more searches, indicating an increased (and unintended) negative response to the messages.

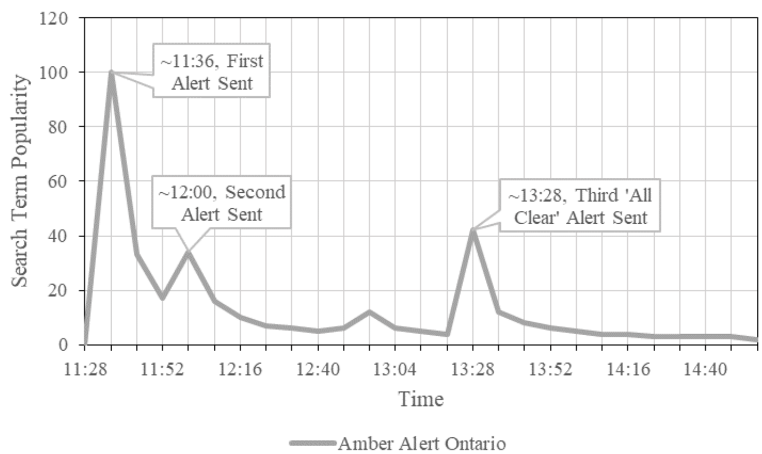

Figure 3.3: Search popularity for "Amber Alert Ontario"

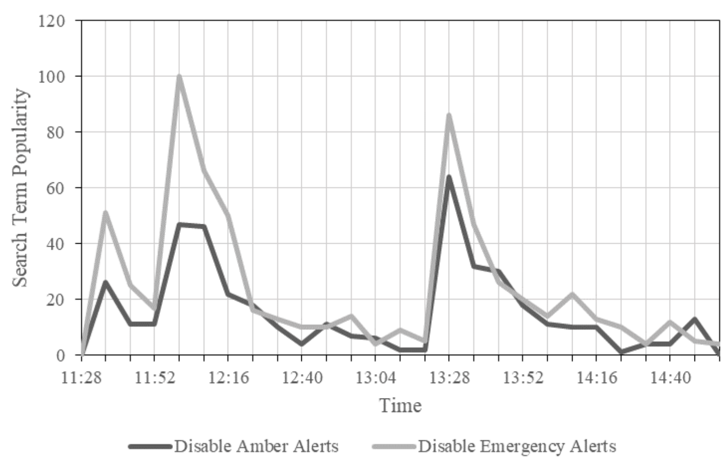

Figure 3.4: Search popularities for just "Disable Amber Alerts" and "Disable Emergency Alerts"

The effects of the three alerts sent and the relevance of the three search terms investigated can be examined through online media and news reports. When the first alert sounded, it sparked a search for information, reflected in the strong popularity of the term "Amber Alert Ontario". This suggests an initial success of the alert system. The alerts had caught people's attention, and people were searching for more information regarding the Amber Alert. However, as reported by local media, a few complaints were posted on social media from those wearing headphones or driving while connected with Bluetooth [8]. With respect to the search popularity of the three terms, there were fewer searched for “Disable Amber Alerts” as compared to those who searched for “Disable Emergency Alerts” at the time of the first alert, however, both were less popular than later searches for these terms.

The second alert was sent half an hour after the first. This alert was effectively the same as the first one, only written in French, Canada’s second official language (with Francophones making up approximately 4.1% of the total population in Ontario) [152]. This second alert sparked significantly more backlash, as noted by the media and supported by the search term popularities. Some people in Toronto and Southern Ontario reported being annoyed that they were receiving multiple Amber Alerts for “an issue [that was] hundreds of miles away” [153]. Others noted being irritated by the fact that the French and English alerts were being sent individually, doubling the number of alerts received, and that they were sent half an hour apart [153]. Given the increased popularity of the search terms “Disable Amber Alerts” and “Disable Emergency Alerts” following the second alert, it is possible that this alert – which provided little to no new information, occurred 30 minutes after the first, and detailed an incident some people deemed geographically irrelevant – initiated the possible beginnings of alarm fatigue in those people searching for a way to disable the system in its entirety.

At around 1:30 pm the third alert was sent out. This one was different from the first two as it contained a message which stated that the missing child had been found and the alert was over. Like the first two messages, this one was accompanied by a loud alert tone. With this use of the Alert Ready mobile system (and corresponding loud alert) for a non-emergency all-clear message, searches for disabling both Amber and emergency alerts spiked once again. This time corresponded to the highest percentage of searches for “Disable Amber Alerts” over the studied

24-hour period, with these searches almost equalling the number of searches for "Disable Emergency Alerts". Although the third alert sparked a lower number of "Disable Emergency Alerts" searches, it was offset by the increase in searches for "Disable Amber Alerts". Taking the relative sum of the two terms, the search popularity of "Disable" terms following the third alert was marginally higher than the popularity of these terms following the second alert. This may suggest the existence of a trend and the need for additional research on Canadian's responses to these alerts.

The official Alert Ready website was updated to take general public feedback following the event. Accounts in Canadian media indicated numerous complaints regarding the system in the wake of the event. Amongst them were quotes from users saying that they "want out" of the system, and that the repetitive use and geographic irrelevance of the system had "trained [them] to ignore emergency alerts" [153]. Media also reported complaints being received by police departments and 911 operators, prompting police officials to issue statements clarifying that they have no control over the alerts, and asking upset callers to stop calling the police [147].

Discussion

As is shown by this small study of Google searches and the media coverage of this event, the wireless alerts sent out via the Alert Ready system prompted mixed reactions. In large part the system was successful, prompting people to look for additional information about the Amber Alert. Of the three search terms, "Amber Alert Ontario" was by far the most popular, with the two search terms relating to disabling the alerts not exceeding 2% of the maximum popularity of "Amber Alert Ontario". It should be noted that it is not known if these alerts contributed to finding the missing child and therefore their effectiveness in this regard cannot be judged.

When just looking at the search results for “Disable Amber Alerts” and “Disable Emergency Alerts”, the three peaks and the change in search popularity over the course of the three alerts can provide insight into potential consequences that should be considered when using this and similar systems for future threats and emergencies. Much like with the searches for “Amber Alert Ontario”, the greatest number of searches corresponded to the time immediately following the alert. However, unlike “Amber Alert Ontario”, the peaks are less steep following the initial spike, with a relatively high percentage of searches continuing for 15 minutes after the alert. This is particularly true for searches following the second and third alerts. The most notable difference between the two “Disable” alerts and the “Amber Alert Ontario” alert is the distribution of searches. While the first alert prompted the most searches for “Amber Alert Ontario” (with subsequent alerts prompting only half as many alerts), it was the second and third alerts that prompted the greatest number of searches for “Disable Amber Alerts” and “Disable Emergency Alerts”.

In looking at the increase in searches for “Disable Amber Alerts” and “Disable Emergency Alerts” following the second and third alert, we can turn to one of the key HBiF concepts identified earlier for insight into potential future consequences. In response to the relatively high number of alerts that were sent out in a short period of time and the fact that the alerts were delivered to mobile devices in a very large geographic area, news reports and the exploratory search term study conducted seem to indicate that many people became annoyed with the alerts and the wireless alerting system as a whole. While it is currently impossible for general consumers to prevent their mobile devices from receiving the Alert Ready alerts (aside from muting the phone completely or disconnecting it from a network supporting the system), it is possible that this event contributed to the beginnings of alarm or warning fatigue for some people. Though a relatively small group of people (as related to the number of people looking for general information about the Amber Alert), the people who sought to learn about disabling the alerts (and others who felt this way and potentially searched for related terms not covered in this study or used another search engine or did not actively search for more information during this time) represent a group of people who may choose to ignore or disregard future alerts sent to them via this system. As discussed earlier in this chapter, people can react this way when they distrust the validity and necessity of alarms as a result of their high frequency and/or high false positive rate. In the case of the Amber Alert, both the potential geographic irrelevance of the alerts (as deemed by the alert recipients) and the number of alerts (received in a short period of time, not providing new information), have the potential to contribute to this.

It is important to remember that creating and disseminating messages about emergencies and threats is a challenging endeavor, and often conflicting concerns need to be considered simultaneously. As has been noted in some of the literature and as was indicated by this exploratory study, too many alerts may prompt people to try to disable alerts or potentially ignore them if they cannot be disabled. However, as the study of normalcy bias has shown, people can be slow to believe that an incident poses an actual threat and often need more than one alert to prompt action. While this is hard to grasp in the context of an Amber Alert, it is easier to understand in the context of an alert about a natural threat such as a tornado or wildfire. In September 2018, the Alert Ready system was used to notify those in the Ottawa area about the threat of a tornado. Following the event, CBC News spoke with people who noted that it was not until they had received multiple alerts that they felt there was truly a threat that required action [154]. While this is just one case, it does showcase the potential importance of having multiple alerts. As such, there can be a fine line between having too many alerts and not providing enough information, and it is a line the must be tread carefully when creating or using notification systems such as Alert Ready. Though daunting, by better understanding how and why people respond to these alerts (ex. information not being deemed relevant), more effective alerts and alerting systems can be created.

As was noted earlier, the Amber Alert on May 14, 2018, was the first official use of the Alert Ready system and in the months since then, changes have been made to further improve the system. During the second national test of the system in November and during the aforementioned Ottawa-area tornado alert, the English and French alerts were sent together (see Figure 3.5).[7] Just prior to the wireless component of the system being launched, a revised version (Version 2.0) of the "National Public Alerting System: Common Look and Feel Guidance[8]" document was released and for the first time included guidance for a wireless public alerting system [155]. Given that this document has been revised four times over the course of five years as Canada's NPAS has expanded, it is likely that future versions will continue to build upon the lessons learned from the application of existing guidelines.[9] This, in combination with increasingly accessible LTE technology required for the wireless system to work, will help to make the Canadian Alert Ready system more effective and enable alerts sent out via its wireless system to reach more people.

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[7] The system was also used for a Toronto area Amber Alert in February 2019 and the French and English messages were also combined. The Peel Region Police indicated that an arrest was made as a "direct result" of the alerts [182]. However, there were still numerous people who called 911 to complain about the alerts and who posed about their frustration with the system on social media [182]. Additionally, the alert was received by some Manitoba residents who were outside of the alert area (were not supposed to have received the alert) [183].

[8] This document is "the current collection of specifications, policy decisions and recommended practices related to the Common Look and Feel (CLF) of public alerts associated with the National Public Alerting System (NPAS) initiative" [155].

[9] The current version even notes that guidelines for the use of social media and other new distribution methods can be expected in future versions.

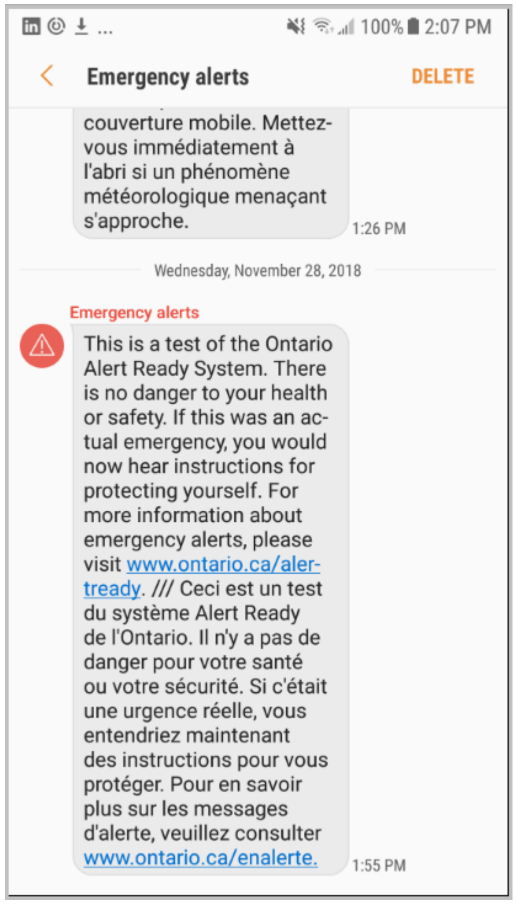

Figure 3.5: Second test of Alert Ready wireless system (November 2018)

Study Limitations

The findings of this study do not conclusively evaluate the use of the Alert Ready wireless system (holistically or during the case study event). Instead, they provide insight into how HBiF can impact the reception of alerts and emergency notification systems, something that needs to be considered when assessing the likelihood that such alerts will provoke intended responses. This in turn, along with an awareness of the available means of emergency alerting, can have an impact on the vulnerability of an at-risk area (such as a WUI community). In addition to the limitations of Google Trends discussed earlier, there are several other limitations to this study which impact the completeness of the findings and discussion. These include:

- The project was undertaken immediately in response to the event, therefore there was no time spent prior to the incident planning for how to best capture the public's response to the alerts.
- Data for only three search terms was collected, resulting in a limited picture of possible responses to the alerts.
- It was not possible to tell if the same people were searching for each/any of the three terms nor if people searched for the same thing multiple times.
- Given the resources and information available, it was not possible to tell who received the alerts and therefore how factors such as their location affected the searches. For example, it is not possible to tell if more people in urban centres such as Toronto or Ottawa received the alert (due to better cellular service) as opposed to people located in potentially more isolated areas in closer proximity to the incident (Thunder Bay).

3.3.3 Discussion - WUI Fire and Evacuation Considerations in Relation to the NPAS

The considerations discussed in the case study are not only relevant to Amber Alerts, but they can also impact other types of alerts, including those related to WUI fires and evacuations. If multiple alerts regarding a wildfire are sent to too large of an area, people may feel that the alerts are irrelevant to them and their location and therefore ignore or dismiss future alerts. This could result in situations where they may not read messages involving new emergencies, such as a new encroaching fire threatening their region, or a mandatory evacuation order. Those who dismiss or ignore the alerts could therefore be putting themselves at greater risk. However, as there is very little research looking specifically at alarm or warning fatigue in a WUI fire context, further research in this area would enable a better understanding of its existence and impact.

It is also important to consider the effects of perceived public responses to alerts on emergency managers. A concern held by some emergency managers and officials is that by informing too many people or too large a region about a WUI fire, there could be unnecessary voluntary evacuations, leading to traffic congestion and negative impacts on fire service personnel responding to the fire. Such concerns can be exacerbated if there are limits to alert length (and therefore the amount of information and level of detail that can be conveyed) and were in-part behind officials deciding not to use WEAs during the deadly October 2017 wildfires in Sonoma County, California[10]. In a report issued about the public alerting program in Sonoma County by the California Governor's Office of Emergency Services in response to the these WUI fires, it was concluded that emergency manager's decision not to use WEAs was based on their "experience, previous policy discussions, and perceived knowledge about the situation" [156]. It was also noted that the emergency manager had a limited understanding and awareness of the WEA system and was working off outdated information regarding its technical capabilities. Given the relative youth of the Canadian wireless alert system and its limited use thus far, it is important that there is continued education for both emergency managers and alert issuing bodies as well as the general public about these alerts. That way, when situations arise in the future for which it would be useful or necessary to use the wireless alerts, people will be better prepared to use them and to respond to them effectively.

In early 2018, the National Institute of Standards and Technology (NIST) in the United States released a report entitled *Public Response to Short Messages Under Imminent Threat* with the aim to help provide evidence-based guidance in the development and use of public alerts,

[10] During the 2018 Camp Fire in California, officials also chose not to use the systems, opting instead for emails, reverse-911 calls and text messages sent out via the county's opt-in CodeRed alerting system [29]. While county officials have not officially stated why WEAs were not used, there is speculation that it was in part due to a lack of familiarity with the system.

including short messages such as WEAs [45]. The report was created in part in response to the expanded capabilities of WEA alerts (by mid-2019), announced by the Federal Communications Commission (FCC) in 2016, which include expanding the length of WEA messages from 90 to 360 characters, supporting alerts in Spanish, and enabling ULRs and phone numbers to be embedded in the alert [157]. In comparison, the Canadian "National Public Alerting System: Common Look and Feel Guidance" document states that a single wireless message can be up to 600 characters, regardless of if the message is in English, French or both languages[11] [155]. The findings of the NIST report, which focused on improving messages such that they can reach a wider audience, increase comprehension and increase perceived credibility, can be used to help inform the creation and use of Canadian alerts as there currently does not exist extensive literature of the sort in Canada.

When looking at the application of Alert Ready wireless alerts in a Canadian WUI fire context, it is important to keep in mind a number of logistical factors. Given that Canadian WUI communities (whether seasonal or permanent) are often located in more isolated, northern regions, access to reliable LTE cellular service which is required to receive the wireless alerts is not guaranteed. This can be seen when looking at Figure 3.6 showing the combined service maps for three of Canada's largest cellular network providers (Rogers, Bell and Telus). Once again, this highlights the importance of having a multipronged approach to notifying people about emergencies or threats as not all will work for all people in all communities.

[11] This character maximum also includes "language demarcation symbols" if an alert is issued in both languages.

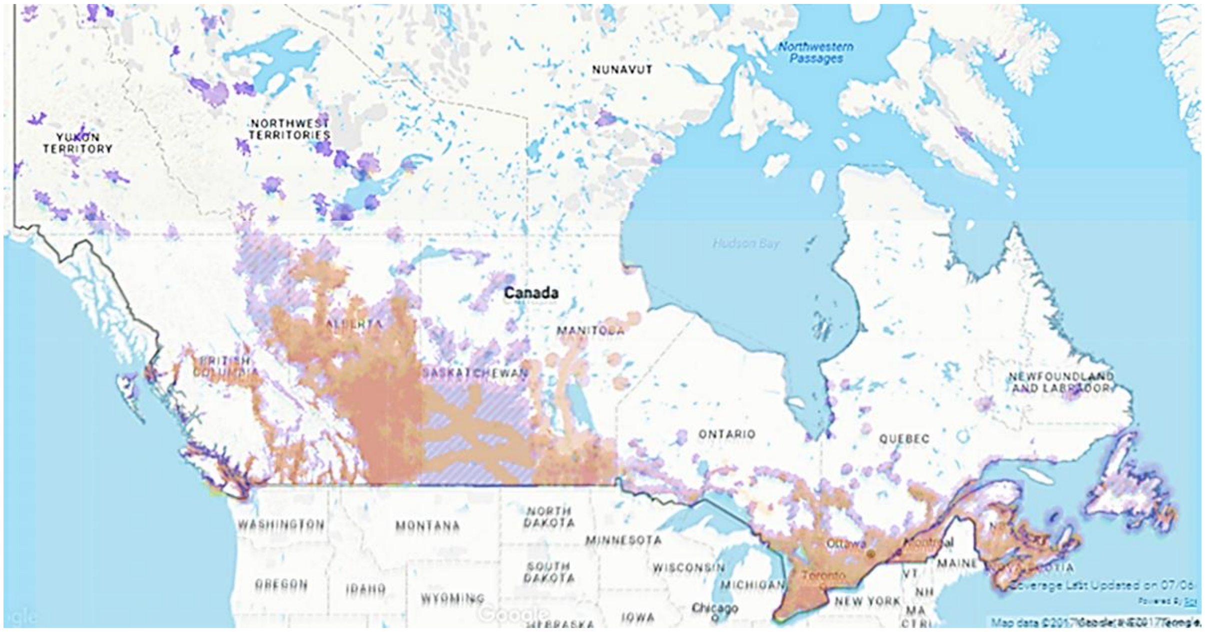

Figure 3.6: Coverage areas for Bell, Telus and Rogers in Canada, modified [158]–[160]

For WUI communities that do have the reliable service necessary to receive Alert Ready wireless alerts, such alerts have great potential. For seasonal communities, where residents may only be there during the summer months or tourists may be visiting for the first time and are generally unfamiliar with the area, this alerting method could be very beneficial. The Alert Ready system does not require people to opt-into the system and it is based on using cellular towers in the area under threat and therefore can reach all those with compatible devices regardless of if they are a long-time resident or a first-time visitor. In time-sensitive events such as a WUI fire, such alerts are also one of the fastest ways to notify people, as opposed to reverse 911 calls or having police officers go door-to-door notifying people.

3.4 Summary

The ability to notify people of a threat or emergency is an important component in managing complicated and dangerous events effectively and safely. Given the complexity of such events, it is important to have a coordinated, multi-pronged approach to provide information and warning to those most in need. In Canada, the NPAS, also known as Alert Ready, has an important role to play in this approach. With the ability to send out alerts via radio, television and wireless messages (that cannot be disabled), it can reach people in large or very targeted areas quickly. Though it has yet to be used in response to a WUI fire, the system has application in the increasingly important realm of wildfire notifications and evacuations. The development and understanding of wildfire evacuation communication methods such as the Alert Ready system is an important element in the widespread and growing need for more comprehensive tools to manage and handle wildfire evacuations.

Just as when looking at other components of responses to WUI fires, it is important to understand how human behaviour will influence how people respond to a message about a wildfire threat or evacuation. Though not a fire incident, the information-seeking behaviours and unintended consequences observed as a result of the Amber Alert sent out in Ontario via the new wireless messaging component of the Alert Ready system on May 14th, 2018 provides insight into some of the challenges and considerations that should be kept in mind when using mass notification systems. It highlighted the role that message relevance (geographical, etc.) plays in people's perception of the necessity and usefulness of an alert, and it provided an opportunity to discuss the challenges associated providing the right amount of information. By better understanding the interplay between behavioural trends and responses to emergency alerts such as those shown in this exploratory study, messages and communication systems can be better designed and utilized.

Moving forward, there are several important areas that should be pursued to better understand how to create and use emergency notification systems more efficiently. Further research looking at alarm and warning fatigue in natural disaster type situations, and WUI fires in particular, would aid in understanding if and how it presents itself and what factors combine to result in this response. In a Canadian specific context, cross-referencing the location of WUI communities with access to reliable cellular service could provide a better understanding of the potential impact of using Alert Ready wireless alerts for WUI fire notification. This in turn could be a factor considered in a comprehensive vulnerability index or assessment of Canadian WUI communities.

Chapter 4: Canadian Case Study – Resident Survey and Evacuation Modelling

The previous chapters draw attention to the importance of understanding human behaviour during WUI fire evacuations and the need for more Canadian-specific information. This chapter will discuss the groundwork laid for the analysis of a Canadian case study community through the creation of a detailed survey and the modelling of several evacuation scenarios in the community using the traffic modelling software PTV VISSIM. Section 4.1 will provide an overview of the case study community and Section 4.2 will detail the creation of a survey asking about expected evacuation actions that will be distributed to the case study community in the coming year. Section 4.3 then details the modelling and analysis of 10 evacuation scenarios of the community using PTV VISSIM, and a discussion about key information and considerations necessary for using such models to assess WUI fire vulnerability.

4.1 Case Study Community

4.1.1 Location and Population

The case study community is a seasonal summer community located within a forested area surrounded by agricultural land in Manitoba on the southern shores of a lake [161]. The population of the community fluctuates greatly over the year, with thousands visiting in the summer months and very few living there permanently year-round. Since the community was first developed in the early 1900s, it has grown to include four primary areas as shown in Figure 4.1: a cabin area; a cottage area; a campground; and a commercial area consisting of retail, vacation accommodations, and restaurants. The cottage area to the east is considered low-density with larger lots (approximately 250 lots) while the cabin area to the west is high density with small lots and portable cabins [161]. This latter area was originally laid out as a transient campground in the early

1930s. When another campground was opened in the community in the mid-1960s, the former became a seasonal cabin area where cabins had to be moved out of the park each winter until 1988 [162]. The area is now comprised of 530 permanent cabins (the majority of which have individual water, sewage and electrical connections). There remain several communal facilities such as woodsheds, toilet buildings and kitchen shelters. This area will be the focus of the initial case study (survey and traffic modelling) and is referred to as the cabin area.

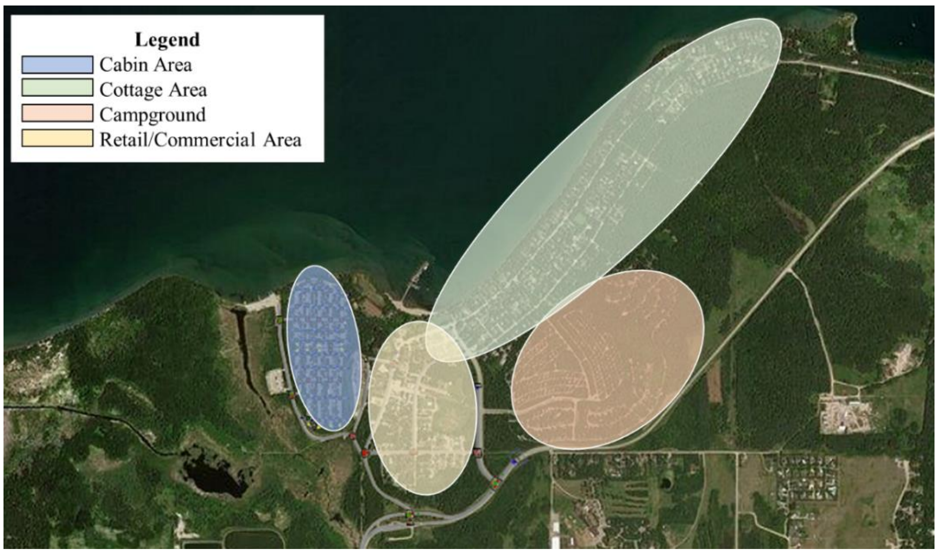

Figure 4.1: Four primary areas of case study community

The current campground has around 500 sites, and the commercial area is comprised of over 30 businesses. There are also numerous parks, boat launches, swimming docks and trails in and around the community. Visitor surveys for the area in the 1980s and 1990s showed that people were spending more time in the area and that the number of first-time visitors increased with most being from out of province [161].[12]

[12] More recent data could not be found.

4.1.2 Surrounding Ecosystem and Vegetation

The community is located in a heavily treed environment, characterized primarily by aspen, mixed hardwood forests, spruce and prairie grasslands [161]. In addition to the forest which characterizes most of the surrounding area, the community itself has maintained a high percentage of vegetation. With respect to wildfire occurrences, few fires have impacted the area surrounding the community, none of which prompted evacuation (one fire in 2017 did prompt the temporary closure of a highway near the site) [163]. The overall lack of fire, in combination with the extensive plantation of coniferous trees in and around the community, has led to a large build-up of volatile fuels [161]. Some prescribed burning and thinning of dense spruce plantations have been undertaken in the surrounding area to reduce the risk of wildfire potential.

The climate in the area is continental, with cold winters, hot summers and relatively little precipitation [161], [164]. The summer months are warm due to prevailing air masses from the south/south-west, and the winter months are cold due to cold fronts coming from the north/northwest [161]. The winds in the community are weaker than in other areas as a result of the forest cover, and the presence of lakes and the turbulence generated by the Manitoba Escarpment resulting in increased cloud cover and showers during the summer months [161].

4.1.3 Perceived Community and Focus Area Vulnerability

While the case study community has not experienced the need for a WUI fire evacuation in recent years, community and agency partners have expressed concern about the community's potential wildfire vulnerability given it's WUI intermix location, the community layout and the changing fire season. The cabin area specifically has been identified by the community as having a potentially high WUI fire vulnerability. One of the objectives outlined in the most recent community plan for the site was improving fire protection and emergency access for the cabin area. Goals included developing a plan for emergency evacuation, designating an old access road (not currently in use) as an emergency egress route for the back cabin area, and providing an emergency egress route for the front cabin area [161]. In looking at the layout of the community, it can be seen that the current ingress/egress routes in the community are rather limited. A single highway is the only way to travel to/from the community (see Figure 4.2), and there are three collector roads connecting the community to the highway. A single road branches off one of these three main roads and serves as the only access to the cabin area. The two sections of the cabin area are each accessed by their own roads (one each) leading off this access road. The two cabin areas are otherwise separate from each other (no internal vehicular connections).

Figure 4.2: Case study community and primary access route via highway

As mentioned earlier, the cabin area is densely occupied, with 530 cabins located in less than 0.15 km^2 (~14 ha). The back cabin area is home to 285 cabins and the front cabin area is home to 245 cabins. According to agency sources, the cabin area is fully occupied multiple times during the summer months, corresponding with the wildfire season. As shown in Figure 4.3, the cabins are located in very close proximity to each other, often with decks or vegetation between them. The water and sewer system within the cabin area is shallow (3 feet) and in some places is above grade. The main water line runs along one of the primary north-south roads and feeds fire hydrants located along it [161]. The nearest fire department is volunteer-based and is approximately 5 minutes away from the community (6-8 minutes from the cabin area).[13]

Figure 4.3: Cabin area properties

While these factors are all likely to contribute to the overall vulnerability of the case study cabin area, the degree of their impact and that of additional factors yet unknown need to be understood in order to provide a comprehensive vulnerability assessment of the community. In order to lay the groundwork for such an assessment, more information is needed about the residents and their potential protective action decisions, and a base model of what an evacuation might look like should be created. The work undertaken as part of this thesis to build this foundation are detailed in the following sections.

[13] The fire department is equipped with a pumper and tanker truck, as well as a first response vehicle and a mosquito truck used for grass and brush fires [184].

4.2 Evacuation Intentions Survey

4.2.1 Purpose

An important step in assessing the vulnerability of the case study community is understanding the factors likely to impact protective action decision-making in a WUI fire scenario (as discussed in Chapter 2). To do this, a survey was created based on the conceptual model developed in Chapter 2, the factors found to have an impact on evacuation decision-making, and the gaps in knowledge identified during the literature review. For example, it was found that most of the factors in the studied research focused on the third stage of the PADM, the protective action decision itself. Therefore, in addition to seeking information about the decision to evacuate or not, the survey seeks to gain more information about the factors that influence the pre-decision phase and the credible threat and risk assessment phase of the PADM. Furthermore, the survey seeks to gain information about the amount of time people anticipate spending on pre-evacuation tasks.

4.2.2 Scope

The survey is specifically tailored to collect data about the expected evacuation actions of residents in seasonal communities without a recent history of wildfire threat, however, it could be modified for use in other types of communities (non-seasonal, indigenous, etc.). The survey will be piloted this summer in a separate seasonal community and then distributed to residents in the cabin area in the coming year, with the potential to distribute it more widely in the community or in other communities in the future.

4.2.3 Methodology

The goal of the survey is to gain insight into the anticipated actions of residents in the cabin area and the factors that impact their decisions. Dillman's *Tailored Design Method* was used for guidance on question formatting, wording, and arrangement [165]. Inspiration for questions was drawn from the *2016 Canadian Census*, specifically with respect to the wording of demographic questions [166]. The *2009 Bushfire CRC Survey* administered after the 2009 Black Saturday Fires in Australia was used as an example of a wildfire specific survey (seeking in some capacity to gain information about protective action decision-making) [167].

A quantitative survey method was chosen to allow for statistical analysis to be performed on the collected data. A combination of closed-ended questions with unordered and order response was used in addition to a few *partially* closed-ended questions allowing respondents to specify an alternative answer. Space is provided at the end of the survey to allow participants to provide additional information that they feel is important, such as expected evacuation responses, additional previous experience or evacuation constraints.

The survey is divided into five main sections seeking to gain different types of information. These include: Cabin Information and Visits; Previous Experience; Warnings and Information Sources; Expected Actions; and Household Information. Questions were arranged this way so as to increase the likelihood of people responding to the survey, with less personal, easy to answer questions at the beginning and more personal questions at the end. The survey is designed with the understanding that the case study community has not been impacted by a wildfire in recent history. Given this and the fact that wildfire response and policy in Canada strongly favours evacuation, more questions focused on information about evacuation expectations than staying and defending. This decision was also influenced by findings from previous studies that have shown that people are less likely to stay and defend if the property threatened is not their primary residence [89].

4.2.4 Survey Creation

Each of the five main question groups are detailed below with example questions. The created survey can be found in Appendix A.

Cabin Information and Visits

This section asks the least personal, presumably easiest to answer questions. Questions seek to gain information about how often and for how long respondents visit their cabins, the type and reliability of services available at their cabins and the number of people and pets typically at their cabin. Distinctions are made between an average visit and a busy visit to the cabin so as to understand how much the cabin occupancy varies and to get an idea of how many people might be present should an evacuation occur. These questions also allow for comparisons to be made between expected evacuation decisions disclosed later in the survey and the information collected in this first section.

Some of the questions in this section can also help to fill several gaps identified in the literature in Chapter 2, specifically, factors that affect the first stage of the PADM, the pre-decisional stage. Figure 4.4 shows one of the questions in the survey seeking to understand if respondents have reliable access to services that could impact their ability to receive or be exposed to a cue. Given the relative remoteness of the community, it is important to understand if people would be able to receive a message or cue delivered via a means requiring one of the services listed, such as an Alert Ready message discussed in Chapter 3. If a person does not have reliable access to the listed services, they may be unable to receive such an alert. It could also impact their ability to search the internet or receive news updates. It is important to note that a wildfire can further impact these services. This question therefore acts as a means of establishing a baseline for service accessibility in the cabin area of the case study community.

Do you have reliable access to these services at your cabin?

	More than 90% of the time	50 – 75% of the time	25 – 50% of the time	0 – 25% of the time	Do not have access
Electricity	◻	◻	◻	◻	◻
Internet	◻	◻	◻	◻	◻
Television	◻	◻	◻	◻	◻
Radio	◻	◻	◻	◻	◻
Cellular Service	◻	◻	◻	◻	◻
Cellular Data	◻	◻	◻	◻	◻
Water	◻	◻	◻	◻	◻

Figure 4.4: Survey question asking about access to services that could impact being able to receive an alert about a wildfire threat or evacuation notice

Previous Experience

Questions in this section seek to understand if respondents have had past exposure to and experience with WUI fires, evacuations, and the Alert Ready system. Given that the community is seasonal and has not been threatened by a WUI fire in recent years, the questions ask about experience both at the cabin and at other residences. Figure 4.5 below is an example of one of the questions in this section.

Have you or someone you know ever experienced any of the following (at primary residence, secondary residence, or a previous residence?)

	Yes, I have	Yes, someone I know has
Received an Alert Ready mobile test alert (not an emergency)	◻	◻
Received an Alert Ready mobile alert for an emergency (Amber Alert, flood warning, tornado warning, etc.)	◻	◻
Been on evacuation notice/stand-by due to wildfire	◻	◻
Been under a voluntary evacuation order due to wildfire	◻	◻
Been under a mandatory evacuation order due to wildfire	◻	◻
Lost personal property due to a wildfire	◻	◻
Been injured by a wildfire	◻	◻
Lost someone due to a wildfire	◻	◻

Figure 4.5: Survey question asking about previous experience with wildfires, evacuation and emergency notification systems

Warnings and Information Sources

As indicated in Chapters 2 and 3, information seeking and emergency notification is a very important part of understanding and predicting WUI evacuation decision-making. The questions in this section aim to understand which sources respondents would be inclined to use and the degree of they would trust information about a WUI fire from different sources. Figure 4.6 is an example of one of the included questions. Additionally, there are questions in this section that ask about the degree to which the respondent has thought about WUI fires and their awareness of prominent Canadian and international WUI fires.

Rank the following sources of information in the order that you would use them to seek information about a wildfire if you were at your cabin **(1 for first, 10 for last, NA if you would not use)**

Rank	Source
___	Friends/family members at the cabin with you
___	Other family/friends
___	Cabin neighbours
___	Radio
___	TV or internet news source (video, print)
___	Social media (Facebook, Twitter, YouTube, etc.)
___	Government website (Provincial government, Parks Canada, etc.)
___	Alert Ready mobile, radio or TV notification
___	Go outside (look for smoke, flames)
___	Police/Fire department

Figure 4.6: Survey question asking about the order the respondent would use different sources to seek information about a WUI fire

Expected Actions

This section contains questions asking about what protective action respondents expect they would take during a WUI fire event and what cue would prompt them to take this action. In addition, questions in this section seek to understand how long people think that they would spend on certain pre-evacuation tasks. Figure 4.7 is an example of a question seeking to do this, specifically in the context of the respondent having decided to evacuate immediately (other timeframes/levels of urgency are also explored). The categories of pre-evacuation tasks were created after looking at similar questions asked in other disaster research studies.[14] This information is important when trying to understand potential trip generation times, a component of traffic modelling that will be discussed in Section 4.3. It is, however, important to understand the limitations of this question. The amount of time people expect to take is not necessarily the same as the amount of time they will actually take to complete pre-evacuation tasks during an evacuation. Some hurricane evacuation literature has compared expected and actual evacuation time estimates and found that answers for some tasks were similar (time to gather household members and pack travel items) while others were quite different (time to protect property) [168]. Given the current lack of time estimates (expected and recollected) for WUI fires in general and specifically from similar communities, the information gained from these questions is more exploratory than quantifiable. The times reported in this question could, however, be used in an evacuation model to see what impact it could have on an evacuation so long as these limitations were understood.

[14] In the case of nuclear power plant incidents, the categories used included: warning receipt, preparation to leave work; return from work; and prepare to leave home [185]. In hurricane literature, studies have asked residents in hurricane-prone areas about their intended evacuation actions, asking about the amount of time they anticipate spending on preparing to leave work, travel from work to home, gathering household members, pack travel items, protect property from storm damage (ex. install storm shutters), and secure their homes before evacuating [168], [186].

If preparing to ***evacuate immediately***: How much time do you anticipate you would spend on the following pre-evacuation tasks? If you would not do the task or it does not apply to you, then write "0" as the estimated time.

Action	Estimated Time
Gather household members (people at cabin who you would evacuate with)	______
Gathering belongings to take with you	______
Loading belongings into vehicle/s	______
Secure cabin (turn off utilities, close windows, lock door, etc.)	______
Other **(please specify)** ____ ____ ____	______

Figure 4.7: Survey question asking about how much time people anticipate that they would spend on pre-evacuation actions if they were planning to evacuate immediately

Household Information

Demographic questions are a staple of disaster research questionnaires as noted in Chapter 2. Questions in the last section collect such information about the respondents as well as people who would typically be at the cabin with the respondents, specifically those who might require additional assistance to take protective actions during a WUI fire. Given that Canada is home to people from many different countries, is popular with tourists and has two official languages, several questions inquired about language comprehension so as to better understand the respondents' ability to comprehend emergency notifications (a component of the pre-decisional phase of the PADM). Figure 4.8 shows one of the language questions asked.

Do feel confident conducting a conversation in French and/or English?

English only	□
French only	□
Both French and English	□
Neither English or French	□

Figure 4.8: Survey question asking if respondents feel comfortable conducting a conversation in Canada's official languages

4.2.5 Survey Administration: Next Steps

The next step in the data collection process is to conduct a small pilot study or pretest of the survey to evaluate the reliability and utility of the methods used (types and format of questions) and to get feedback on the clarity of the survey. This will also help to gauge how the survey will be received and if respondents understand the information being sought. Based on the pilot study, necessary modifications can be made to improve the survey before it is distributed to the entire cabin area. This pilot study should be conducted with a small sample of the residents within the same community or from a similar community (ex. a small, seasonal community in a forested area) [169]. This is planned for the coming summer.

It is important to consider and plan for how the survey will be distributed to the case study community. Generally, a drop-off pick-up approach has the highest response rate, however, it can be very time intensive and expensive [170]. Web-based surveys are the fastest growing form of surveying as it is low cost and fast. Though the most convenient, their response rate is generally lower. Mail-out surveys tend to also have a relatively low response rate. To combat this, a mixed mode methodology can be adopted where multiple types of survey distributions are used. Given that the case study community is seasonal and most densely populated on summer weekends (particularly long weekends), the drop-off pick-up method may be difficult to do on its own. If the resources were available, the survey could be distributed in person at the beginning of a long weekend and collected at the end. This could be paired with an online or mail-out survey sent to residents who were not present at the time of the survey distribution. In order to decide on the best method, more information about the occupants of the cabin area and the resource limitations will need to be obtained.

The findings from this survey can be used to inform a traffic model of an evacuation in the community (such as that created in Section 4.3) as well as helping in the development of a more comprehensive modelling approach with a behavioural model component.

4.3 Community Evacuation Modelling

4.3.1 Overview

Being able to predict what an evacuation would look like is an important step when assessing a community's wildfire vulnerability. As interest in offering community WUI fire vulnerability assessments grows within engineering consultancy, having an understanding of the complexity of such an undertaking and of the type and amount of information necessary to create an evacuation model is critical. Having a framework which identifies and addresses the many factors that can impact an evacuation would greatly benefit parties seeking to conduct such assessments.

In order to begin developing such a framework (to both aid in the movement towards comprehensive evacuation modelling and to caution against conducting ill-informed vulnerability assessments), several evacuation scenarios were modelled and analyzed using the traffic simulation software PTV VISSIM. The purpose of this was to create a baseline analysis of what an evacuation in the case study community might look like, given relatively limited information (a site visit was not possible and information from reliable sources was difficult to obtain). While this is not ideal for a comprehensive evacuation analysis, it is not unlike what many consultancy companies might face when asked to conduct a vulnerability assessment. As such, in addition to identifying points of congestion and gauging how different factors affected total and individual evacuation times within the case study community, the analysis of the evacuation model and results will help to identify key information that is required to conduct a more comprehensive analysis. This knowledge will not only benefit the next stages of this vulnerability assessment research project within the community but will also help to provide a first-stage framework for others (either researchers or consultants) wanting to undertake such assessments.

4.3.2 Evacuation Modelling

As noted in Chapter 1, evacuation modelling is a tool that can be used to help plan for and execute evacuations. Through the simulation of human decision-making and behaviour as well as wildfire dynamics and traffic flow, a comprehensive evacuation model could help to tackle the challenge of creating safer communities in the changing WUI. While such a model does not exist currently, there is work being done within the fire safety engineering community to create one [25], [44], [171]. There are modelling tools which do already exist that focus on simulating one of these primary components necessary for a comprehensive model, to varying degrees of complexity and granularity. Examples of such models are discussed in detail in an NFPA report on building a WUI fire evacuation modelling framework [25]. In looking specifically at existing traffic models, they can be used to simulate different evacuation procedures and strategies and/or specific evacuation scenarios. There are, however, important considerations that need to be made when modelling evacuations using standard traffic modelling software as WUI evacuation scenarios differ from standard traffic conditions. Some examples of potential differences include the degree to which evacuees are familiar with what they should do, where they should go, and how they should get there; driving behaviours; primary one-way flow; and greatly overloaded networks. As such, these existing models need to be able to replicate how network conditions and traveller behaviour will differ given these "abnormal" conditions. It is also important that the limitations of the model with respect to the degree it can replicate and account for these unique conditions be understood and clearly defined.

4.3.3 Traffic Modelling

Within traffic engineering, there are four primary steps involved in traffic modelling: travel demand; trip distribution; modal split; and traffic assignment. Common methods used to model each of these steps as well as considerations that should be made in the context of modelling evacuations specifically are detailed below.[15]

Travel Demand

Traffic demand modelling is used to determine the traffic load on the transportation network. In the case of an evacuation, this relates to the number of people who will evacuate (trip generation) and when the evacuees will depart from their initial location (departure timing). For trip generation, the area/region that needs to evacuate must be determined followed by the number of people within that area who will evacuate (as opposed to staying-and-defending or sheltering-in-place). This determines the number of trips that will depart from an origin (a house, a neighbourhood, a city, etc.) and end up at a destination (generally represented using an origin-destination (OD) matrix). There are several different ways that trip generation can be determined, including descriptive models (regression analysis, cross-classification/category analysis, etc.) and random utility models.[16]

[15] In the field of evacuation modelling, some steps have been researched more than others which will impact the level of understanding of these steps and the ability to accurately model them.

[16] As trip generation is not something that needs to be determined via these means for the model of the case study conducted as part of this thesis, the details of these sub-models are not provided here. However, such details can be found in Ronchi et al. (2017) [25].

Evacuation participation and evacuation departure timing are generally modelled in one of two ways, sequentially or simultaneously [46]. The sequential approach separates trip generation and departure timing into two separate steps. Once the area to be evacuated is identified, the share of the people in that area who will evacuate is determined via descriptive or random utility modelling. The departure timing is then determined, often using varying forms of response curves (instantaneous departure, uniform distribution, Rayleigh distribution, Poisson distribution, Weibull distribution, sigmoid curve, etc.) which identify the percentage of departures in each time interval [46]. While a sequential modelling approach is used most often (due to its relative mathematical simplicity and less site-specific data requirements [172]), one of its main drawbacks is that there is no real behavioural basis on which to justify the response curves [46]. In contrast, a simultaneous travel demand model uses a repeat binary logit model to determine the share of people who will choose to evacuate and leave at that time or will postpone the evacuation decision. This process is repeated multiple times at set intervals. The choice made at each interval is determined based on the differential utility associated with evacuating which is based on the prevailing conditions [46]. The factors discussed in Chapter 2 are examples of factors that could be chosen by modellers to impact the decision to evacuate.

Comparisons between the sequential and simultaneous modelling approaches have shown that the latter more closely represents observed evacuation travel demand behaviour as its flexibility allows it to estimate how evacuees respond dynamically to changes in hazard and road conditions as well as evacuation orders [46]. However, simultaneous models require more calibration and data. As such, the method chosen for a WUI evacuation model will depend on the purpose of a comprehensive evacuation model (real-time use, planning, etc.) and the corresponding time and data limitations.

Trip Distribution

Trip distribution modelling is used to represent how trips (or tours) are distributed throughout the transportation network, both spatially and temporally. This involves determining evacuees' destinations and whether there will be sub-destinations within the overall evacuation. The simplest and most popular approach to choosing evacuee destinations is to use proximity or other criteria such as destination attraction potential to assign evacuees to a destination [46]. This is generally done using gravity-based distribution, however, multinomial logit models can also be used [25], [65].

Depending on the purpose and number of trips taken by evacuees, either a trip-based or activity-based modelling approach can be used [25]. With the former approach, evacuees are modelled travelling directly from A to B (origin to destination – home to an evacuation shelter, home to relative's house, fire station to a threatened neighbourhood, etc.). With an activity-based approach, intermediate activities are represented (travelling from office to school to home to evacuation shelter, etc.) and therefore tours, or chains of trips, are modelled. The approach chosen should therefore reflect the evacuation scenario that is being modelled (ex. evacuating during the middle of the night vs. mid-afternoon), keeping in mind the amount of time and computing power necessary to run the simulation.

Modal Split

Modal split determines which modes of transportation will be used during the evacuation (personal vehicle, public transportation, etc.). Many factors such as the characteristics of the disaster, the distance to safety, mode availability and access, evacuee location at the time of an event, and population groups can all impact the transportation modes used during an evacuation [65]. Given the characteristics of WUI fire evacuations, private vehicles and potentially buses are the modes most likely to be used [25]. In addition to the type of mode, the number of modes used by a single household is also important as it can impact the number of vehicles in the transportation network during the evacuation.

There are various ways that modal split can be modelled. The simpler models estimate the mode choice independently of the other steps (heuristic and random utility models) [25]. Alternatively, integrated modelling simulates step choices (such as distribution and mode) simultaneously. While such models have the potential to provide a more accurate modal split, there is the potential to make assumptions which simplify the modelling process depending on the evacuation scenario being modelled (given the modes most commonly used during WUI evacuations).

Traffic Assignment

Traffic assignment modelling is used to assign evacuees to routes, thereby modelling route choice decisions [46]. Two of the primary factors involved in traffic assignment are how a route is assigned (static or dynamic) and when the route is assigned (pre-trip or enroute).[17] When using static assignment, steady-state network conditions are assumed and assignment is based on a user equilibrium approach [25]. In contrast, dynamic assignment assumes that the system changes over time as a result of various factors such as the number of users in the network and path choices [173]. Dynamic assignment can use either a deterministic or stochastic route choice model, depending on the nature of the variables used.

Pre-trip assignment means that a route is assigned at the origin before the trip begins. In this case, either a single path from origin to destination is determined (fully pre-trip, with no

[17] Others include capacity restraints, approach used for studying supply-demand interactions, segmentation of demand based on different user classes, and elasticity of demand [25].

changes made during the trip), or decision strategies for enroute choices are determined [173]. With enroute assignment, trip decisions are made during the trip based on information received while travelling. In both cases, trip decisions are made by considering the cost attributes (time, distance, financial cost, etc.) of different paths from origin to destination. To simulate these choices, random utility models, specifically deterministic or stochastic (probabilistic) choice models are used. With a deterministic choice model, travellers will choose the path that has maximum average utility (a path can only be used if the cost associated with it is the lesser of all alternative paths) [173]. A stochastic route choice model assumes that the *perceived* utility of a path is a random variable. Therefore, it expresses the probability that users will choose each available path [173]. Given that conditions can change quickly during an evacuation, a dynamic, enroute assignment approach is generally viewed as the best option.

Modelling Scope

The scope of a model, or the level of detail that can be simulated, should be determined based on the intended purposed of the model as the type of information obtained and the computational power/time required can vary greatly. The scope effects how vehicles are represented and how interactions between vehicles (and between vehicles and the network) are represented. There are three primary scales: macroscopic, mesoscopic and microscopic. Macroscopic models use a fluid analogy approach, looking at parameters such as volume, speed, and density within a road section and the relationships between them [25]. At the other end of the spectrum are microsimulation models which represent the individual choices of each traveller (vehicle) and the interactions between different travellers and between travellers and the environment [25]. Different parameters can be assigned to each traveller (vehicle characteristics, driver reaction time and aggressiveness, etc.) and sub-models are used to model traveller choices and interactions (car-following, acceleration/deceleration, lane-changing, etc.) [25]. Mesoscopic models combine some properties of micro and macroscopic models to create an intermediate scale of modelling. Packages of vehicles are modelled as opposed to individual vehicles and traffic flow is simulated based on the interactions between packages [25].

4.3.4 PTV VISSIM Traffic Modelling Software

PTV VISSIM is a microsimulation traffic simulation software commonly used in the transportation engineering and planning field. It is capable of modelling pedestrians in addition to multimodal traffic [174]. The model is based on several mathematical sub-models relating to car following, lateral movements (lane selection, lane changing, etc.), tactical driving behaviour, pedestrian modelling, fixed routes, and dynamic routing and assignment [175]. It is commonly used for corridor studies on motorways, signalized intersection performance and adaptation, and traffic calming to name a few applications [175]. Though not common, the software has also been used in a research capacity to model hurricane evacuations [176]–[178]. To the awareness of the author, no previous wildfire evacuation applications were identified in the available literature, however, VISSIM was one of the software packages reviewed in the NFPA Framework for Modelling Wildfire Urban Evacuation [25].

4.3.5 Scope

It was within the scope of this community evacuation simulation and analysis to provide a baseline which will be used for the development of a more comprehensive and accurate evacuation model within the next stage of the community vulnerability study. A site visit was not possible during the time of this project and as such the model is based on the information that could be obtained online and from a contact within a community agency. The main area of interest within the community is the cabin area located on the west side (as identified in Section 4.1). A total of 10 different evacuation scenarios were modelled, with variations being made to the evacuation timeframe, number of evacuees and evacuation destination. The analysis focused on the evacuation from the cabin area to the highway which serves as the only road into/out of the community. In addition to the vehicles evacuating from the cabin area, evacuation traffic originating from the other parts of the community (cottage area, campground, commercial/retail area) was also included to create a more realistic representation of a potential evacuation. Additional traffic on the highway caused by evacuations upstream was not considered, nor was background traffic within the community or trips made by people trying to enter the community. For a comprehensive analysis these would be important to consider, however, they were outside the scope of this analysis. Figure 4.9 outlines the community, the modelled area and the focus area analyzed in this study.

Figure 4.9: Case study community, modelled area and focus area

4.3.6 Methodology

Model Development

To create the model space within VISSIM, the network geometry was created using a series of *Links* which represent roadways and intersections. A Google Maps satellite view image of the site was scaled within VISSIM and set as the background image used to trace roads within the community. As the road widths were not known, a value of 2.5m was assumed and used for roads within the cabin area, and 3.0m was used for the remaining roads based on approximate measurements taken by the author from Google Maps.[18] Exact metrics can be made in future site assessments, for now these are suitable assumptions for first-stage modelling. All intersections within the study area were unsignalized, therefore, all intersection interactions were modelled using VISSIM's *Stop Signs, Priority Rules* and *Conflict Areas* functions. Speed limits within the community were determined using Google Maps Street View. Given that dynamic assignment was going to be used for the analysis, *Parking Lots* served as the origin and destination points of the simulated vehicles. These were assigned to different *Zones* which corresponded to those in the OD matrices used for traffic generation. Each branch of the road network within the cabin area was designated as a different zone (total of 19). A zone was created to represent the rest of the community and one was created for each evacuation destination on the highway (one for evacuating South-West and one for evacuating East). *Reduced Speed Areas* were used at sharp turns in the road network to temporarily slow traffic down and *Desired Speed Decisions* were used when speed limits within the network changed. Figure 4.10 shows the modelled network in VISSIM.

[18] Given the modelled scenario, the road widths did not have an impact on the simulation.

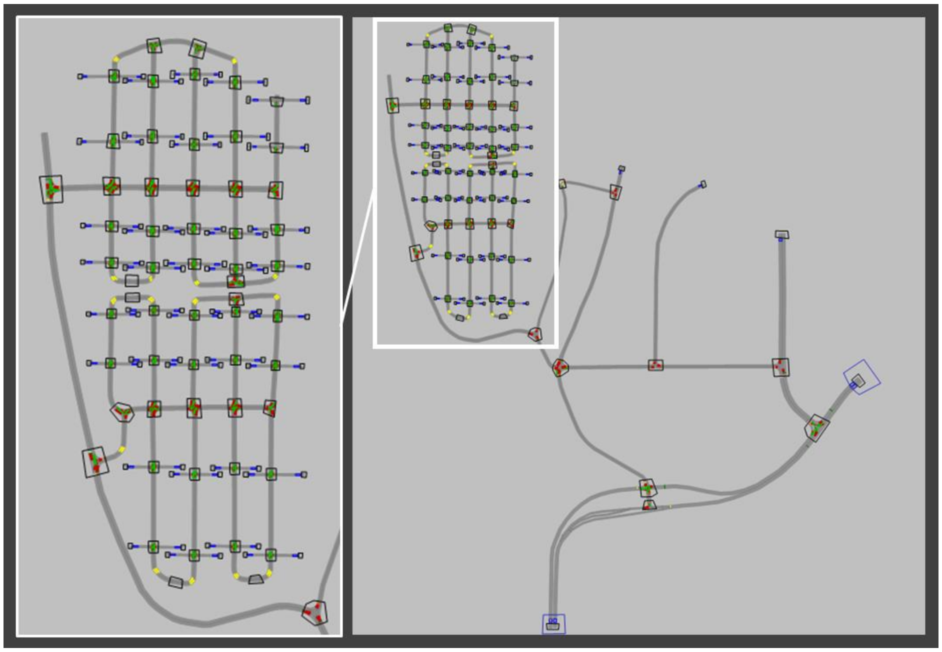

Figure 4.10: Case study community road network in VISSIM

Several network simplifications were made to make modelling more efficient. Instead of representing each individual cabin as its own parking lot on its own link, four small links were created to represent the cabins off each branch of the road network within the cabin area. Two were created near the middle/front of each branch and two were created near the back of each branch. This was done so that the simulation could better represent likely routes taken by evacuees, specifically those located farther along the branch roads (ex. might be more inclined to loop around and exit via another branch). As each branch was classified as a zone (corresponding to the OD matrix), the total trips leaving each cabin area zone was split between the four parking lots, with 30% coming from each front parking lot and 20% coming from each back parking lot. This distribution was chosen given the location of the links representing cabins. As the community was not modelled in full, the traffic coming from the community zone was distributed between three primary roads leading out of the community towards the south. The traffic was distributed to these three roads based on what was assumed to be the most likely egress route for evacuees leaving the community (60%, 20% and 20%). This assumption was made based on the location of cottages and the campground within the community.[19]

Running Simulations

To see the impact that the number of evacuating vehicles and the duration of evacuation initiation timeframe had on the evacuation of the cabin area, 10 different scenarios were simulated. These are detailed in Table 4.1. They are meant to help gain a better understanding of the potential worst-case-scenarios and the factors that contribute to them. Scenarios 1 and 2 act as base cases where only the cabin area is evacuated (no traffic from the rest of the community). This allowed the impact of such traffic to be analyzed by comparing later scenarios with community traffic (Scenarios 3 and 4) to these base cases. Scenarios 5 through 8 allow for the analysis of the impact that modifying one factor (or all factors) had on the evacuation (number of vehicles from the cabin area, number of vehicles from the community, evacuation initiation timeframe). Scenarios 9 and 10 were modelled to see how substantially increasing the evacuation initiation timeframe would impact the evacuation in comparison to shorter timeframes. It is acknowledged that alternative and/or additional scenarios could have been modelled, however, given the lack of information about the site and the current scope of this research, these scenarios were deemed sufficient to provide a good baseline for future analysis.

[19] The campground (over 450 sites) is accessed exclusively off one of the modelled roads. The main body of the community can be accessed by all three roads. The two-lane road onto which the campground exits was therefore given a greater distribution of traffic.

Table 4.1: Modelled evacuation scenario descriptions and number of error-free simulations run

Scenario No.	Description	Number of Simulations Run
1	1 car per cabin (530) 1-hour departure window South-West evacuation 0 cars from community	5
2	1 car per cabin (530) 1-hour departure window East evacuation 0 cars from community	5
3	1 car per cabin (530) 1-hour departure window South-West evacuation 1000 cars from community	3
4	1 car per cabin (530) 1-hour departure window East evacuation 1000 cars from community	3
5	1 car per cabin (530) 2-hour departure window South-West evacuation 1000 cars from community	3
6	2 cars per cabin (1060) 2-hour departure window South-West evacuation 1000 cars from community	3
7	2 car per cabin (1060) 2-hour departure window South-West evacuation 2000 cars from community	3
8	1 car per cabin (530) 2-hour departure window South-West evacuation 2000 cars from community	3
9	2 car per cabin (1060) 4-hour departure window South-West evacuation 2000 cars from community	3
10	1 car per cabin (530) 4-hour departure window South-West evacuation 1000 cars from community	3

The travel demand for the model was determined based on knowledge about the number of residences in the community (and the number of campsites). The number of cabins in the cabin area was obtained from a map provided by a community agency contact, with 530 individual residences being identified. As the number of vehicles present at each cabin was unknown at this stage, the modelled scenarios assumed either one or two vehicles per cabin. A community agency contact stated that on summer weekends the cabins were usually fully occupied. Therefore, to represent a potential worst-case-scenario (greatest number of people) it was assumed that there would be 530 vehicles or 1060 vehicles evacuating from the cabin area. No recent information could be found about the number of cottages and commercial rental properties within the main part of the community, however, the number of campsites was determined to be approximately 460 [179]. As such, after looking at Google Maps satellite images of the community, it was decided that in total, 1000 vehicles would be assumed to be coming from the community and campground. It is important to note that this number is arbitrary and an accurate account of the number of vehicles that would need to leave this area would improve the accuracy of the evacuation. Several scenarios were also tested with 2000 vehicles coming from the community to see how much of an impact this increase would have on the evacuation.

The time at which the evacuating vehicles left their origin parking lot was determined stochastically using the Poisson distribution.[20] Each scenario was run three to five times, using different random seeds so as to simulate stochastic variations of vehicle arrivals in the network. The overall timeframe during which all the vehicles would leave their origin parking lot was specified for each OD matrix. No previous research relating to WUI fire evacuation timelines could

[20] The average time gap between two vehicles results from the hourly volume and it is used the average value of a negative exponential distribution. VISSIM uses time gaps from this distribution (which relates to a Poisson Distribution) [174].

be found. As such, several timeframes were tested: 1-hour; 2-hours; and 4-hours. Though arbitrary, these timeframes were selected because greater congestion occurs when more vehicles are on the network at the same time (therefore representing a potential worst-case-scenario). Also, unlike hurricane evacuations, WUI fires can prompt immediate evacuations with little warning (as was the case with many of the WUI fires discussed in Chapter 1). As the number of cabin and community evacuees were included in the same OD matrix, the timeframe associated with that OD matrix was applied to all evacuating vehicles.

With respect to trip distribution, an OD matrix was created for each scenario, representing the number of trips originating from the respective zones. A trip-based approach was used for simplicity, and as a result of a lack of information about trips normally taken within the community. This could also represent an evacuation occurring at night when most people are home and would need to take fewer side trips to collect family and belongings. The 10 scenarios were determined based on looking at the community's location and the information that was known about the community population and layout. Based on the location of the community in relation to the forested area around it, it was assumed that there would be a higher likelihood of a fire impacting the site from the North/East therefore most of the scenarios had a South/West evacuation destination. Two scenarios were simulated using an East evacuation destination for comparison and to create a baseline for what such an evacuation could look like.

Given that the community is remote and seasonal, there is no public transportation. Only a chartered bus company services the area [180]. Therefore, the traffic composition (modal split) was determined to be 100% personal vehicles. VISSIM default properties and distributions were used for the following vehicle features:

- Vehicle length and width (3.75m – 4.76m and 1.85m – 2.07 respectively)

- Acceleration and deceleration
- Vehicle speeds using linear distributions for speed limits of 20km/h (20km/h – 25 km/h), 30km/h (30km/h – 35km/h), and 50km/h (48km/h – 58km/h).
- Car following behaviour (Weidemann 74 car following model) [174], [175]

A dynamic, enroute traffic assignment approach was used for the simulations. Dynamic assignment in VISSIM is usually done by running back-to-back iterations of the same scenario, with drivers basing their decisions off of the experience of drivers in preceding simulations. However, unlike commuting to work, WUI evacuations do not occur on a regular basis where people can learn from their past experience. As such, each simulation was run separately. Instead of drivers basing their decisions on previous simulations, the initial path choice is based on the shortest distance and subsequent decisions are made as each vehicle approaches an intersection (the vehicle chooses its path dynamically while it travels). At each intersection, the vehicle revaluates its chosen route, updating its previous decision based on how effective a path was (the length of travel time on each edge) in the previous time interval within the same simulation. This interval was set to be 5-minutes to allow drivers to update their route choices more frequently. VISSIM's stochastic path choice model (Kirchhoff) was select as was required for this type of simulation with the default Kirchhoff exponent of 3.5 being used (sensitivity parameter). Eq. 1 shows the Kirchhoff distribution formula used in VISSIM where Uj is the utility of route j, P(Rj) is the probability of route j to be chosen, and K is the sensitivity of the model [175]:

Eq. 1 $$p(R_j) = \frac{U_j^k}{\sum_i U_i^k}$$

Scenario Analysis

Data Collection Points, Vehicle Travel Time Measurements, and Queue Counters were used to collect information about vehicle throughput, total and individual evacuation times, queue lengths and travel times. Data collection points and queue counters were placed at the entrance to intersections on roads of interest (focus on primary intersections and cabin area intersections) and directly before the network exit parking lots. Vehicle travel time measurements were taken along stretches of road (cabin area access road and highway access roads). Table B.1 in Appendix B provides more information about the specific locations of each.

4.3.7 Results and Analysis

Overall comparisons between the 10 scenarios were made by looking at the total evacuation time (TET) – when the last vehicle left the network – and the individual evacuation time (IET) of vehicles in the two sections of the cabin area. The area designated as "Back Cabin Area" is the section closest to the lake and the "Front Cabin Area" is the area farthest from the lake.

Simulation errors occurred when running one of the scenarios, resulting in one or more vehicles not exiting the network. During one simulation run of Scenario 4, the software removed one vehicle from the network after it spent 60 seconds waiting for a lane change, and during another simulation run, three vehicles were removed for the same reason. This occurred on the easternmost road leading out of the community. In order to allow for comparative analysis of the scenarios, the scenarios that resulted in errors were run additional times with new random seeds until there were three error-free scenarios. The results of the other scenarios were not included in the analysis as the reduced number of vehicles impacted the TETs and the queue lengths. For Scenarios 4, two additional simulations had to be run as the second and forth simulations both resulted in an error. The potential for errors such as these to occur must be taken in to account when using software to simulate evacuations (resulting from the limitations and programming of the software).

As noted earlier, VISSIM uses as stochastic driver behaviour model and therefore, with the variations in the random seed used for each simulation, there is a level of randomness in the results. For demonstration of concept, the analysis approach used in this study is that which will be used for more specific simulations that will be run once additional data about the site is obtained and therefore more confidence is had in the model inputs. The 95% confidence intervals were calculated for each simulation run with the assumption that the population will have a normal distribution. At this stage, this also helped to determine if additional simulations of each scenario should be run (this applies to the individual evacuation times and queue length analysis as well). Table 4.2 shows the range of expected total evacuation times based on this confidence interval. This table seems to indicate that the stochastic variation will not have a large impact on the overall evacuation time, however, this would need to be confirmed with additional simulation runs such as those planned for the next stage of the project. For the sake of comparing scenarios, investigating the software, and testing assumptions about the impact of key-input parameter variation (timeframe and number of vehicles), the number of simulations run as part of this baseline study was deemed appropriate. Table B.2 in Appendix B shows details of each simulation run, including the TET of each simulation of each scenario, the aggregate average TET for each scenario, the random seeds used, and the overall simulation time. Figure 4.11 below shows the average total evacuation time for each of the simulations as well as the evacuation initiation timeframe (period of time during which vehicles left their origin zone).

Table 4.2 Expected average total evacuation times

Scenario	95% Confidence Expected Total Evacuation Time Range (hr)
1	1:05:05 - 1:06:17
2	1:04:56 - 1:06:19
3	2:00:31 - 2:02:26
4	1:47:45 - 1:53:18
5	2:02:41 - 2:04:41
6	2:47:36 - 2:49:21
7	3:54:55 - 4:03:40
8	2:57:46 - 3:03:24
9	4:03:22 - 4:04:34
10	4:03:08 - 4:04:07

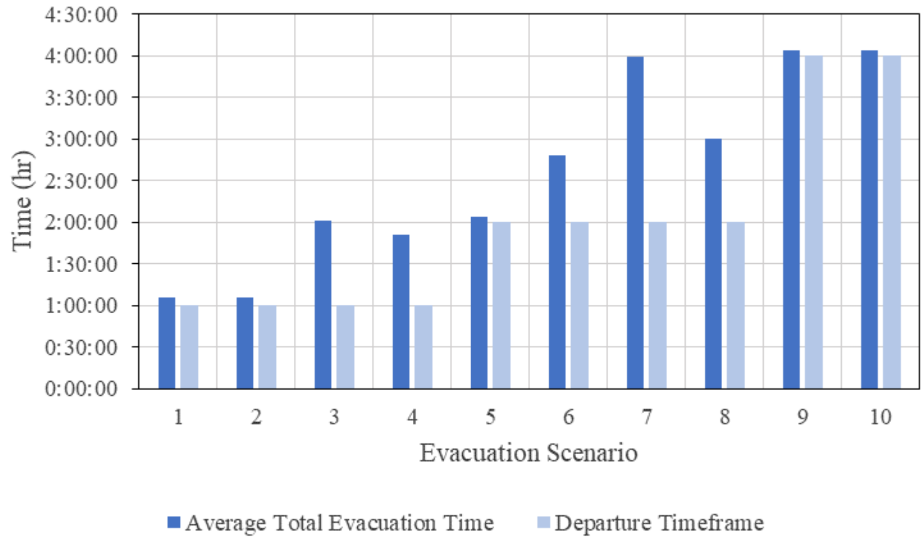

Figure 4.11: Total evacuation time and departure timeframes

The aggregate IETs for the vehicles originating from the front and back cabin areas were also compared for each scenario. Figure 4.12 – Figure 4.14 show the aggregate average and median, the aggregate minimum, and the aggregate maximum IETs for each of the two cabin areas. The corresponding tables can be found in Appendix B (Tables B.3 – B.6). Figure 4.15 shows the five-number summary for the front and back cabin areas for each scenario (minimum, first quartile, median, third quartile, and maximum). The 95% confidence interval was calculated for each scenario and varied between a few seconds to a few minutes with the larger intervals occurring in scenarios with greater congestion (particularly for the front cabin area).

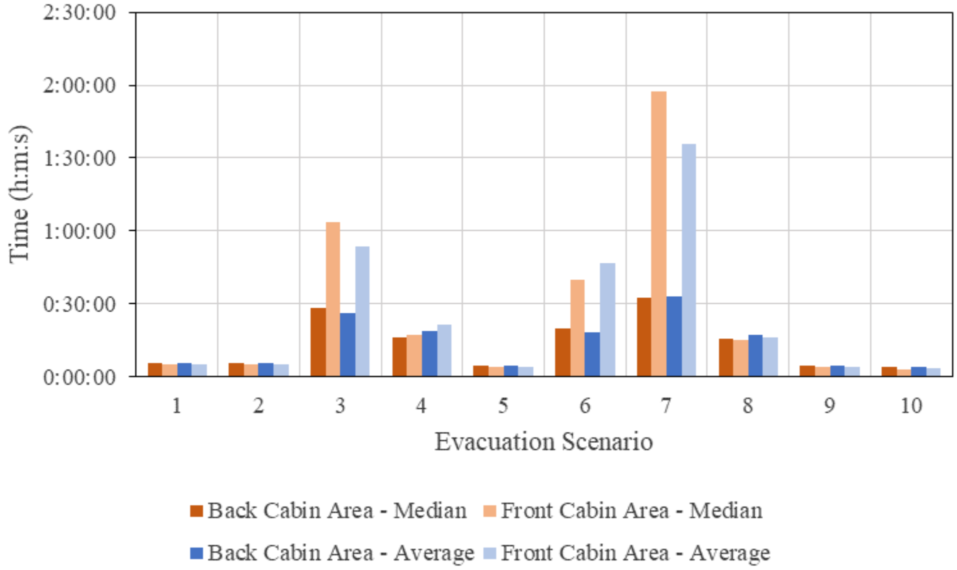

Figure 4.12: Aggregate average and median individual evacuation times

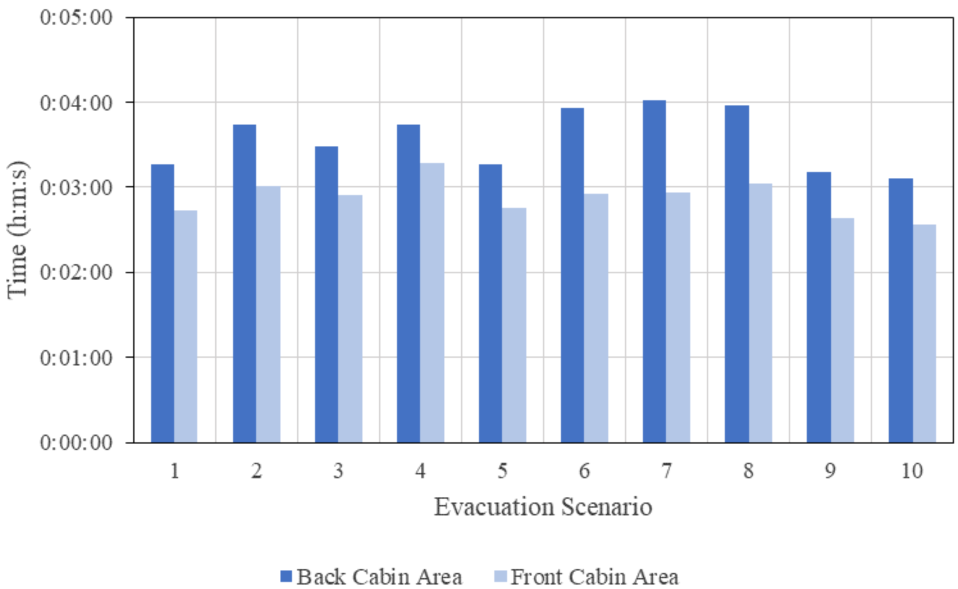

Figure 4.13: Aggregate minimum individual evacuation times

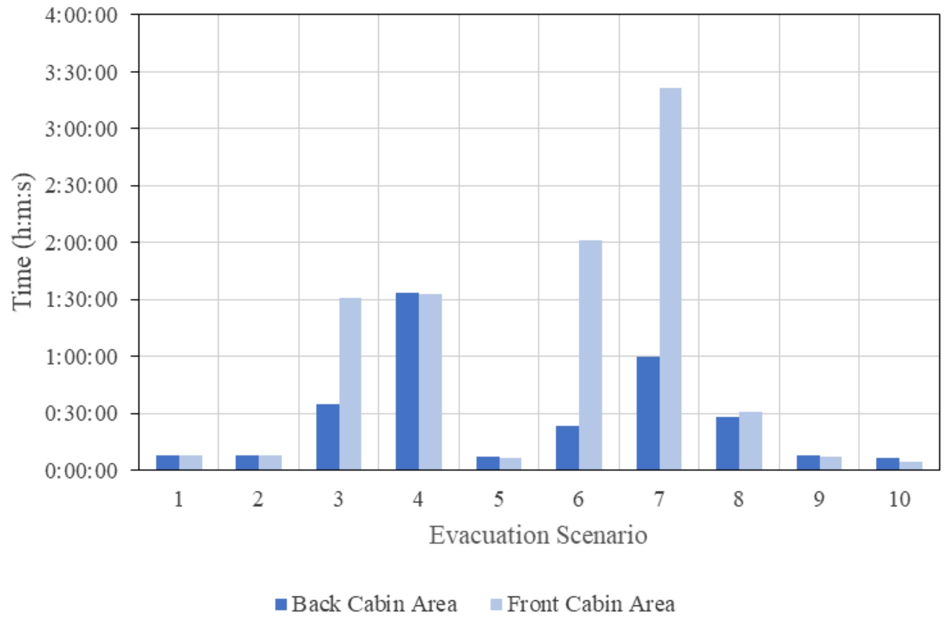

Figure 4.14: Aggregate maximum individual evacuation times

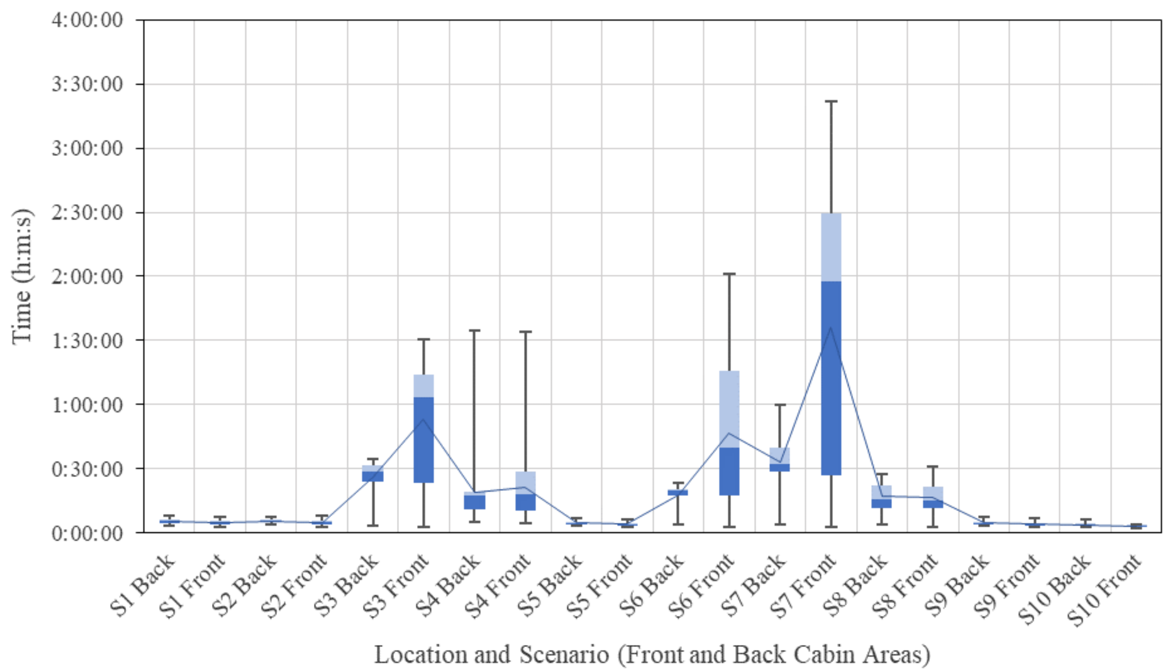

Figure 4.15: Five number summary (minimum, 1st quartile, median, 3rd quartile, maximum) and average for the front and back cabin areas in each scenario

As can be seen in Figure 4.13, the relationship between the minimum IETs for the two sections was similar for all the scenarios. There was greater variation between the maximum IETs (Figure 4.14), with Scenarios 3, 6 and 7 showing a longer time for those in the front cabin area. This is similar to the findings shown in Figure 4.12 for the average and median IETs. Scenarios 3 and 7 resulted in the greatest difference between the average (and median) for the front and back cabin areas. These scenarios also resulted in a larger difference between the average and the median (with the median being greater than the average for the front cabin area). Both of these scenarios contained the greatest number of evacuees within their given evacuation initiation timeframe, indicating that the number of evacuees is one of the key determinants of individual evacuation times. However, as Scenario 5 and Scenario 9 which had longer initiation timeframes involved the same number of evacuees as Scenarios 3 and Scenario 7 respectively resulted in short IETs, the timeframe also plays an important role.

Congestion occurred at primary intersections in most scenarios, largely impacting the individual and total evacuation times. The greatest congestion corresponded with scenarios that had a greater number of evacuating vehicles and/or a decreased evacuation initiation timeline. Scenarios 1, 2, 5, 9 and 10 had minimal congestion (as observed within the model during the simulation and the recorded queue lengths.) Figure 4.16 below shows the location of the measured queues, Figure 4.17 shows the maximum recorded queue lengths for all primary intersection within the network, Figure 4.18 shows the maximum queue lengths within the cabin area and Figure 4.19 shows them for the main network intersections. The average queue lengths were also recorded; however, they were averaged over the entire length of the simulation and not just the time when the vehicles were in the network. As such, the recorded values do not reflect the queue lengths over the correct time and therefore they were not compared within this analysis.

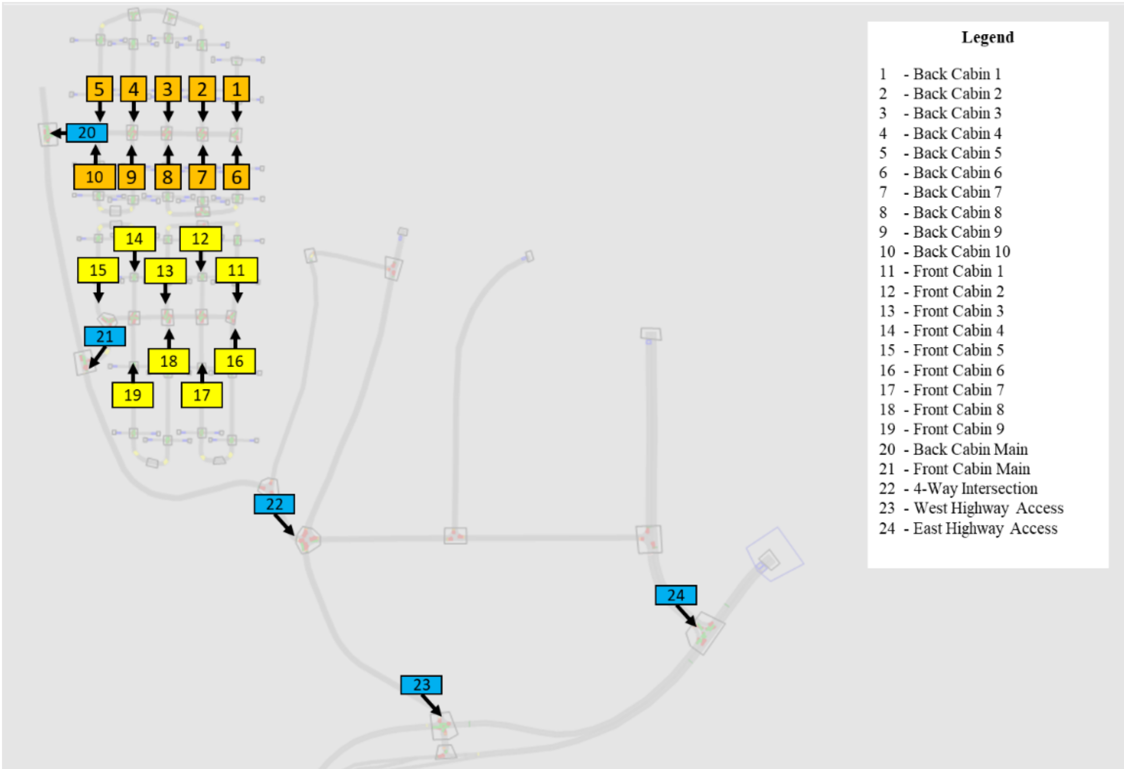

Figure 4.16: Queue measurement locations

As is shown in the figures below, the longest queue lengths occurred at the intersections where cabin area and community evacuees interacted (4-way stop, east and west highway access roads). The longest queues were observed during scenarios that had a greater number of evacuees and/or a shorter evacuation initiation timeframe (as was seen with the total and individual evacuation times). At the 4-way intersection, Scenarios 3 and 7 caused queues reaching all the way back to the back cabin area access intersection, with Scenarios 4, 6 and 8 causing queue lengths past the front cabin area access intersection. Scenarios 3, 7 and 8 resulted in the longest queue lengths at the west highway access intersection, corresponding to increased traffic coming from the community on that road. Given that most of the evacuation scenarios had a west/south destination, fewer cars used the east highway access road. The longest queues occurred at this intersection during Scenarios 4, 7 and 8.

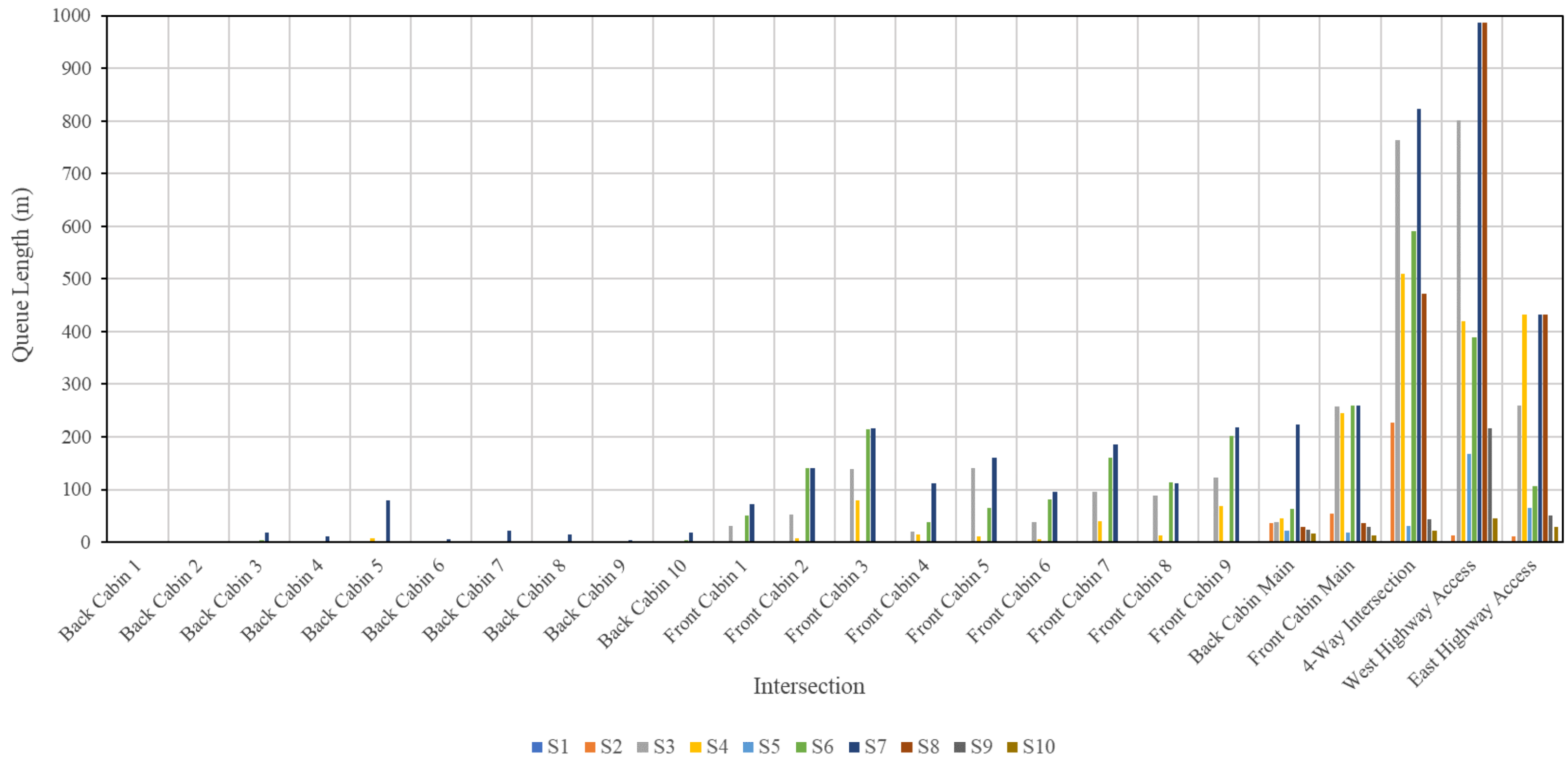

Figure 4.17: Maximum queue lengths for all primary intersections

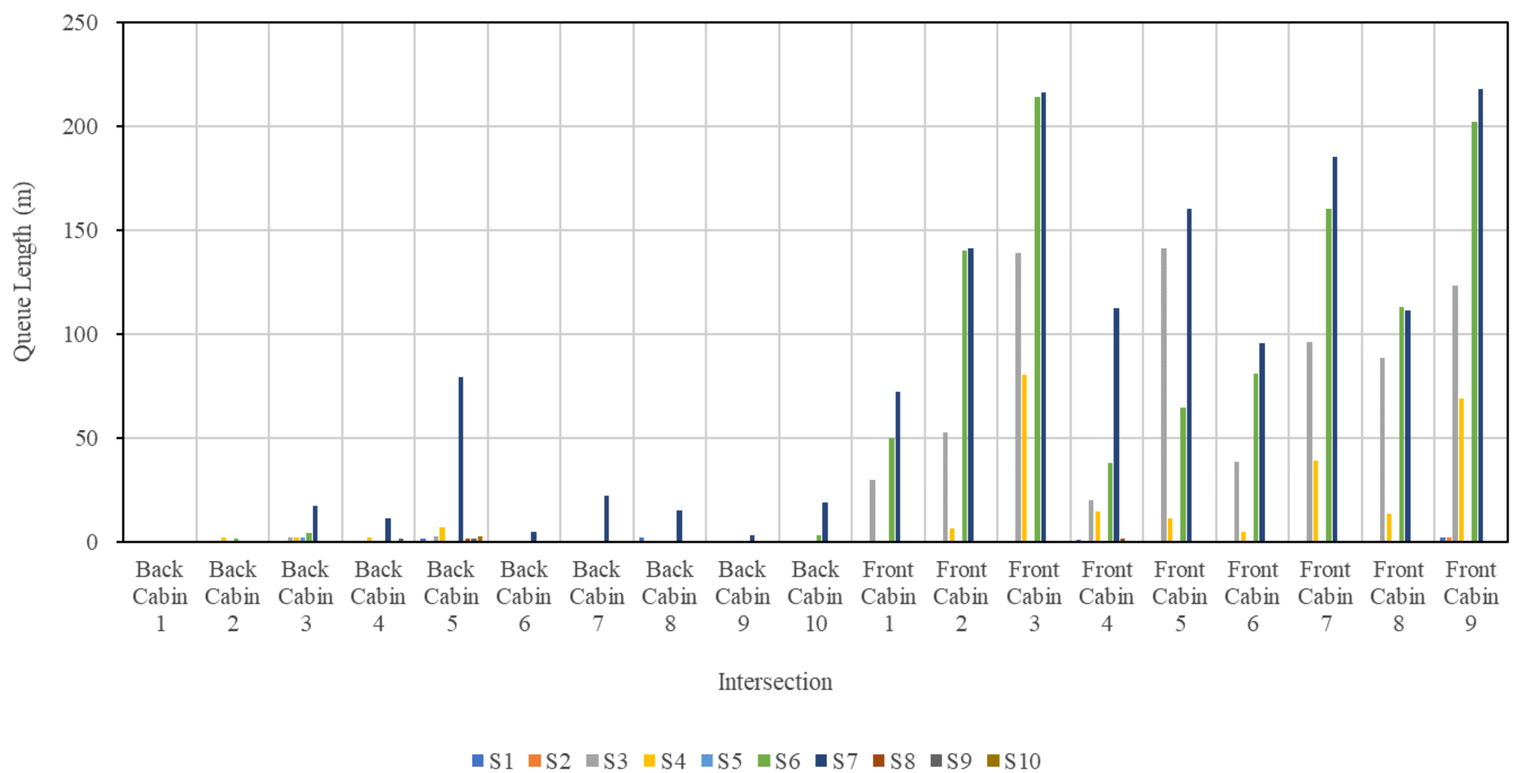

Figure 4.18: Maximum queue lengths for intersections within the cabin area

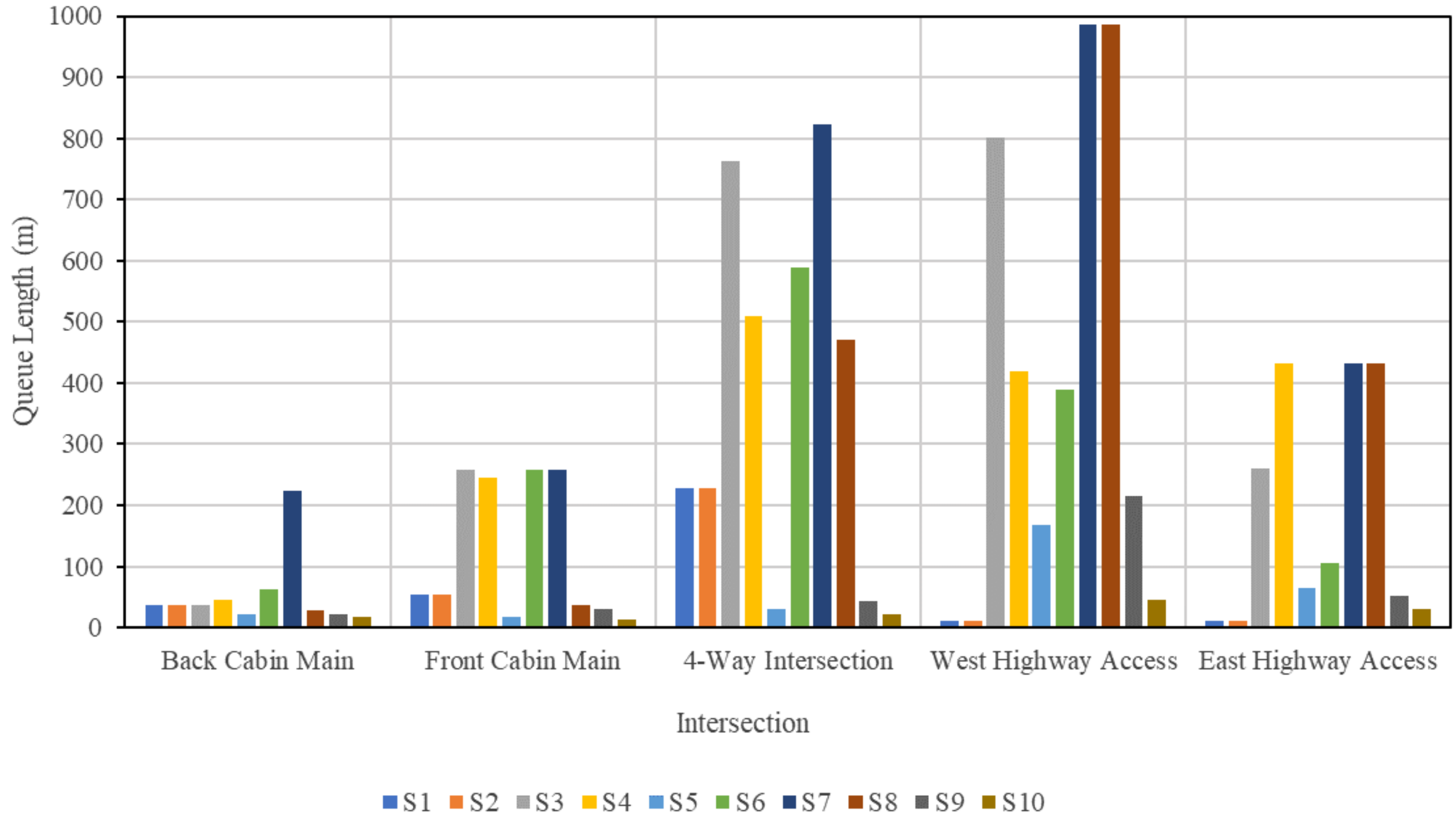

Figure 4.19: Maximum queue lengths for main network intersections

Between the back and front cabin areas, the greater queues were observed in the front cabin area. This is in line with the longer individual evacuation times observed for front cabin area evacuees. The only notable queue lengths within the back cabin area occurred during Scenario 7 while several evacuation scenarios caused substantial queues in the front cabin area. At the entry points into the cabin areas, four scenarios caused queues of more than 100m for the front cabin area while only one caused such a queue for the back cabin area. These findings reflect the type of intersections connecting these cabin areas to the main access road. Those travelling from the back cabin area have priority on the main access road, meaning that once congestion from the 4-way intersections reaches the front cabin access road, evacuees from this area have to wait for all of the vehicles from the back cabin area to evacuate before they can exit the front cabin area (unless there is a large enough gap between cars or a vehicle were to stop and let a car from the front cabin area into the flow).

The queue lengths varied more within scenarios than the total and individual evacuation times did. The 95% confidence interval varied greatly between simulations and between intersections within simulations. Table B.7 in Appendix B shows the maximum queue lengths and the confidence intervals for each scenario. The queue lengths depend greatly on when vehicles leave (distributed timewise during the initiation timeframe stochastically in VISSIM), where they leave from, and the decision the vehicles make enroute. Given the observed variability, additional simulation runs would be needed to improve the confidence interval to be able to confidently estimate queue lengths in the network. However, the current results do indicate which scenarios are likely to result in the greatest congestion and at which intersections this congestion will occur.

Several direct comparisons were made between individual scenarios to identify the impact of the changed scenario parameters. Table 4.3 below shows the results of these comparisons. In each case, the total evacuation and individual evacuation times were compared. The first two comparisons show the impact that the destination had on the evacuation times, with and without traffic from the community (Comp. 2 and Comp. 1 respectively). When just the cabin traffic was considered, the TETs were almost identical and the IETs for the front and back areas varied only slightly. When traffic from the community was considered, the TET was 11 minutes greater for the westward direction. The IETs for the front and back cabin areas were substantially longer for the westward evacuation, approximately 32 and 7 minutes longer respectively.

The third and forth comparisons show the impact that community traffic had on the evacuation times for an evacuation in each direction. Comp. 3 showed that with the presence of community traffic the TET almost doubled, and the IET increased by 20 minutes (fivefold) for the back cabin area and by 48 minutes (elevenfold) for the front cabin area. The impact of community traffic was less for the eastward evacuation, with the TET increasing by 44 minutes, the back cabin area IET increasing by 13 minutes (threefold) and the front cabin area IET increasing by 16 minutes (fourfold).

The fifth comparison shows the impact that doubling the evacuation initiation timeframe had on evacuation times. As expected, the IETs decreased substantially with a greater initiation timeframe as there were fewer vehicles in the network at any given time, resulting in evacuation times similar to those seen in Scenario 1. The difference in the TET was quite small (approximately 2 minutes), indicating that the overall evacuation timeline would be similar if all vehicles initiated evacuation within one hour or within two.

Table 4.3: Scenario Comparisons – total and individual evacuation times

Comparison No.	Scenarios	Parameters	Average Total Evacuation Time (h:m:s)		Average Individual Evacuation Time (h:m:s)	
1	S1 - S2	Same Time Same Volume Different Direction	S1	1:05:41	Back	0:05:25
					Front	0:04:55
			S2	1:05:37	Back	0:05:36
					Front	0:05:06
2	S3 - S4	Same Time Same Volume Different Direction	S3	2:01:28	Back	0:26:01
					Front	0:53:22
			S4	1:50:31	Back	0:18:43
					Front	0:21:20
3	S1 - S3	Same Time Different Volume Same Direction	S1	1:05:41	Back	0:05:25
					Front	0:04:55
			S3	2:01:28	Back	0:26:01
					Front	0:53:22
4	S2 - S4	Same Time Different Volume Same Direction	S2	1:05:37	Back	0:05:36
					Front	0:05:06
			S4	1:50:31	Back	0:18:43
					Front	0:21:20
5	S3 - S5	Different Time (double) Same Volume Same Direction	S3	2:01:28	Back	0:26:01
					Front	0:53:22
			S5	2:03:41	Back	0:04:41
					Front	0:04:05
6	S5 - S6	Same Time Different Volume (double cabin) Same Direction	S5	2:03:41	Back	0:04:41
					Front	0:04:05
			S6	2:48:28	Back	0:18:02
					Front	0:46:46
7	S5 - S8	Same Time Different Volume (double community) Same Direction	S5	2:03:41	Back	0:04:41
					Front	0:04:05
			S8	3:00:35	Back	0:16:57
					Front	0:16:20
8	S5 - S7	Same Time Different Volume (double both) Same Direction	S5	2:03:41	Back	0:04:41
					Front	0:04:05
			S7	3:59:17	Back	0:33:13
					Front	1:35:52
9	S3 - S7	Different Time (double) Different Volume (double both) Same Direction	S3	2:01:28	Back	0:26:01
					Front	0:53:22
			S7	3:59:17	Back	0:33:13
					Front	1:35:52
10	S7 - S9	Different Time (double) Same Volume Same Direction	S7	3:59:17	Back	0:33:13
					Front	1:35:52
			S9	4:03:58	Back	0:04:42
					Front	0:04:08
11	S5 - S10	Different Time (double) Same Volume Same Direction	S5	2:03:41	Back	0:04:41
					Front	0:04:05
			S10	4:03:38	Back	0:03:51
					Front	0:03:15

Comparisons 6 through 8 used Scenario 5 as a base case and showed the impact that increasing the amount of traffic coming from the cabin area and community (separately and combined) had on the evacuation. When the number of vehicles leaving the cabin area was doubled, the TET increased by 45 minutes, the back cabin area IET increased fourfold and the front cabin area IET increased elevenfold (Comp. 6). When the number of vehicles leaving the community was doubled, the TET increased by 57 minutes, and both the back and front cabin area IET increased approximately fourfold (Comp. 7). It was observed in the simulation that when just the community traffic was doubled, the cabin area vehicles were able to evacuate more quickly as compared to when just the cabin area traffic was doubled. This happened largely as a result of congestion occurring on the central road leading out of the community which prevented community evacuees from turning left and heading to the 4-way intersection (reducing the traffic at the 4-way intersection). This is reflected in the fact that while the TET was greater for Scenario 7 than Scenario 6, the IETs for the cabin area were reduced (the longer TET was caused by vehicles evacuating from the rest of the community not the cabin area). When the number of vehicles leaving both the cabin area and the community was doubled, the TET increased by nearly two hours, the back cabin area IET increased sevenfold and the front cabin area IET increased approximately twenty-fourfold (Comp. 8).

The ninth comparison shows the impact of doubling all scenario parameters (initiation timeframe and number of evacuating vehicles leaving the cabin area and community). In terms of the TET, there was a difference of approximately two hours between the two scenarios, with the TET for each being twice the respective evacuation initiation timeframe (two hours for Scenario 3 and four hours for Scenario 7). For the back cabin area IETs there was a difference of 7 minutes

(1.3 times longer in Scenario 7) and for the front cabin area, there was a difference of 42 minutes (1.8 times longer in Scenario 7).

Comparisons 10 and 11 show the impact of increasing the initiation timeframe from 2-hours to 4-hours with a total of 3060 vehicles (Comp. 10) and with a total of 1530 vehicles (Comp. 11). The relationship between the TET for Comp. 10 and the respective evacuation initiation timeframes were quite different. When the initiation timeframe was shorter the TET was double the timeframe, and when the initiation timeframe was longer the TET was only four minutes longer than the initiation timeframe. The IETs for this comparison were also quite different, with the shorter initiation time increasing the IET sevenfold and twenty-threefold for the back and front cabin areas respectively (similar to the degree of difference seen in Comp. 8). Conversely, when fewer cars were in the network as was the case for Comp. 11, the relative differences between the TETs and the absolute differences between the IETs were minimal. In both compared scenarios, the TET was approximately four minutes more than the initiation time, and the IETs for both the front and back cabin areas differed by less than one minute.

4.3.8 Key Considerations for Evacuation Modelling

The 10 different evacuation scenarios modelled and analyzed help to identify potential challenges to evacuating the case study community as well as highlighting key information needed and considerations that should be made to better understand what an evacuation might look like. As expected, the individual evacuation times and the total evacuation time increased when there were a greater number of vehicles in the network, either as a result of the total number of evacuees increasing or the timeframe in which all vehicles entered the network decreasing. The intersections that saw the most congestion were the 4-way stop (the first location where cabin area traffic and community traffic met) and the highway access points. When the network was congested, the front cabin area took longer to evacuate than the back cabin area, with evacuees having longer individual evacuation times. Figure 4.20 showcases examples of the congestion observed within the network simulation.

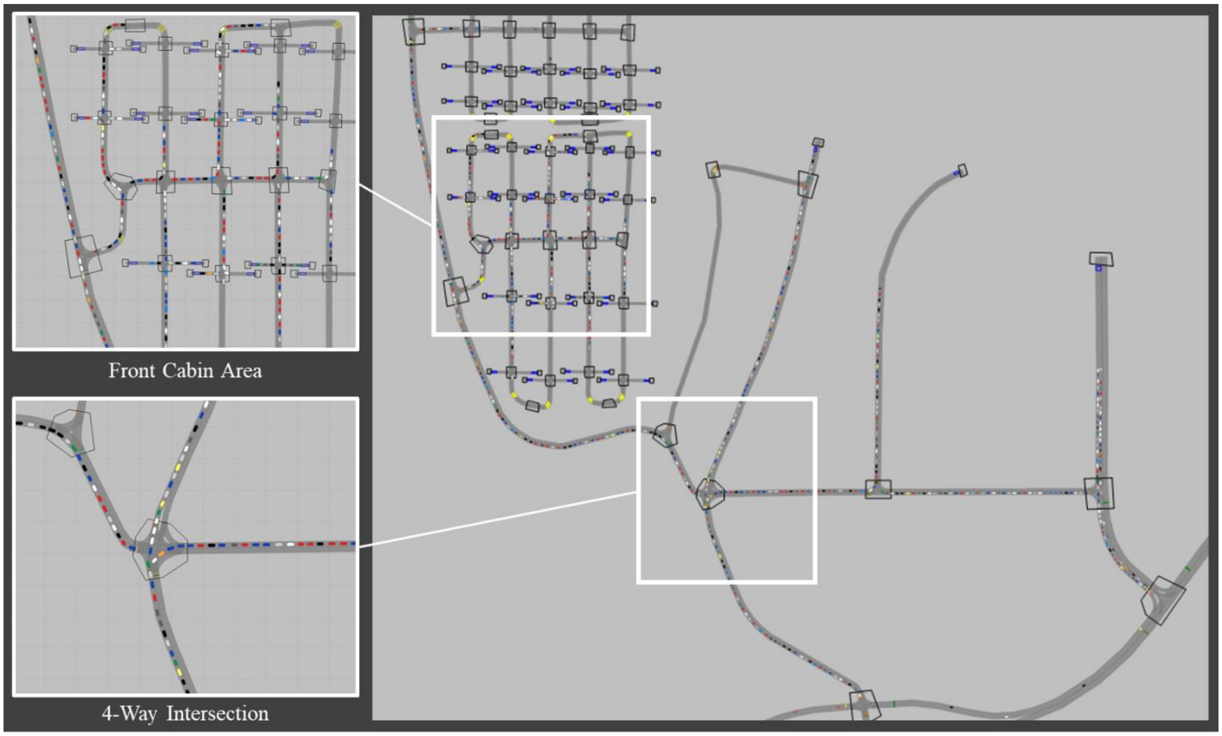

Figure 4.20: Network congestion in Scenario 7

In looking at these results, or those of any model, it is important to keep in mind the assumptions that were made and the amount and quality of information that was known about the community. Table 4.4 summarizes key assumptions that were made in the modelling of this case study and the impact that these assumptions had on the simulation outcomes. All assumptions ultimately had the potential to impact the congestion observed within the network (where, when, and to what degree) as well as the total and individual evacuation times. Having more information about the number of vehicles that might use the network in the community would improve the accuracy of how many vehicles to simulate in the model and where they should originate from (cabin area vs. community, within cabin area and within community). This in turn impacts where congestion occurs and to what degree (as was shown in the comparison of the modelled scenarios). Similarly, having a better idea about how long people will take to initiate evacuation can also impact this. In the 10 scenarios, it was assumed that both the community and the cabin area evacuees all left within the same timeframe. As Chapter 2 discussed, the decision to evacuate can be impacted by numerous factors and it is important to understand which factors would be most impactful for different areas of the community. For example, if the cabins are occupied by people who visit every summer and are familiar with the area, while the campground and parts of the community are occupied by first-time visitors unfamiliar with the community, this could impact when people leave (and which routes they take). The survey discussed in Section 4.2 seeks to help fill some of the current gaps in knowledge about the case study community residents. The number of people in each area could also play a role in the length of the evacuation initiation period. Once a better understanding was had, simulations could be run using multiple, overlapping OD matrices with different timeframes representing different evacuees to gauge the impact that this would have on an evacuation.

Just as including community traffic had a large impact on the evacuation of the cabin area, traffic on the highway would also play an important role, especially given that highway traffic would have the right of way potentially making it difficult for vehicles from the community to enter the highway (and therefore causing long queues and greater congestion within the community and cabin area). While this was outside the scope of this simulation, further analysis of the community should include an understanding of the amount of traffic that could be expected on the highway during an evacuation scenario. This would be determined largely by the location and size of a wildfire. As such, in addition to having information about the number of people in the surrounding area, it is also important to study the vegetation, topography, and weather patterns in the area to more accurately predict where a fire would be likely to occur and how it would threaten the community and therefore in which direction the community would need to evacuate.

Table 4.4: Key Assumptions and Impacts on Simulation Results

No.	Assumption	Impact
1	Number of vehicles evacuating from cabin area and community	● Determines number of vehicles in the network ● Potential to affect the evacuation initiation time (more people, more vehicles, more time to "pack up" and leave origin ● Will affect congestion (in cabin area and where cabin/community traffic meet) ● Affect total and individual evacuation times
2	Distribution of community traffic on roads leading out of the community	● Affects the amount of congestion within the network as a whole and the queue lengths (amount of congestion) at specific intersections ● Affect total and individual evacuation times
3	No highway traffic	● Affects queues at highway access points which in turn impacts the queues and congestion within the cabin area and community ● Affect total and individual evacuation times
4	South/West evacuation more likely	● Affects which intersections are more congested, (potentially which road community traffic would take) ● Affect total and individual evacuation times
5	Normal traffic behaviour (only one turning lane onto highway, no lane reversal, right of way and priority rules at intersections)	● Affects speeds, behaviour at intersections, use of oncoming lanes ● These will impact evacuation times and the distribution of traffic within the network ● Affect total and individual evacuation times
6	No Counterflow	● Evacuating vehicles did not have to deal with traffic travelling the opposite direction at intersections (impacting queues and congestion) ● Affect total and individual evacuation times
7	No background traffic or evacuees making intermediate trips	● Affects the number of vehicles in the network (amount of congestion) ● All traffic travelling to same destination ● Affect total and individual evacuation times
8	Community evacuates in the same timeframe as cabin area; community evacuees only use south exits out of community	● Affects the number of vehicles in the network (amount of congestion) ● Impacts the number of vehicles that would be travelling on the highway upstream of the modelled highway access points ● Affect total and individual evacuation times
9	Second car distributed evenly throughout the cabin area (one or two cars per cabin)	● Affect the routes taken by evacuees within the cabin area which impacts queues and congestion within the cabin areas and at the cabin area access intersections ● Affect total and individual evacuation times
10	Sightlines and Curb Radii	● Affect how vehicles behave at intersections ● Affect total and individual evacuation times

Understanding typical traffic flow within the community would also aid in being better able to predict what an evacuation would look like. It could provide a clearer picture of how people move within the community (common/more popular routes, typical speeds, etc.) Additionally, having more information about evacuee driving behaviour (in general) would provide a clearer picture of what could potentially happen during an evacuation of this community. Specifically, understanding how people treat right-of-way at 4-way stops or priority rules at other types of unsignalized intersections would be beneficial as this could impact which roads in the network would have the greatest queues and therefore potential evacuation times. Such information would have to be taken from studies of past evacuations, a field of study that is underdeveloped currently.

With respect to the accuracy of the network, surveying could be done in areas of the community and cabin area where the Google Maps data was blurry or not as specific as required. For example, many of the intersections within the cabin area were obscured by tree cover, impacting the accuracy of their representation within the model. Additionally, the visibility and sight lines for all cabin area intersections were unknown, impacting the modelled speeds and right-of-way. Depending on the level of detail deemed necessary for a risk assessment, more specific information about such network geometry may be required. In order to make such decisions, a site visit is important to assess the community in more detail. It is still important to remember, however, that even though such information would help to improve the accuracy of an evacuation model, there would still be uncertainty due to the many factors that can impact an evacuation.

It is also important to consider the impact that the features of the modelling software being used will have on the outcome of the model. VISSIM's default car following and lane changing sub-model parameters were used as information about evacuation specific driving behaviour could not be found. As the focus area of the study (cabin area) had only one lane in each direction, the lane changing model did not have a large impact on the overall evacuation and the speeds and driving behaviour was largely dictated by congestion for much of the key simulated scenarios. A software feature that did have a bigger impact on the simulations was how VISSIM generates the traffic at each of the origin parking lots. While the Poisson distribution model is one of the most commonly used distribution models in traffic modelling, it is not clear if such a distribution is representative of what would occur during an evacuation. The dynamic nature of the decision to evacuate and the sheer number of factors that can influence this decision (Chapter 2) make it difficult to use a standard response curve given that there is no real behavioural basis to justify their representation of evacuation departure times. Running multiple simulations to allow for stochastic variation within the simulations does allow for some variation in the time when evacuees depart, however, this does not address the fundamental issue with this distribution approach (in the context of evacuations). As with the assumptions discussed above, this model feature has the potential to impact network congestion and the total and individual evacuation times displayed in the simulations.

Another key consideration when simulating WUI evacuation is the sheer number of decisions made by an evacuee that can impact the outcome. In looking at the small section of the case study community modelled here, even with the number of assumptions/simplifications that were made, there are still numerous different routes that each of the 1530 – 3060 evacuating vehicles could take. Figure 4.21 below illustrates the number of decisions available at each of the primary intersections for the cabin area evacuees. This means that there are thousands of potential variations of what could happen just based on route choice and before accounting for community and highway traffic. While many of these alternatives can be eliminated based on their likelihood and the scenario being simulated (Ex. no intermediate trips into the community, all evacuees evacuating directly to the highway). In VISSIM, evacuee decisions are made by each vehicle prior to reaching an intersection where the software determines the best route to the vehicle's destination and assigns it to a route randomly using the Kirchhoff model for generalized costs. Depending on how familiar an evacuee was with the area and how well they were able to interpret the flow of traffic during the evacuation, the realism of this method used in the simulation will vary. As the network in the section of the community that was modelled has very few different options for evacuees leaving the cabin area, it is likely that this will not have a large impact on the overall evacuation. However, there are many more options for vehicles leaving the rest of the community, and as it was shown that community evacuees can have a large impact on the cabin area evacuees, variations in community vehicle travel paths could have a large effect on the overall evacuation (congestion and evacuation times). This would also depend on the amount of traffic coming from the community.

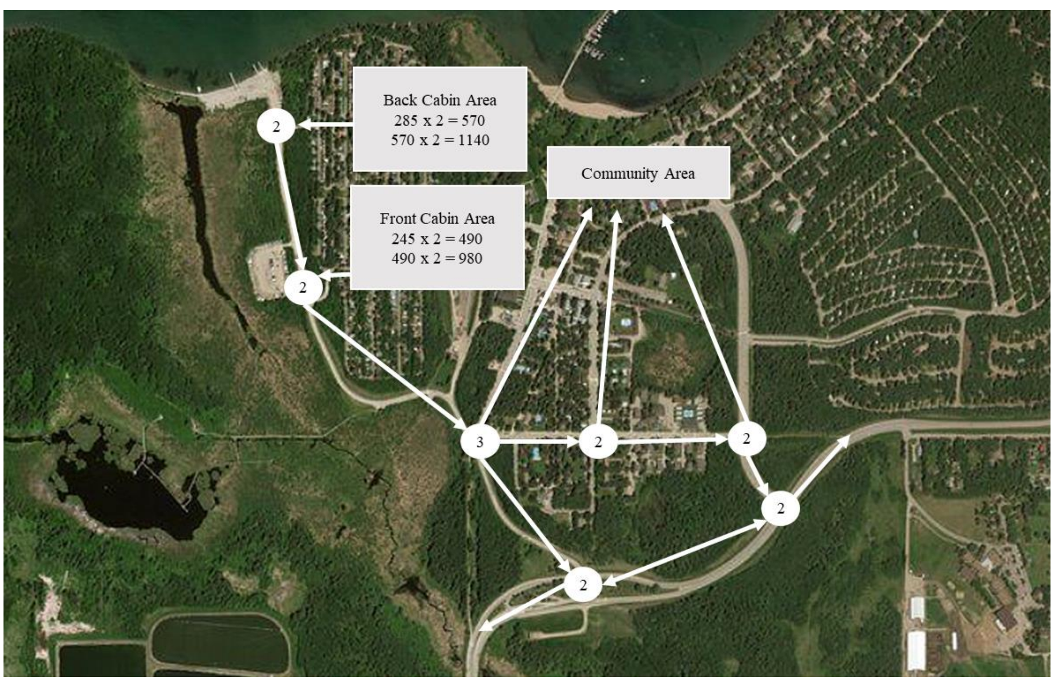

Figure 4.21: Number and location of potential evacuee decisions

4.4 Summary

The first-stage analysis of this seasonal, Canadian WUI case study community lays the groundwork for undertaking a more comprehensive vulnerability assessment of the community and for undertaking similar assessments of other threatened communities. The created survey, which is built on an extensive literature review of WUI and hurricane evacuation research, provides a means by which to collect important information from community members such that their protective actions can be better understood and used as variables in the assessment. The data collected from this survey will also help to fill a current gap in Canadian WUI research.

The evacuation scenarios modelled using VISSIM highlighted key scenarios and factors that contribute to longer evacuation times for the cabin area as well as provide insight into the type of information needed to model such evacuations. The more traffic in the network, whether from more evacuees or a shortened departure initiation timeframe, the more congestion and longer evacuation times were observed. The model showed the importance of considering the impact that the surrounding area will have on the focus area, the potential impact of assumptions related to traffic distribution and behaviour, and the role that the modelling software itself plays. This is important if an existing software is being used to model an evacuation or if one is being developed.

The results and discussion in this chapter, in combination with the bigger picture findings from earlier chapters, aids in the development of a framework for assessing WUI vulnerability. Such a framework will be critical for the successful and safe commercialization of WUI vulnerability assessments which are becoming of interest to many communities and engineering companies alike. This will be discussed further in the next chapter summarizing the work conducted and the work that needs to be done moving forward.

Chapter 5: Conclusion and Recommendations

5.1 Summary of Findings

Canadian science, technology and engineering are struggling to keep pace with the increasingly complex challenges posed by wildland fire, specifically in the WUI [8]. With Canadian wildfires and fire seasons continuing to grow and intensify, the need to improve the safety of the WUI is becoming increasingly important. Understanding how people behave in response to WUI fire threats and to the communication systems and emergency procedures set up to help them is critical if companies, agencies, researchers and governments want to be able to keep pace with and respond to the growing safety challenges in the WUI. In response to this, this thesis provides a framework for understanding how HBiF can impact the way people respond an react to WUI fires. It provides a foundation on which to build a comprehensive WUI community vulnerability assessment, as will be done in the next phase of this project.

Using a multifaceted approach, this thesis broke down the complexities of HBiF and their impact on key WUI evacuation processes into an accessible form that can more easily be understood and incorporated into fire safety engineering and emergency management. The literature review in Chapter 2 provided a detailed summary of the factors identified by wildfire and hurricane research to have an effect on protective action decision-making during such events. By organizing the factors according to the Protective Action Decision Model, a better understanding of how each stage of the decision-making process is impacted by a variety of factors, as well as which stages are more developed in this respect was obtained. Chapter 3 provided a more nuanced understanding of human behaviour in response to a specific factor, emergency alerts and information through an exploratory analysis of Canada's Alert Ready system. Chapter 4 built on the findings from Chapters 2 and 3 and laid the groundwork for a WUI vulnerability assessment of a Canadian case study community. A survey was developed to help fill a gap in Canadian WUI research and to understand the anticipated actions and the factors influencing protective action decision-making in seasonal Canadian WUI communities. In addition to identifying key congestion locations and congestion-inducing factors in the case study community, the evacuation scenarios modelled in VISSIM also created a baseline for future development of WUI evacuation models. The key findings from each research component in this thesis are detailed in the following sections.

5.1.1 Protective Action Decision-Making

There are many factors that can impact protective action decision-making including sociodemographic factors, social and environmental cues, preparation and experience, familial responsibilities, location, and credible threat and risk assessment. Within wildfire and hurricane literature, more factors have been identified to impact the protective action decision itself than have been for the pre-decision, risk assessment and credible threat stages of the PADM. Other research gaps identified include more nuanced information about gender and previous experience; interactions between factors (additive, subtractive, multiplicative); mediating factors; factors impacting specific pre-evacuation actions, route and destination choices; the time implications of the identified factors; data from additional countries; and the influence of changing WUI demographics and landscapes.

Depending on the circumstances and other factors at play, a single factor can have different impacts on protective action decision-making. For many factors such as previous experience and environmental cues, their impact ultimately depends on how they are internalized by an individual and whether they are seen to contribute to the level of personal danger perceived. The degree of trust that an individual has in a source will impact how they respond to the information it is providing about a threat.

5.1.2 Emergency Alerts and Communication

Though not a fire incident, the information-seeking behaviours and responses showcased in the analysis of Alert Ready's first official mobile alert provide insight into some of the challenges and considerations that need to be kept in mind when using mass notification systems. It highlighted the role that message relevance (geographical, urgency, new information, etc.) plays in people's perception of the necessity and usefulness of an alert. It showcased the challenge of providing timely, accurate and informative information while not annoying or desensitizing people with multiple alerts. It is therefore important that guidelines be in place to guide the development of emergency messages sent using the Alert Ready wireless system. While Canada does have general guidelines about the length of such messages, guidance on the actual content and structure of a message should also be provided. As Canada's wireless alerting system is quite new, looking to countries with more developed systems such as the United States provides a good first step.

The potential of wireless alerting systems such as Alert Ready and WEAs to be used for WUI fire and evacuation notification rests largely in their ability to reach very large and/or very specific groups of people in a short timeframe. In order for them to be a viable tool in WUI fire emergencies, the telecommunication systems that they rely on must be accessible and reliable. As many parts of the Canadian WUI do not currently have such infrastructure, having a multifaceted approach to emergency communication that is sensitive to the technological limitations of different areas is key. By continuing to develop wireless systems and including them as components in a holistic and diversified emergency communication system, the chances of reaching those most in need of information during a WUI fire increases.

5.1.3 First-Stage Canadian Case Study

The 10 evacuation scenarios modelled highlighted key scenarios and factors that are likely to contribute to longer evacuation times for the cabin area. The more traffic in the network, whether from more evacuees or a shortened departure initiation timeframe, the more congestion and longer evacuation times were observed. The greatest congestion is likely to occur at intersections where community and cabin area traffic interact, with the community traffic having a large impact on the total and individual evacuation times. This highlighted the importance of considering traffic from neighbouring areas even when the aim of a simulation is to analyze a particular area. When the network was congested, individual evacuation times were substantially longer for the front cabin area than the back cabin area as a result of the intersection right of way.

Assumptions relating to traffic distribution, network layout and driver behaviour can have a sizable impact on the outcome of a simulation. The limitations, sub-models and assumptions embedded in the simulation software also impact the model results and therefore they need to be considered when choosing (or designing) a software and their implications need to be understood when analyzing model outputs. Additionally, the larger and more intricate a network is, the more route choice decisions can be made by the simulated drivers. While uncertainty can be reduced by running a greater number of simulations and by making assumptions based on the specific evacuation scenario or knowledge about the actual community being modelled, it is important to recognize the complexity of modelling evacuation scenarios.

5.2 The Role of Research Findings in a Larger Canadian WUI Framework

The framework created herein for the use of human behaviour in WUI fires can help to fill in gaps within the current *Blueprint for Wildland Fire Science in Canada* [8]. Though the blueprint creates a business case for increasing WUI fire science funding, it could be strengthened by the incorporation of human behaviour, which impacts each of the six identified knowledge gaps and research themes to some degree.[21]

The first-stage conceptual model provides structure to the protective action decision-making process and the factors that impact each stage of this process. The model can help to guide researchers looking to collect such data (what factors are likely to have an effect, stages lacking data, etc.) globally and within Canada specifically. It acts as a first step towards creating a quantifiable model of human behaviour in WUI fires which is necessary for the creation of a comprehensive WUI evacuation model. Such a tool could be used by urban and emergency planners to assess the impact of new construction as well as make informed modifications to existing communities deemed to be at risk. First responder training could be updated to address the implications of such a conceptual model, enabling their interventions to be sensitive to expected resident responses. An understanding of resident response will allow authorities to better prepare guidance and allocate resources to meet the current population's expectations, vulnerabilities, and capabilities. Additionally, regulations regarding WUI safety can be updated to account for expected resident responses. Similarly, the analyzed responses to the Alert Ready system's official use over the past year can be used to help prompt more in-depth research in this area and to promote the development of more comprehensive guidance for the structure and content of messages sent out via the system.

The first-stage analysis of a seasonal Canadian WUI case study community has laid the groundwork for undertaking a more comprehensive vulnerability assessment of the community

[21] Themes: Understanding Fire in a Changing World, Recognizing Indigenous Knowledge, Building Resilient Communities and Infrastructure, Managing Ecosystems, Delivering Innovative Fire Management Solutions, and Reducing the Impacts of Wildland Fire on Canadians [8].

and for undertaking similar assessments of other threatened communities. Having a survey based on the findings of an extensive literature review provides a means by which to collect important information about Canadians' protective actions and decisions. It can be modified and distributed in multiple communities or act as a starting point for the development of new surveys which can be used to collect additional data and help fill a current gap in the country's wildfire research. The evacuation model created, and the scenarios simulated, help provide a baseline for more advanced evacuation models and provide insight into potential evacuation challenges within a specific case study community. It highlights some of the challenges of trying to represent human behaviour within traffic (and evacuation) models, as well as the impact that different factors can have on simulation results and the considerations that should be made as a result. This in turn can aid in the development of more comprehensive models as well as caution against using simulation tools without fully understanding their abilities and limitations.

5.3 Future Research and Recommendations

The framework for using human behaviour in fire to improve wildland urban interface evacuations presented in this thesis is a starting point from which further advancements can be made. It is the first step in filling a current gap in the Canadian WUI fire science, engineering and safety arena and contributes to expanding existing frameworks for WUI safety. The first-stage conceptual model presented in Chapter 2 can be further developed, quantified, calibrated and validated with additional data on protective action response from WUI fire events. This is necessary for the eventual creation of a computational simulation of WUI fire evacuations. The model can also be expanded to include information from new studies as they are made available (including Canadian studies) and possibly research from other disaster types or research written in languages other than English. With respect to emergency notification systems in Canada, further research looking at alarm and warning fatigue in natural disaster type situations, and WUI fires specifically, will aid in understanding if and how it presents itself and what factors combine to result in this response. In a Canadian specific context, cross-referencing the location of WUI communities with access to reliable cellular service could provide a better understanding of the potential impact of using Alert Ready wireless alerts for WUI fire notification. This in turn could be a factor considered in a comprehensive vulnerability index or assessment of Canadian WUI communities.

The next stage of the case study vulnerability assessment will involve piloting the survey and making modifications based on the feedback received. The survey distribution method will need to be decided based on the resources available, the occupancy of the cabin area, and the time constraints resulting from the seasonal nature of the community. This decision should therefore be made after the community dynamics are better understood, such as after a site visit and/or conversation with informed community partners. The data collected using this survey will not only help in the vulnerability assessment of this specific community, but it will also shed light on the protective actions and decisions of a type of Canadian community not previously studied.

With respect to evacuation modelling, additional scenarios and simulations could be run once more information about the community is known (from site visits, conversations with community partners, survey results, etc.). These could then be compared to the baseline created in this thesis to better understand the impact of additional information. If it was found in discussion with community partners that the addition of secondary egress routes for the cabin areas was still planned, simulations could be run which incorporate such routes (either to evaluate the impact of pre-determined route locations or evaluating the best location for such routes). A preliminary analysis of two alternative egress route locations can be found in Appendix C. This thesis has also highlighted the capabilities as well as the limitations of existing traffic software to represent human behaviour in fire. In order to accurately be able to represent evacuation decision-making and actions it is likely that a sub-model focused solely on this would be required.

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Appendix A: Case Study Community Survey

A.1 Cabin Information and Visits

1. Do you own or rent this cabin?

Sole Homeowner (or with partner)	◻
Shared Homeowner (extended family, friends, timeshare, etc.)	◻
Renter (permanent tenant, holiday rental, etc.)	◻

2. Number of years visiting this cabin?

0 – 5 years	◻
6 – 10 years	◻
11 – 15 years	◻
16 – 20 years	◻
More than 20 years	◻

3. How often do you visit this cabin?

0 – 2 times a year	◻
3 – 4 times a year	◻
5 – 6 times a year	◻
7 – 10 times a year	◻
More than 10 times a year	◻

4. What is the average length of single stay at the cabin?

1 – 2 days	◻
3 – 4 days	◻
5 – 7 days	◻
Between 1 week and 1 month	◻
Greater than 1 month	◻

5. Do you visit or stay at your cabin during the following months?

	Yes	No
Winter (December – February)	□	□
Spring (March – May)	□	□
Summer (June – August)	□	□
Fall (September – November)	□	□

6. During the last three years, have spent time at your cabin during the following holidays?

	Yes	No
Easter Long Weekend	□	□
Victoria Day Long Weekend	□	□
Canada Day Long Weekend	□	□
Labour Day Long Weekend	□	□
Thanksgiving Long Weekend	□	□

7. Are pets ever at your cabin when people are there?

Yes, 100% of the time	□
Yes, more than 70% of the time	□
Yes, 30% - 70% of the time	□
Yes, less than 30% of the time	□
Never	□

8. Does your cabin have a back-up generator?

Yes	□	No	□	Unsure	□

9. Do you have access to the following devices when you are at your cabin?

	Yes	No
Computer (laptop or desktop)	□	□
Tablet (iPad, Samsung Galaxy, etc.)	□	□
Mobile Phone	□	□
Radio	□	□
Television	□	□
Landline Phone	□	□

10. Do you have reliable access to these services at your cabin?

	More than 90% of the time	50 – 75% of the time	25 – 50% of the time	0 – 25% of the time	Do not have access
Electricity	□	□	□	□	□
Internet	□	□	□	□	□
Television	□	□	□	□	□
Radio	□	□	□	□	□
Cellular Service	□	□	□	□	□
Cellular Data	□	□	□	□	□
Water	□	□	□	□	□

11. How is your cabin heated?

Furnace (forced air)	□
Boiler (radiant heat)	□
Gas-Fired Space Heater	□
Electric Space Heater	□
Wood-Burning or Pellet Stove	□
Gas Fireplace	□
Wood Fireplace	□
Unsure what type	□

For Questions 12 – 14, answer based on the number of people who would be at your cabin on a normal visit (***typical visit***). For Questions 15 – 17, answer based on the greatest number of people who would be at your cabin (***busy visit***).

12. During a ***typical*** visit to your cabin:

	0	1	2	3	4	5	6	More than 6 **(please specify)**
Average number of people at cabin?	□	□	□	□	□	□	□	________
Average number of pets at cabin?	□	□	□	□	□	□	□	________
Average number of vehicles present at cabin? (cars, trucks)	□	□	□	□	□	□	□	________
Average number of vehicles parked elsewhere in community? (cars, trucks)	□	□	□	□	□	□	□	________
Average number of motorcycles?	□	□	□	□	□	□	□	________
Average number of all-terrain vehicles?	□	□	□	□	□	□	□	________
Average number of watercrafts? (motorized boats, seadoos, etc.)	□	□	□	□	□	□	□	________

13. During a ***typical*** visit to your cabin, how many people in each of the following age groups would be at the cabin?

Age Group	10 and younger	11-20	21-30	31-40	41-50	51-60	61-70	71-80	80 and older
Number of People	____	____	____	____	____	____	____	____	____

14. During a ***typical*** visit, who is present at the cabin?

	Yes	No
Immediate family members	□	□
Extended family members	□	□
Friends and/or acquaintances	□	□
Other **(please specify)** ______________________________	□	□

15. During a ***busy*** week/weekend visit:

	0	1	2	3	4	5	6	More than 6 **(please specify)**
Average number of people at cabin?	□	□	□	□	□	□	□	________
Average number of pets at cabin?	□	□	□	□	□	□	□	________
Average number of vehicles present at cabin? (cars, trucks)	□	□	□	□	□	□	□	________
Average number of vehicles parked elsewhere in community? (cars, trucks)	□	□	□	□	□	□	□	________
Average number of motorcycles?	□	□	□	□	□	□	□	________
Average number of all-terrain vehicles?	□	□	□	□	□	□	□	________
Average number of watercrafts? (motorized boats, seadoos, etc.)	□	□	□	□	□	□	□	________

16. During a ***busy*** visit to your cabin, how many people in each of the following age groups would be at the cabin?

Age Group	10 and younger	11-20	21-30	31-40	41-50	51-60	61-70	71-80	80 and older
Number of People	____	____	____	____	____	____	____	____	____

17. During a ***typical*** visit, who is present at the cabin?

	Yes	No
Immediate family members	□	□
Extended family members	□	□
Friends and/or acquaintances	□	□
Other **(please specify)** ______________________________	□	□

A.2 Previous Experience

18. Have you heard of the Alert Ready notification system?

Yes, I have heard about it and know what it is	◻
It sounds familiar, but I don't know what it is	◻
No, I have never heard about it	◻

19. Have you heard of the FireSmart Canada Program?

Yes, I have heard about it and know what it is	◻
It sounds familiar, but I don't know what it is	◻
No, I have never heard about it	◻

20. Have you or someone you know ever experienced any of the following (at primary residence, secondary residence, or a previous residence?)

	Yes, I have	Yes, someone I know has
Received an Alert Ready mobile test alert (not an emergency)	◻	◻
Received an Alert Ready mobile alert for an emergency (Amber Alert, flood warning, tornado warning, etc.)	◻	◻
Been on evacuation notice/stand-by due to wildfire	◻	◻
Been under a voluntary evacuation order due to wildfire	◻	◻
Been under a mandatory evacuation order due to wildfire	◻	◻
Lost personal property due to a wildfire	◻	◻
Been injured by a wildfire	◻	◻
Lost someone due to a wildfire	◻	◻

21. If you have received a wildfire evacuation order before:

	Yes	No	Non-Applicable
Did you evacuate under a *voluntary* evacuation order?	◻	◻	◻
Did you evacuate under a *mandatory* evacuation order?	◻	◻	◻
If you have evacuated due to a wildfire in the past, were you happy with your decision (after the fact)?	◻	◻	◻
If you chose not to evacuate during a wildfire in the past, were you happy with your decision (after the fact)?	◻	◻	◻

A.3 Warnings and Information Sources

22. Rank the following sources of information in the order that you would use them to seek information about a wildfire if you were at your cabin **(1 for first, 10 for last, NA if you would not use)**

Rank	Source
___	Friends/family members at the cabin with you
___	Other family/friends
___	Cabin neighbours
___	Radio
___	TV or internet news source (video, print)
___	Social media (Facebook, Twitter, YouTube, etc.)
___	Government website (Provincial government, Parks Canada, etc.)
___	Alert Ready mobile, radio or TV notification
___	Go outside (look for smoke, flames)
___	Police/Fire department

23. Is your answer to Question 22 influenced by not having access to certain services at your cabin? (computer, internet, cellular signal, etc.)

Yes	□	No	□

24. Would you expect to receive an official warning about a wildfire threatening your community? (Official Alert Ready notification via TV, Radio, or text; information from police or fire department, etc.)

Yes	□	No	□

25. Which of these sources would you classify as a trusted source for information about a wildfire?

	Very trustworthy	Trustworthy	Neutral	Untrustworthy	Very untrustworthy
Friends/family members at the cabin with you	◻	◻	◻	◻	◻
Neighbours	◻	◻	◻	◻	◻
Other family/friends (not present)	◻	◻	◻	◻	◻
Radio	◻	◻	◻	◻	◻
TV or internet news source (video, print)	◻	◻	◻	◻	◻
Social media (Facebook, Twitter, YouTube, etc.)	◻	◻	◻	◻	◻
Government website (Provincial Government, Parks Canada, etc.)	◻	◻	◻	◻	◻
Alert Ready mobile, radio or TV notification	◻	◻	◻	◻	◻
Your own observation of smoke, flames or embers	◻	◻	◻	◻	◻
Police/Fire department	◻	◻	◻	◻	◻

26. In general, how concerned are you that a wildfire could affect you one day?

Very, it is something that I think about often	◻
Somewhat, I think about it occasionally	◻
Not really, it has crossed my mind once or twice	◻
Not at all, it is not something I worry about	◻

27. How likely do you think that it is that a wildfire could impact your cabin community?

Very unlikely	◻
Unlikely	◻
Likely	◻
Very likely	◻
Haven't thought about it	◻

28. How would you classify the degree to which you have thought about wildfire planning?

Have not thought about what I would do if a wildfire occurred	□
Feel I should think about what to do, but haven't	□
Have thought about it but still deciding what I would do	□
Have thought about it and decided that I didn't need to do anything	□
Have decided what to do and are in the process of developing a plan	□
Have made a fire plan about what to do if a wildfire occurs	□
Other **(please specify)** ____	□

29. Do you think that wildfires are an issue:

	Yes	Somewhat	Neutral	Not Really	No
Globally?	□	□	□	□	□
In the United States?	□	□	□	□	□
In Canada?	□	□	□	□	□
In my province?	□	□	□	□	□
In my community?	□	□	□	□	□

30. Have you heard of these Canadian wildfires?

	Yes	No
Slave Lake Fire, Alberta, 2011	□	□
Fort McMurray, Alberta 2016	□	□
2017 British Columbia Wildfires	□	□
2018 British Columbia Wildfires	□	□
2018 Manitoba Wildfires	□	□

31. Have you heard of these international wildfires?

	Yes	No
Portugal 2017	□	□
Greece 2018	□	□
California 2017 (Thomas Fire, Tubbs, etc.)	□	□
California 2018 (Camp Fire, Woolsey Fire, etc.)	□	□

A.4 Expected Actions

32. What do you anticipate your response to a wildfire would be if you were at your cabin:

Stay and try to protect my property throughout the fire	□
Do as much as possible to protect my property but leave if threated by the fire	□
Wait to see what the fire is like before deciding whether to stay and defend or leave	□
Wait for police, fire or emergency services to tell me what to do	□
Leave as soon as I know there is a fire threatening my region	□
Leave as soon as I know there is a fire threatening my community	□
Would not be at my cabin because I intend to not be there at times of high fire danger	□
Other **(please specify)** ____	□

33. Do you anticipate that you would respond differently if a wildfire threatened your primary residence?

Yes, I would be more likely to try to defend my house	□
Yes, I would be more likely to wait and see	□
Yes, I would be more likely to evacuate	□
No, I would respond the same way	□

34. If you anticipate evacuating from your cabin in response to a wildfire threat, what would prompt you to evacuate?

	I would leave immediately	I would begin preparing to leave and then do so	I would begin preparing and then wait	I would seek more information before taking any action	It would have no effect
A day of high fire danger	□	□	□	□	□
Being told by relatives, friends or neighbours to leave	□	□	□	□	□
Seeing video footage and pictures of the fire on social media	□	□	□	□	□
Hearing about the fire on the news (TV, radio, internet)	□	□	□	□	□
Receiving a voluntary evacuation order	□	□	□	□	□
Receiving a mandatory evacuation order	□	□	□	□	□
Observing neighbours leaving	□	□	□	□	□
Being told by the police, firefighter or emergency services to leave	□	□	□	□	□
Seeing or smelling smoke	□	□	□	□	□
Seeing flames	□	□	□	□	□

35. How many vehicles do you anticipate you would use to evacuate?

1	□
2	□
3	□
More than 4	□

For Questions 36 and 37, answer based on the amount of time (minutes or hours) that you think you would spend on the listed actions in preparation for an evacuation from your cabin. For Question 36, answer based on the amount of time you would spend if you were thinking that you ***might*** evacuate (final decision not yet made), and answer Question 37 based the amount of time you would spend if you were ***going*** to evacuate (decision made).

36. If preparing to ***potentially evacuate***: How much time do you anticipate you would spend on the following pre-evacuation tasks? If you would not do the task or it does not apply to you, then write "0" as the estimated time.

Action	Estimated Time
Gather household members (people at cabin who you would evacuate with)	______
Gathering belongings to take with you	______
Loading belongings into vehicle/s	______
Secure cabin (turn off utilities, close windows, lock door, etc.)	______
Other **(please specify)** ____ ____ ____	______

37. If preparing to ***evacuate immediately***: How much time do you anticipate you would spend on the following pre-evacuation tasks? If you would not do the task or it does not apply to you, then write "0" as the estimated time.

Action	Estimated Time
Gather household members (people at cabin who you would evacuate with)	______
Gathering belongings to take with you	______
Loading belongings into vehicle/s	______
Secure cabin (turn off utilities, close windows, lock door, etc.)	______
Other **(please specify)** ____ ____ ____	______

38. If you plan to stay and defend during a wildfire threat, how confident do you feel that you'd be able to:

	Very confident	Confident	Neutral	Not very confident	Not confident at all
Do what is required to protect yourself and others?	◻	◻	◻	◻	◻
Do what is required to protect your cabin?	◻	◻	◻	◻	◻
Get help from other people? (Neighbours, friends, etc.)	◻	◻	◻	◻	◻
Get help from fire/emergency services?	◻	◻	◻	◻	◻

A.5 Household Information

39. What best describes your gender?

Female	◻
Male	◻
Prefer to self-describe:	◻
Prefer not to respond	◻

40. What is your age?

18 – 29 years old	◻
30 – 39 years old	◻
40 – 49 years old	◻
50 – 59 years old	◻
60 – 69 years old	◻
70 – 79 years old	◻
80 years and older	◻

41. Do you identify as an Indigenous person (First Nations (North American Indian), Métis or Inuk (Inuit))?

No, not an Indigenous person	◻
Yes, First Nations (North American Indian)	◻
Yes, Métis	◻
Yes, Inuk (Inuit)	◻

42. What language do you speak most often at home?

English	◻
French	◻
Other **(please specify)** ____	◻

43. Do you speak any other languages on a regular basis?

No	◻
Yes, English	◻
Yes, French	◻
Other **(please specify)** ____	◻

44. Do feel confident conducting a conversation in French and/or English?

English only	◻
French only	◻
Both French and English	◻
Neither English or French	◻

45. Do feel confident reading in French and/or English?

English only	◻
French only	◻
Both French and English	◻
Neither English or French	◻

46. Are there people in your household (people at the cabin with you) who would require assistance during an evacuation?

	Yes	No
Yes, infants or children	◻	◻
Yes, elderly person/s	◻	◻
Yes, person/s with a disability	◻	◻
Yes, ill person/s	◻	◻
Yes, other **(please specify)** ________________________________	◻	◻

47. Do you or does anyone in your household use a physical mobility aid?

No	◻
Yes, a motorized scooter	◻
Yes, a wheelchair	◻
Yes, a walker	◻
Yes, a cane	◻
Yes, service animal	◻
Yes, other **(please specify)** ______________________________________	◻

48. Do you work in any of the following industries?

Fire fighting	◻
Police service	◻
Forestry or forest management	◻
National or provincial parks	◻
Paper and pulp industry	◻
Emergency management	◻
None of the above	◻

49. Is the anything else that you would like us to know about your wildfire preparation, previous experience or expected actions?

Appendix B: Traffic Modelling Data

Table B.1: Location of Data Collection Points, Vehicle Travel Time Measurements and Queue Counters

Type	No.	Placement	Location
Data Collection Points	1	At Intersection	Back Cabin Area
	2		Front Cabin Area
	3		Cabin Area Access Road
	4		Highway Access West Road
	5		West/Southbound Highway Right Lane
	6		West/Southbound Highway Left Lane
	7		Eastbound Highway Left Lane
	8		Eastbond Highway Right Lane
	9		Highway Access East Right Lane
	10		Highway Access East Left Lane
Vehicle Travel Time Measurements	1	Between Intersections	Back Cabin Area - Front Cabin Area
	2		Front Cabin Area - 4Way Stop
	3		4Way Stop - Highway Access West
	4		3Way Intersection - Highway Access East
Queue Counter	1	At Intersection	Back Cabin Area
	2		Front Cabin Area
	3		4WaySub
	4		HighwayLeft
	5		HighwayRight
	7		Sub29_30
	8		Sub36_37
	9		Sub27_28
	10		Sub25_26
	11		Sub34_35
	12		Sub32_33
	13		Sub23_24
	14		Sub31
	15		Sub21_22
	16		Sub9_10
	17		Sub19_20
	18		Sub17_18
	19		Sub7_8
	20		Sub5_6
	21		Sub15_16
	22		Sub13_14
	23		Sub3_4
	24		Sub11_12
	25		Sub1_2

Table B.2: Scenario simulation information and total evacuation times

Scenario	Simulation Duration (s)	Simulation No.	Random Seed	Total Evacuation Time (min)	Average Total Evacuation Time (min)	Average Total Evacuation Time (hr)	Standard Deviation	95% Confidence Interval (min)
1	4200	1	10	65.50	65.69	1:05:41	0.6814	0.5972
		2	20	64.85				
		3	30	66.35				
		4	40	66.42				
		5	50	65.31				
2	4200	1	10	65.23	65.62	1:05:37	0.7941	0.6960
		2	20	64.79				
		3	30	66.53				
		4	40	66.42				
		5	50	65.14				
3	7700	1	10	121.31	121.47	2:01:28	0.8458	0.9571
		2	20	120.72				
		3	30	122.39				
4	7200	1	10	113.34	110.52	1:50:31	2.4528	2.7756
		3	30	108.85				
		5	50	109.38				
5	7700	1	10	124.70	123.68	2:03:41	0.8855	1.0020
		2	20	123.12				
		3	30	123.22				
6	11000	1	10	168.72	168.47	2:48:28	0.7740	0.8759
		2	20	167.60				
		3	30	169.09				
7	15000	1	10	235.33	239.29	3:59:17	3.8648	4.3734
		2	20	243.05				
		3	30	239.48				
8	15000	1	10	181.47	180.58	3:00:35	2.4902	2.8180
		2	20	182.50				
		3	30	177.77				
9	15000	1	10	244.54	243.97	4:03:58	0.5296	0.5993
		2	20	243.50				
		3	30	243.88				
10	15000	1	10	243.41	243.63	4:03:38	0.4327	0.4897
		2	20	244.13				
		3	30	243.35				

Table B.3: Aggregate average individual evacuation times

Scenario No.	Back Cabin Area	Front Cabin Area
1	0:05:25	0:04:55
2	0:05:36	0:05:06
3	0:26:01	0:53:22
4	0:18:43	0:21:20
5	0:04:41	0:04:05
6	0:18:02	0:46:46
7	0:33:13	1:35:52
8	0:16:57	0:16:20
9	0:04:42	0:04:08
10	0:03:51	0:03:15

Table B.4: Aggregate minimum individual evacuation times

Scenario No.	Back Cabin Area	Front Cabin Area
1	0:03:16	0:02:44
2	0:03:44	0:03:01
3	0:03:29	0:02:55
4	0:03:44	0:03:17
5	0:03:16	0:02:45
6	0:03:56	0:02:55
7	0:04:01	0:02:57
8	0:03:58	0:03:03
9	0:03:11	0:02:38
10	0:03:06	0:02:34

Table B.5: Aggregate median individual evacuation times

Scenario No.	Back Cabin Area	Front Cabin Area
1	0:05:29	0:05:02
2	0:05:34	0:05:07
3	0:28:26	1:03:29
4	0:15:53	0:16:58
5	0:04:33	0:03:56
6	0:19:35	0:39:48
7	0:32:21	1:57:26
8	0:15:35	0:15:19
9	0:04:31	0:03:57
10	0:03:50	0:03:11

Table B.6: Aggregate maximum individual evacuation times

Scenario No.	Back Cabin Area	Front Cabin Area
1	0:07:52	0:07:37
2	0:07:45	0:07:58
3	0:34:37	1:30:48
4	1:33:20	1:32:50
5	0:07:09	0:06:23
6	0:23:17	2:00:57
7	0:59:57	3:21:48
8	0:27:47	0:30:47
9	0:07:37	0:07:05
10	0:06:12	0:04:13

Table B.7: Maximum Queue Length and 95% Confidence Interval

		S1		S2		S3		S4		S5	
No	Intersection Name	Max Queue Length (m)	95% Conf. Interval (m)	Max Queue Length (m)	95% Conf. Interval (m)	Max Queue Length (m)	95% Conf. Interval (m)	Max Queue Length (m)	95% Conf. Interval (m)	Max Queue Length (m)	95% Conf. Interval (m)
1	Sub1_2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	Sub3_4	0.00	0.00	0.00	0.00	0.00	0.00	2.13	4.18	0.00	0.00
3	Sub5_6	0.00	0.00	0.00	0.00	1.95	3.82	1.95	3.82	2.31	4.52
4	Sub7_8	0.00	0.00	0.00	0.00	0.00	0.00	2.10	4.11	0.00	0.00
5	Sub9_10	1.47	2.88	0.00	0.00	2.54	4.99	7.19	7.90	0.00	0.00
6	Sub11_12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	Sub13_14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	Sub15_16	2.01	3.95	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	Sub17_18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	Sub19_20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11	Sub21_22	0.00	0.00	0.00	0.00	29.96	12.74	0.00	0.00	0.00	0.00
12	Sub23_24	0.00	0.00	0.00	0.00	52.68	28.39	6.62	12.98	0.00	0.00
13	Sub25_26	0.00	0.00	0.00	0.00	139.03	27.79	80.14	10.46	0.00	0.00
14	Sub27_28	1.11	2.17	0.00	0.00	20.14	22.47	14.44	16.23	0.00	0.00
15	Sub29_30	0.00	0.00	0.00	0.00	141.32	17.61	11.18	11.17	0.00	0.00
16	Sub31	0.00	0.00	0.00	0.00	38.52	12.69	5.07	9.94	0.00	0.00
17	Sub32_33	0.00	0.00	0.00	0.00	96.10	19.37	39.00	39.30	0.00	0.00
18	Sub34_35	0.00	0.00	0.00	0.00	88.55	9.89	13.50	4.13	0.00	0.00
19	Sub36_37	1.97	3.87	1.96	3.85	123.26	49.04	69.20	15.92	0.00	0.00
20	BackSub	36.63	5.40	36.27	5.42	37.28	3.65	45.24	23.47	21.72	4.35
21	FrontSub	53.90	10.11	54.70	16.33	258.29	0.45	245.76	12.18	18.07	1.00
22	4WaySub	250.73	17.13	227.03	13.47	763.49	6.63	509.23	17.91	30.41	0.34
23	HighwayLeft	13.07	0.11	12.14	0.33	800.91	0.01	419.64	11.59	168.00	40.72
25	HighwayRight	0.00	0.00	11.54	0.41	259.35	35.60	432.62	0.02	65.09	17.84

Table B.7: Maximum Queue Length and 95% Confidence Interval (continued)

		S6		S7		S8		S9		S10	
No	Intersection Name	Max Queue Length (m)	95% Conf. Interval (m)	Max Queue Length (m)	95% Conf. Interval (m)	Max Queue Length (m)	95% Conf. Interval (m)	Max Queue Length (m)	95% Conf. Interval (m)	Max Queue Length (m)	95% Conf. Interval (m)
1	Sub1_2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	Sub3_4	1.80	3.53	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	Sub5_6	4.34	4.26	17.29	10.07	0.00	0.00	0.00	0.00	0.00	0.00
4	Sub7_8	0.00	0.00	11.54	12.70	0.00	0.00	1.83	3.58	0.00	0.00
5	Sub9_10	0.00	0.00	79.12	59.03	1.80	3.53	1.65	3.23	2.47	4.84
6	Sub11_12	0.00	0.00	5.07	9.95	0.00	0.00	0.00	0.00	0.00	0.00
7	Sub13_14	0.00	0.00	22.18	22.14	0.00	0.00	0.00	0.00	0.00	0.00
8	Sub15_16	0.00	0.00	15.26	20.70	0.00	0.00	0.00	0.00	0.00	0.00
9	Sub17_18	0.00	0.00	3.48	6.83	0.00	0.00	0.00	0.00	0.00	0.00
10	Sub19_20	3.34	6.55	18.86	7.54	0.00	0.00	0.00	0.00	0.00	0.00
11	Sub21_22	49.77	20.29	72.46	19.60	0.00	0.00	0.00	0.00	0.00	0.00
12	Sub23_24	140.13	21.16	141.43	7.00	0.00	0.00	0.00	0.00	0.00	0.00
13	Sub25_26	214.10	33.24	216.04	47.95	0.00	0.00	0.00	0.00	0.00	0.00
14	Sub27_28	38.22	18.83	112.65	5.79	1.69	3.31	0.00	0.00	0.00	0.00
15	Sub29_30	64.62	38.37	160.31	16.77	0.00	0.00	0.00	0.00	0.00	0.00
16	Sub31	80.83	29.37	95.60	0.28	0.00	0.00	0.00	0.00	0.00	0.00
17	Sub32_33	160.14	51.14	185.05	0.24	0.00	0.00	0.00	0.00	0.00	0.00
18	Sub34_35	112.92	15.33	111.44	14.26	0.00	0.00	0.00	0.00	0.00	0.00
19	Sub36_37	201.86	26.61	217.90	24.73	0.00	0.00	0.00	0.00	0.00	0.00
20	BackSub	63.46	15.40	223.81	76.14	28.89	15.10	22.80	3.14	17.19	3.83
21	FrontSub	258.67	0.09	258.68	0.31	36.15	22.63	29.83	4.42	12.57	0.49
22	4WaySub	589.67	32.70	823.61	0.00	470.97	37.53	43.18	6.15	22.11	5.29
23	HighwayLeft	388.19	9.09	986.13	0.00	986.12	0.01	215.83	49.23	44.45	2.30
25	HighwayRight	105.99	52.30	432.50	0.14	432.61	0.03	51.34	6.23	29.48	4.41

Appendix C: Modelling Additional Cabin Area Egress Routes

To begin the process assessing the impact of network design modifications, two alternative cabin area egress routes were modelled for the case study community. The same assumptions and modelling approach as those detailed in Chapter 4 were used. Figures C.1 and C.2 show the location of the two additional roads. The first road (extra back cabin area road) connects the back cabin area to a parking lot access road. This road currently exists within the community however it is not in use. As noted in the community plan, there is the potential to turn this road into an emergency egress route for use in the case of an evacuation. The second road (extra cabin area highway access road) connects the main cabin area road directly to the highway. As this road does not exist, its location is arbitrary, however the southern most part of the road was made to follow an existing walking path.

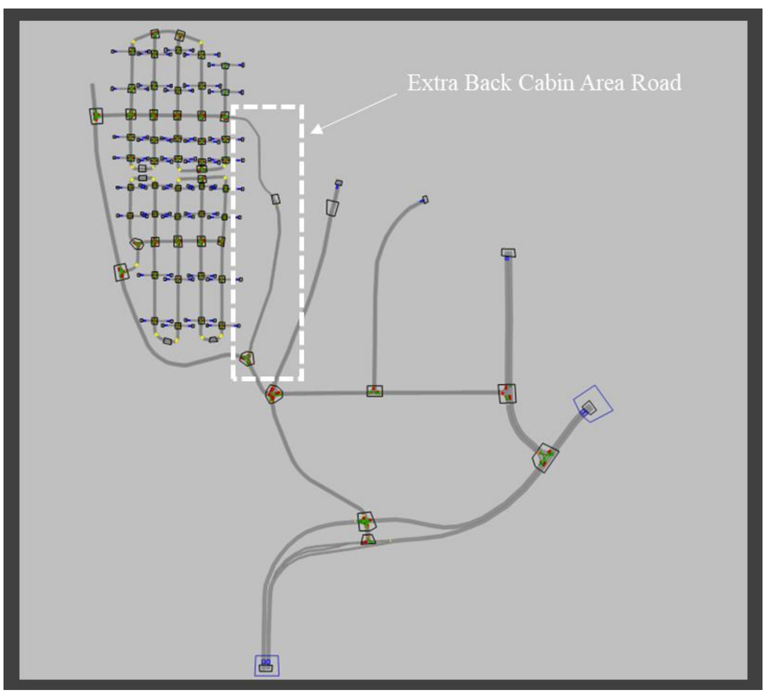

Figure C.1: Location of Extra Back Cabin Area Road

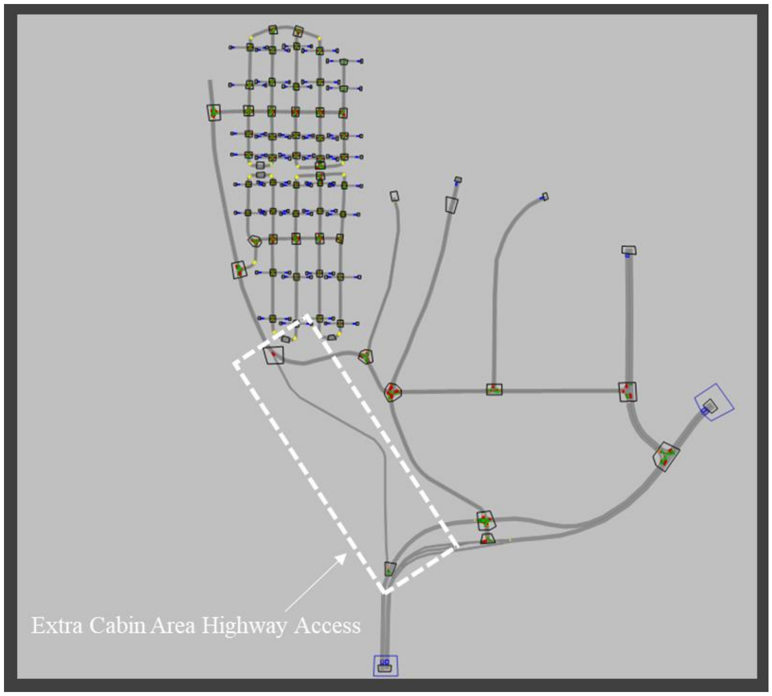

Figure C.2: Location of Extra Cabin Area Highway Access Road

Scenarios 3 and 7 were modelled for each of the modified networks as these were identified as the worst-case scenarios in the previous analysis (Table C.1). As with this analysis, the total and individual evacuation times were compared along with the queue lengths. Each scenario was run three error-free times.[22] Table C.2 identifies the expected total evacuation times and Figure C.3 depicts the average total evacuation time for each scenario in relation to the corresponding departure initiation timeframe (see Table C.3 for the total evacuation times and 95% confidence intervals for each simulation run). Figures C.4 – C.7 illustrate the average, median, minimum and maximum individual evacuation times for the front and back cabin areas in each scenario, as well as the 5-number summary (see Tables C.4 – C.7 for the corresponding data). Figures C.8 – C.10 show the measured queue lengths within the network and Table C.8 depicts the corresponding data and 95% confidence intervals.

[22] The extra cabin area highway access road for the Scenario 3 was run a total of 4 times as one run resulted in an error due to a vehicle being removed from the network after waiting 60 seconds for a lane change.

The most notable findings are as follows:

- The addition of the extra back cabin area road had no impact on the total evacuation time whereas the addition of the extra cabin area highway access road decreased the total evacuation time by nearly 45 minutes for Scenario 3 and nearly 1.5 hours for Scenario 7.
- The extra back cabin area road increased the maximum individual evacuation time for the back cabin area, but otherwise had a minimal impact. The extra cabin area highway access road substantially reduced the individual evacuation times for both the front and back cabin areas in Scenario 3 and Scenario 7 (less than 25 minutes in both cases).
- The extra cabin area highway access road substantially reduced the queue length at the 4-way intersection. The queue length was reduced from 760m (base case) to 130m for Scenario 3, and from 820m (base case) to 400m for Scenario 7.

Though preliminary, this analysis showcased that the location of additional egress routes is critical in their effectiveness and should therefore be considered carefully.

Table C.1: Modelled evacuation scenario descriptions and number of error-free simulations run

Scenario No.	Description	Number of Simulations Run
3 - Base Case	1 car per cabin (530) 1-hour departure window South-West evacuation 1000 cars from community	3
3 - Extra Back Cabin Area Road	1 car per cabin (530) 1-hour departure window South-West evacuation 1000 cars from community	3
3 - Extra Cabin Area Highway Access Road	1 car per cabin (530) 1-hour departure window South-West evacuation 1000 cars from community	3*
7 - Base Case	2 car per cabin (1060) 2-hour departure window South-West evacuation 2000 cars from community	3
7 - Extra Back Cabin Area Road	2 car per cabin (1060) 2-hour departure window South-West evacuation 2000 cars from community	3
7 - Extra Cabin Area Highway Access Road	2 car per cabin (1060) 2-hour departure window South-West evacuation 2000 cars from community	3

Table C.2: Expected average total evacuation times

Scenario	95% Confidence Expected Total Evacuation Time Range (hr)
3 - BC	2:00:31 - 2:02:26
3 - EBCAR	2:00:41 - 2:02:03
3 - ECAHAR	1:18:13 - 1:25:52
7 - BC	3:54:55 - 4:03:40
7 - EBCAR	3:58:32 - 4:02:45
7 - ECAHAR	2:40:38 - 2:44:29

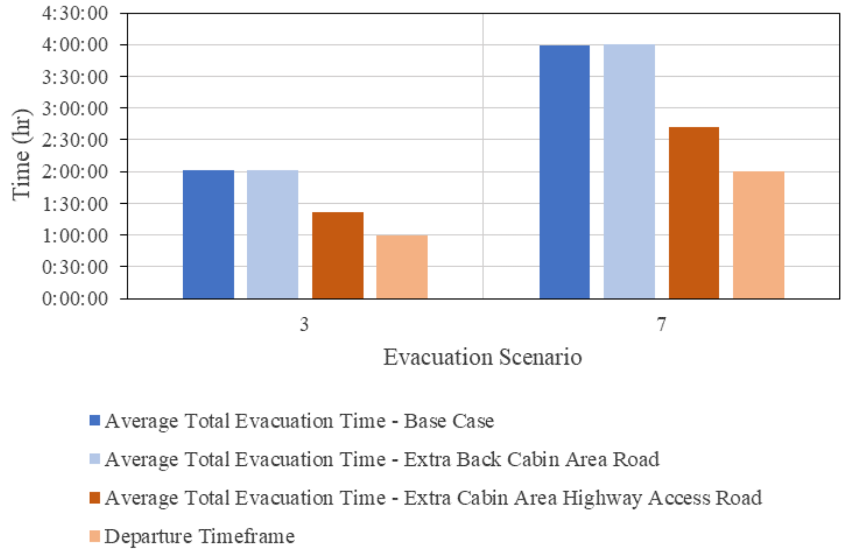

Figure C.3: Total evacuation time and departure timeframes

Table C.3: Scenario simulation information and total evacuation times

Scenario	Simulation Duration (s)	Simulation No.	Random Seed	Total Evacuation Time (min)	Average Total Evacuation Time (min)	Average Total Evacuation Time (hr)	Standard Deviation	95% Confidence Interval (min)
3 Base Case	7700	1	10	121.3125	121.473	2:01:28	0.84575	0.957056
		2	20	120.719				
		3	30	122.3875				
3 Extra Back Cabin Area Road	7700	1	10	121.5543	121.3614	2:01:22	0.602776	0.682105
		2	20	120.6858				
		3	30	121.8442				
3 Extra Cabin Area Highway Access Road	7700	2	20	84.10583	82.04317	1:22:03	3.382066	3.827168
		3	30	83.88367				
		4	40	78.14				
7 Base Case	15000	1	10	235.3257	239.2856	3:59:17	3.864802	4.373435
		2	20	243.0477				
		3	30	239.4835				
7 Extra Back Cabin Area Road	15000	1	10	240.3033	240.6421	4:00:39	1.86094	2.105852
		2	20	242.6492				
		3	30	238.9738				
7 Extra Cabin Area Highway Access Road	15000	1	10	160.7667	162.5557	2:42:33	1.700468	1.92426
		2	20	164.151				
		3	30	162.7495				

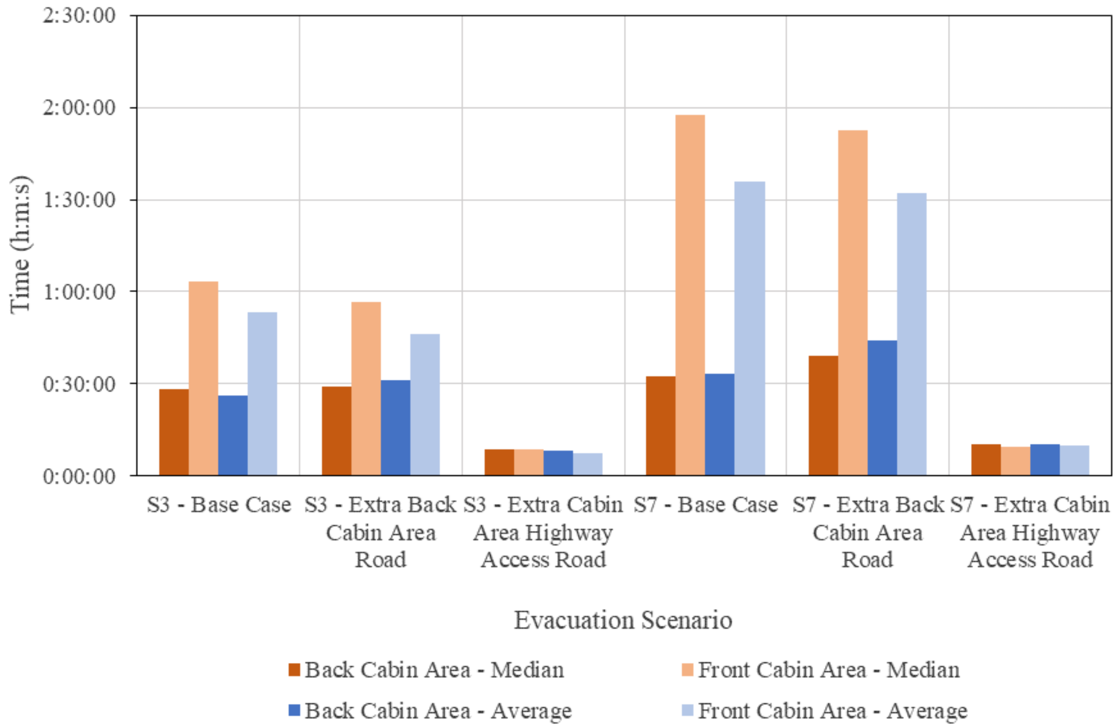

Figure C.4: Aggregate average and median individual evacuation times

Table C.4: Aggregate average individual evacuation times

Scenario No.	Back Cabin Area	Front Cabin Area
3 – Base Case	0:26:01	0:53:22
3 – Extra Back Cabin Area Road	0:31:16	0:46:24
3 – Extra Cabin Area Highway Access Road	0:08:26	0:07:27
7 – Base Case	0:33:13	1:35:52
7 – Extra Back Cabin Area Road	0:44:09	1:32:12
7 – Extra Cabin Area Highway Access Road	0:10:34	0:10:06

Table C.5: Aggregate median individual evacuation times

Scenario No.	Back Cabin Area	Front Cabin Area
3 – Base Case	0:28:26	1:03:29
3 – Extra Back Cabin Area Road	0:28:58	0:56:43
3 – Extra Cabin Area Highway Access Road	0:08:55	0:08:30
7 – Base Case	0:32:21	1:57:26
7 – Extra Back Cabin Area Road	0:39:11	1:52:42
7 – Extra Cabin Area Highway Access Road	0:10:16	0:09:43

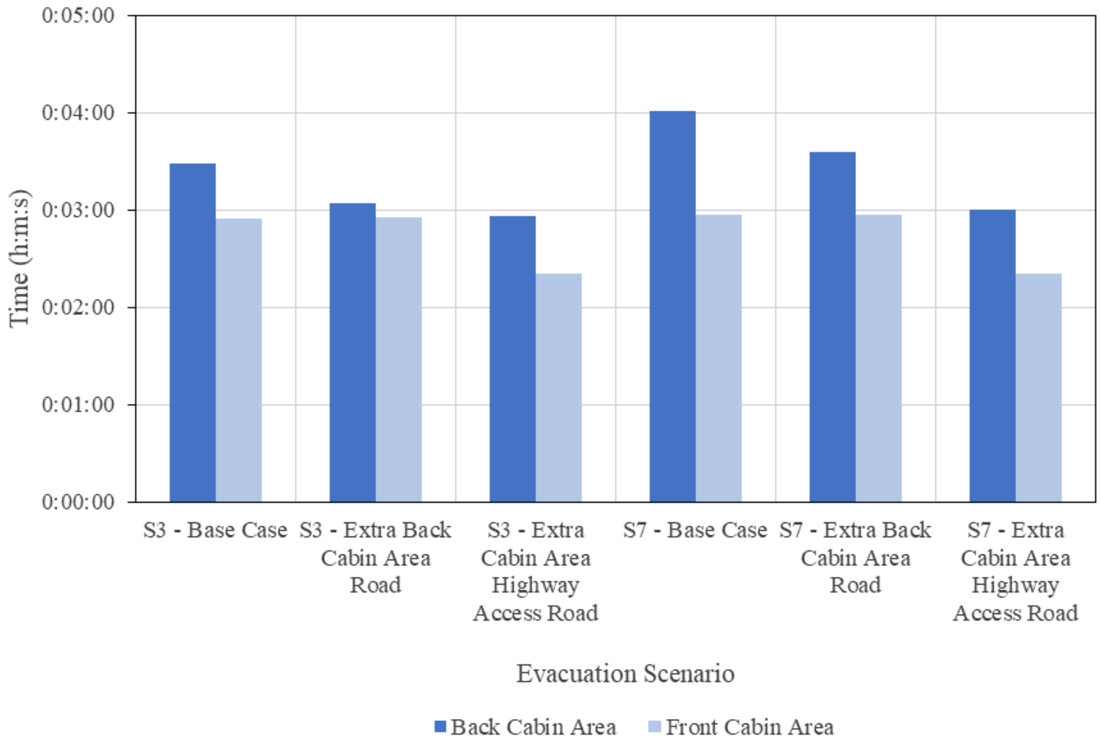

Figure C.5: Aggregate minimum individual evacuation times

Table C.6: Aggregate minimum individual evacuation times

Scenario No.	Back Cabin Area	Front Cabin Area
3 – Base Case	0:03:29	0:02:55
3 – Extra Back Cabin Area Road	0:03:04	0:02:55
3 – Extra Cabin Area Highway Access Road	0:02:56	0:02:20
7 – Base Case	0:04:01	0:02:57
7 – Extra Back Cabin Area Road	0:03:36	0:02:57
7 – Extra Cabin Area Highway Access Road	0:03:00	0:02:21

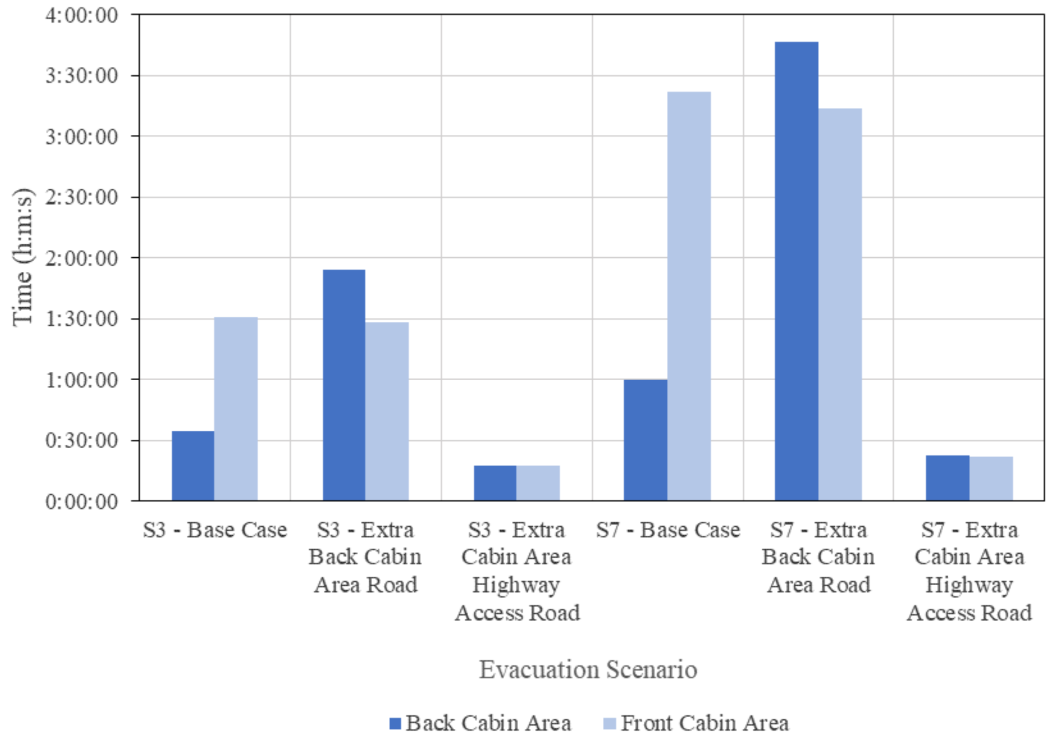

Figure C.6: Aggregate maximum individual evacuation times

Table C.7 Aggregate maximum individual evacuation times

Scenario No.	Back Cabin Area	Front Cabin Area
3 – Base Case	0:34:37	1:30:48
3 – Extra Back Cabin Area Road	1:54:12	1:28:16
3 – Extra Cabin Area Highway Access Road	0:17:34	0:17:41
7 – Base Case	0:59:57	3:21:48
7 – Extra Back Cabin Area Road	3:46:43	3:13:33
7 – Extra Cabin Area Highway Access Road	0:22:27	0:21:54

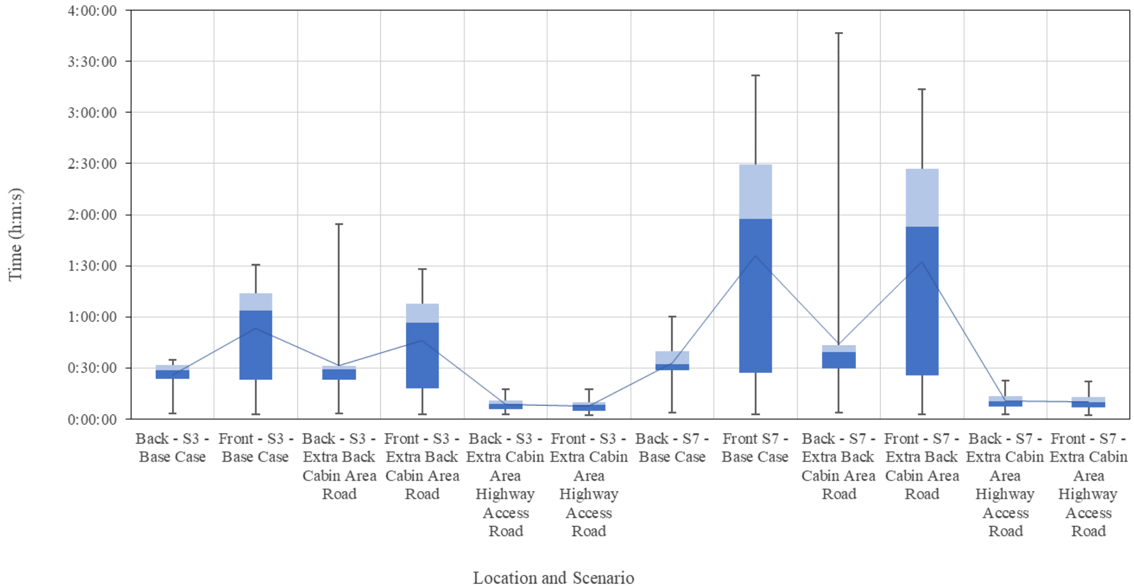

Figure C.7: Five number summary (minimum, 1st quartile, median, 3rd quartile, maximum) and average for the front and back cabin areas in each scenario

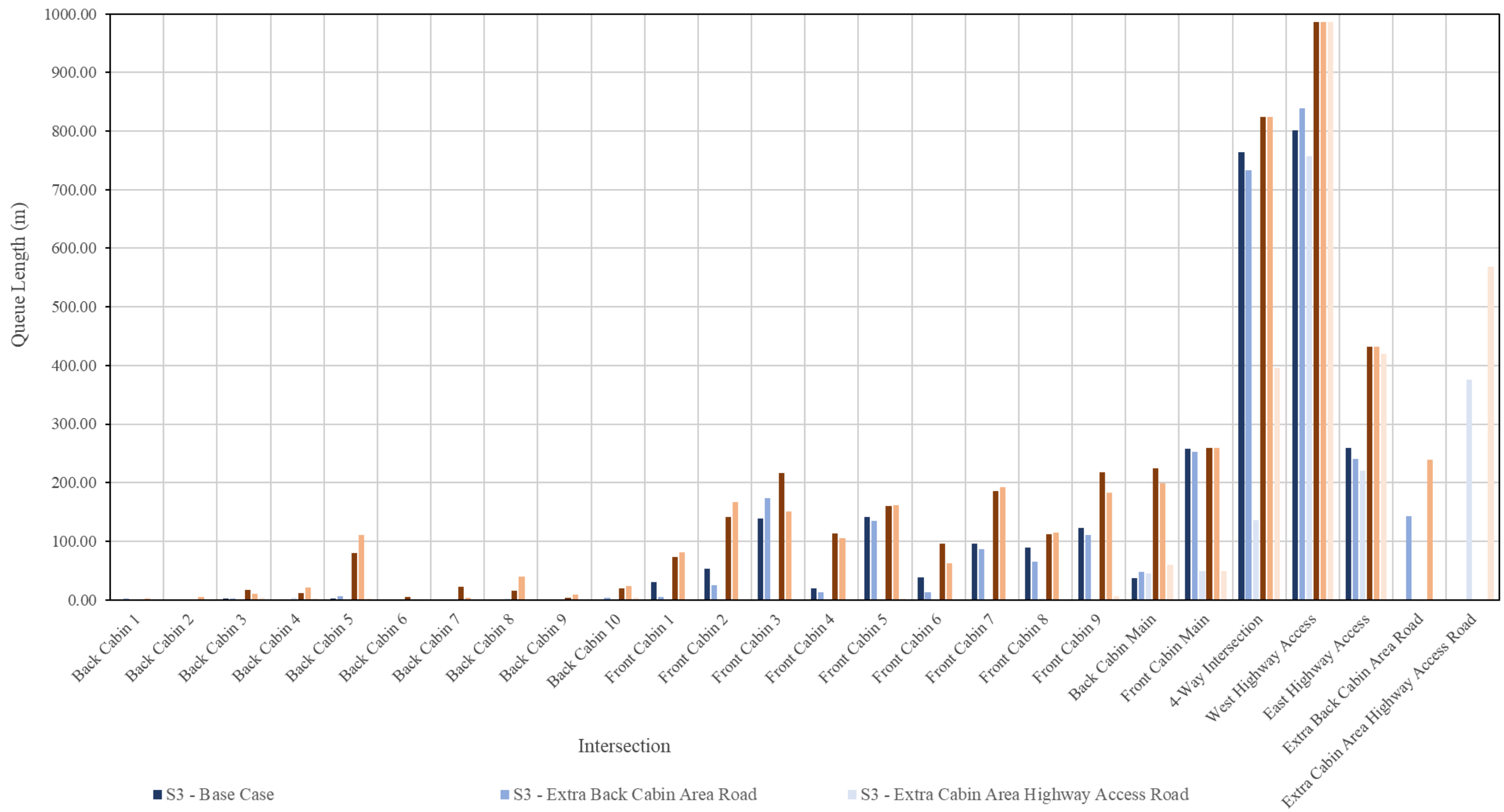

Figure C.8: Maximum queue lengths for all primary intersections

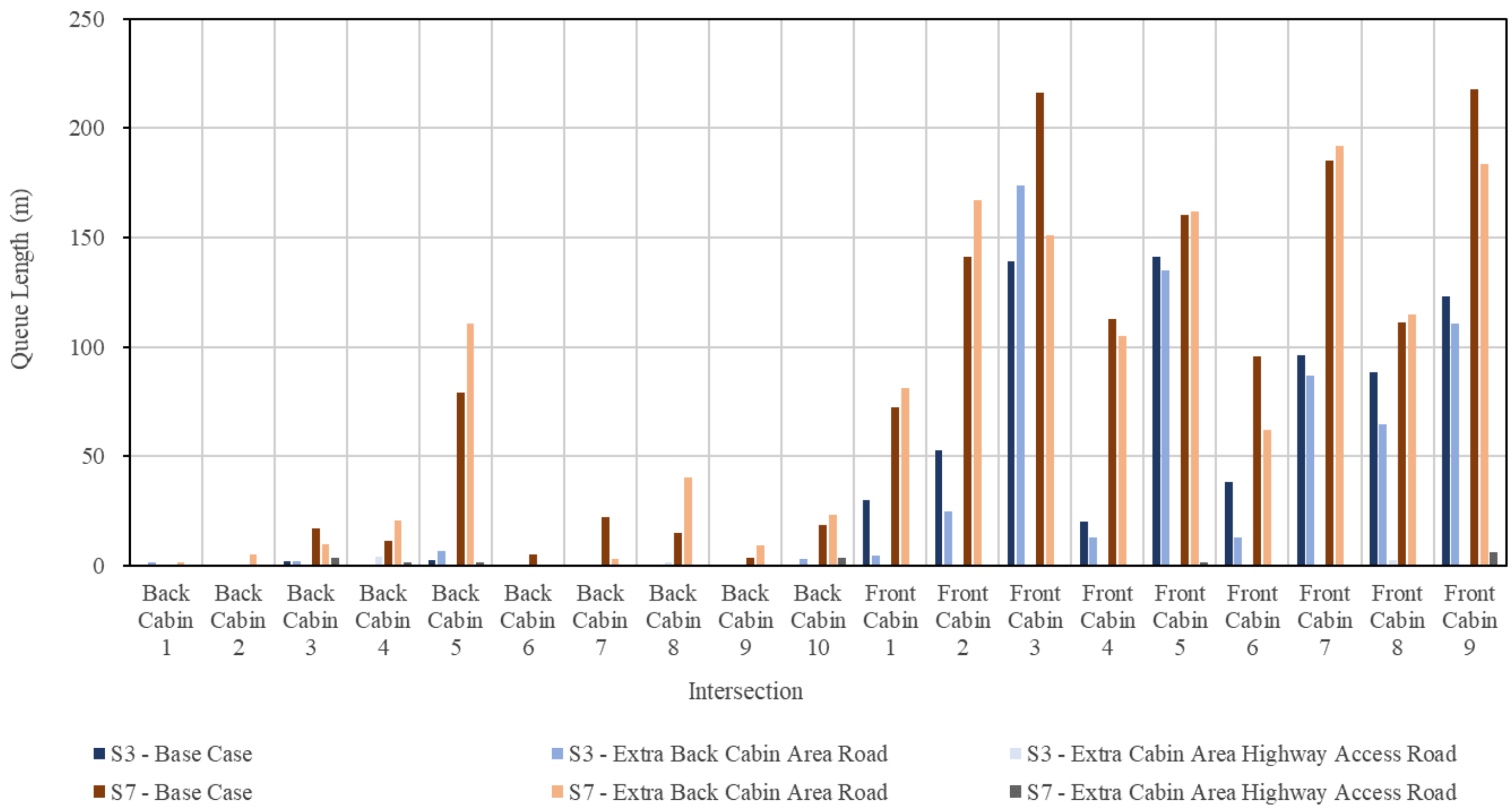

Figure C.9: Maximum queue lengths for intersections within the cabin area

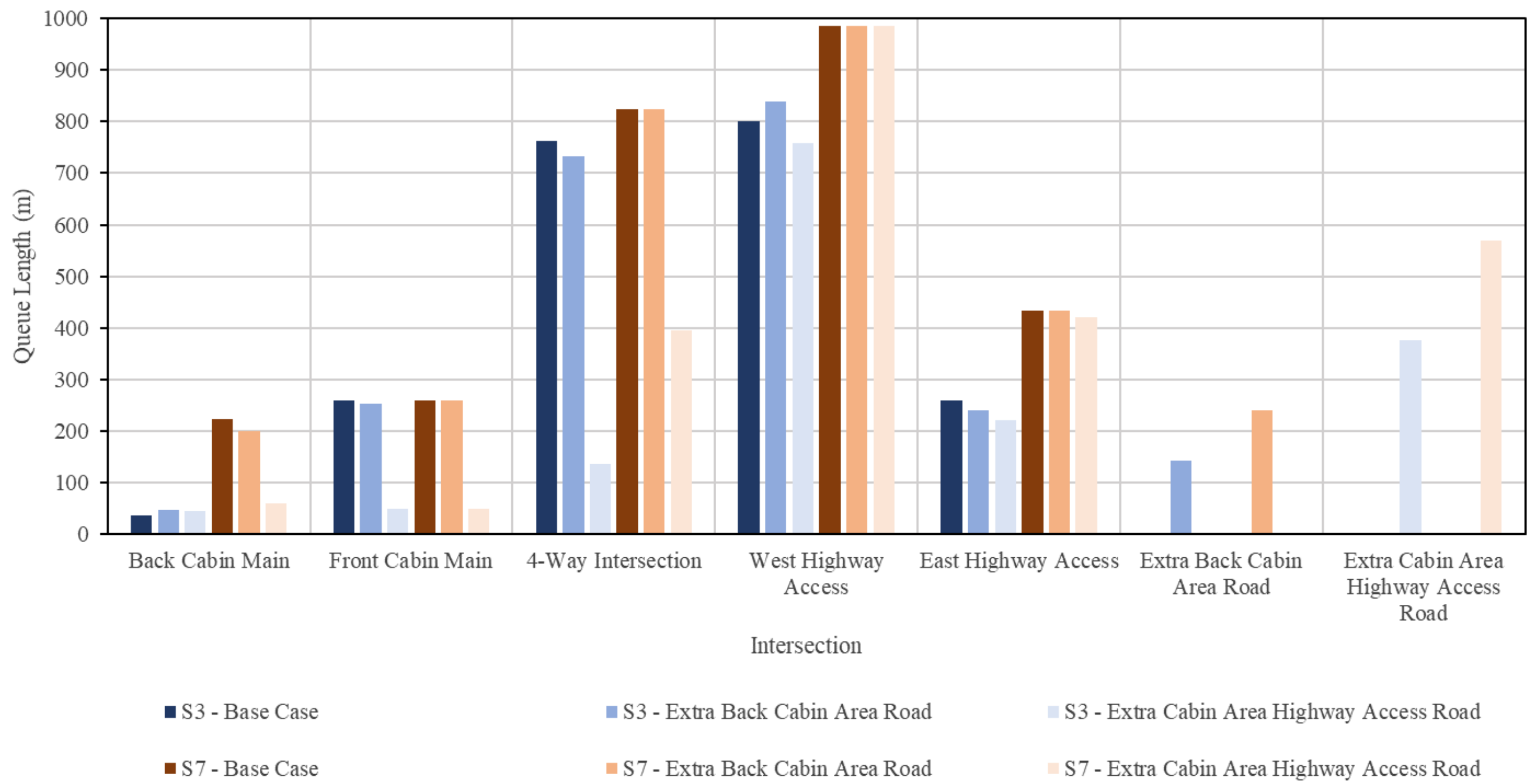

Figure C.10: Maximum queue lengths for main network intersections

Table C.8: Maximum Queue Length and 95% Confidence Interval

		S3 – Base Case		S3 – Extra Back Cabin Area Road		S3 – Extra Cabin Area Highway Access Road		S7 – Base Case		S7 – Extra Back Cabin Area Road		S7 – Extra Cabin Area Highway Access Road	
No	**Location**	**Max Queue (m)**	**95% Conf. Inter. (m)**	**Max Queue Length (m)**	**95% Conf. Inter. (m)**	**Max Queue Length (m)**	**95% Conf. Inter. (m)**	**Max Queue Length (m)**	**95% Conf. Inter. (m)**	**Max Queue Length (m)**	**95% Conf. Inter. (m)**	**Max Queue Length (m)**	**95% Conf. Inter. (m)**
1	Sub1_2	0.00	0.00	1.60	3.13	0.00	0.00	0.00	0.00	1.46	2.86	0.00	0.00
2	Sub3_4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	5.34	10.47	0.00	0.00
3	Sub5_6	1.95	3.82	2.01	3.94	0.00	0.00	17.29	10.07	10.10	4.87	3.87	3.87
4	Sub7_8	0.00	0.00	0.00	0.00	3.98	7.80	11.54	12.70	20.95	6.62	1.58	3.10
5	Sub9_10	2.54	4.99	6.70	0.16	0.00	0.00	79.12	59.03	110.62	34.62	1.80	3.53
6	Sub11_12	0.00	0.00	0.00	0.00	0.00	0.00	5.07	9.95	0.00	0.00	0.00	0.00
7	Sub13_14	0.00	0.00	0.00	0.00	0.00	0.00	22.18	22.14	3.29	6.44	0.00	0.00
8	Sub15_16	0.00	0.00	0.00	0.00	1.57	3.08	15.26	20.70	40.18	24.54	0.00	0.00
9	Sub17_18	0.00	0.00	0.00	0.00	0.00	0.00	3.48	6.83	9.40	10.23	0.00	0.00
10	Sub19_20	0.00	0.00	3.10	6.08	0.00	0.00	18.86	7.54	23.16	7.94	3.66	7.17
11	Sub21_22	29.96	12.74	4.68	4.63	0.00	0.00	72.46	19.60	81.18	47.56	0.00	0.00
12	Sub23_24	52.68	28.39	25.11	20.01	0.00	0.00	141.43	7.00	166.96	46.68	0.00	0.00
13	Sub25_26	139.03	27.79	174.02	38.58	0.00	0.00	216.04	47.95	151.27	8.00	0.00	0.00
14	Sub27_28	20.14	22.47	13.02	15.08	0.00	0.00	112.65	5.79	105.04	26.26	0.00	0.00
15	Sub29_30	141.32	17.61	135.25	27.83	0.00	0.00	160.31	16.77	161.85	7.39	1.54	3.02
16	Sub31	38.52	12.69	13.01	16.79	0.00	0.00	95.60	0.28	62.12	2.76	0.00	0.00
17	Sub32_33	96.10	19.37	86.77	2.19	0.00	0.00	185.05	0.24	191.83	13.44	0.00	0.00
18	Sub34_35	88.55	9.89	64.90	28.13	2.64	5.17	111.44	14.26	114.78	4.54	0.00	0.00
19	Sub36_37	123.26	49.04	110.95	14.59	0.00	0.00	217.90	24.73	183.51	35.82	6.15	6.03
20	Back Cabin Area Access	37.28	3.65	47.88	25.04	44.57	4.62	223.81	76.14	199.27	26.32	60.03	23.99
21	Front Cabin Area Access	258.29	0.45	252.03	12.50	48.72	9.54	258.68	0.31	258.53	0.34	49.54	11.89
22	4WaySub	763.49	6.63	732.85	35.77	135.51	68.69	823.61	0.00	823.61	0.00	395.81	75.06
23	Highway Access Left	800.91	0.01	838.75	74.16	757.63	52.49	986.13	0.00	986.12	0.01	986.11	0.02
25	Highway Access Right	259.35	35.60	239.90	28.40	220.27	25.54	432.50	0.14	432.56	0.11	420.04	24.52
26	Extra Back Cabin Area Road	0	0	142.7	18.2	0	0	0	0	239.3	69.153	0	0
27	Extra Highway Access	0	0	0	0	376.2	46.138	0	0	0	0	568.7	179.66

Appendix D: A Provisional Conceptual Model of Human Behaviour in Response to Wildland Urban Interface Fires

D.1 Abstract

With more frequent and destructive wildfires occurring in the growing wildland urban interface (WUI), the ability to ensure the safe evacuation of potentially large groups of people is of increasing importance. This is a challenging task made only more difficult by the fact that there is often little warning and that evacuations often need to take place in a short period of time. The creation of credible and effective evacuation models is needed within the fire safety engineering community to help address this challenge. Although potentially difficult to represent, a critical component in developing such models is the consideration of what people will do in response to a WUI fire. In this literature review, research relating to WUI fire evacuations was collected to identify the factors that influence protective action decision-making and response during these events, specifically whether someone chooses to evacuate or not. To supplement the findings, related hurricane evacuation literature was also reviewed for such factors. The factors that were identified relate to sociodemographic factors, social and environmental cues, preparation and experience, familial responsibilities, location, and credible threat and risk assessment. These factors were organized according to the Protective Action Decision Model (PADM) to create a conceptual model of protective action decision-making. This is the first step in being able to incorporate such factors and their corresponding impact on public response into comprehensive WUI evacuation models.

D.2 Introduction and Purpose

The danger posed by wildfires and the damage they can cause are issues of growing global concern. Environmental changes such as warmer temperatures, increased drought and earlier snowmelt are contributing to an increased wildfire threat and a longer fire season [1]–[3]. The increasing likelihood of more extreme weather as a result of climate change is also playing a role in the growth of wildfire potential [2]. In some countries, previous fire management strategies with a focus on complete fire suppression have led to a build-up of fuels which contribute to the increased risk of wildfire [1], [4]. As the number of large wildfires continues to increase in many parts of the world as a result of these factors, the degree of destruction these fires can cause is intensified by changes in land use and socioeconomics [5].

A growing proportion of these wildfires threaten communities living nearby or within the wildlands, known as the wildland urban interface or the ‘‘WUI’’. WUI communities exist ‘‘where humans and their development meet or intermix with wildland fuel’’ [6] and as such, the WUI is a complex area comprised of diverse groups of people and geographical areas. It includes both intermix and interface communities, with varying densities, levels of remoteness, and interaction with the wildland [7]. Intermix communities include areas where wildland vegetation and housing intermingle, and interface communities are those that are in close vicinity to areas of large, dense wildland vegetation [8]. Given their proximity to the wildland, WUI communities are generally the most vulnerable to wildfires and the subsequent property damage and physical, social, environmental, and psychological impacts as a result [8]. In addition, other vulnerabilities such as fewer and more dangerous egress routes and a lack of easily accessible firefighting resources contribute to the additional challenges faced by WUI communities [9].

The 2016 Fort McMurray Fire in Canada [10] and the 2016 Haifa Fire in Israel [11] each resulted in the evacuation of tens of thousands of people. The California Wildfires of 2017 and 2018 resulted in numerous fatalities and the evacuation of tens and hundreds of thousands of people respectively [12], [13]. These fires, in addition to the deadly 2017 Portugal Wildfires [14] and the 2018 Greece Wildfires [15], bring attention to the fundamental need to protect people before and during response to WUI fire[23] events. While it is the policy in many countries for people to evacuate areas at risk during WUI fires [16]–[18], many times the public evacuates only minutes before the fire reaches their communities, if they are able to evacuate at all [19]. Additionally, a large percentage of WUI fire deaths have occurred during evacuation itself [20], as was the case during the 2017 Portugal Wildfires. It is therefore of growing importance to have comprehensive tools to aid in the planning and execution of safe and effective WUI fire evacuations.

Modelling tools are available to simulate components of evacuations; however, some gaps in capabilities exist. Current modelling tools are either statistical or empirical in nature and/or feature only one aspect of the incident; e.g. the fire development, the emergency response, the evacuation response, etc. [21]. As such, these models are incapable of explicitly representing the temporal nature and the highly coupled nature of an incident. Having a type of time-based, inclusive simulation approach would better enable the vulnerability of communities to be assessed. This would not only be beneficial for WUI evacuations, but for other types of community evacuations as well.

Additionally, current evacuation simulation tools focus primarily on people or traffic movement, and in turn, neglect to simulate evacuation decision-making and behaviour that would

[23] WUI fire refer to wildfires/bushfires/forest fires that infringe upon the wildland urban interface.

prompt or prohibit evacuation movement to take place. Instead, a model often represents the probability of a particular response rather than representing the decision-making process through which an individual passes before selecting a response. In order to create such comprehensive evacuation tools, it is necessary to understand what factors affect evacuations and what information is necessary for evacuation models to be useful and effective. This understanding of evacuee decision-making comes from exploring existing research on public response to WUI fires and other disasters.

The majority of current and past research on the factors that affect WUI fire protective action decision-making—sociodemographic factors, social and environmental cues, preparation and experience, risk assessment, etc.—available to the authors in English originates from the United States and Australia. Behavioural research on WUI fires is relatively new compared to research studying other disaster types, and therefore a smaller amount of data has been collected. Fortunately, despite the differences among disaster types, there are a number of similarities which enable our understanding of WUI fire evacuations to be enhanced through an understanding of public response to other disaster types. For example, with respect to evacuations, there are similar challenges among longer-duration (or slow-onset) disasters regarding notification, timing, ingress and egress decisions and actions [22]. There is a substantial body of research that looks at such challenges and the factors that affect them with respect to disasters in general [23]–[27]. Additionally, the overall process that one goes through to make decisions and respond to natural or technological disasters is ultimately the same [28]. As such, looking at research relating to other disasters can further our understanding of how people will act and behave during WUI fires.

While looking in detail at research from all disaster types (floods, earthquakes, man-made disasters, etc.) would provide the most comprehensive understanding of evacuation factors, it was within the scope of this study to compare two disaster types. Relevant U.S. and Australian WUI fire research was identified and reviewed along with hurricane research from the United States to determine potential environmental and social factors that affect protective action decision-making and response. Hurricane evacuations were chosen so as to maximize the amount of information available for comparison given the wealth of United States' hurricane literature (available in English). Focusing on American studies also meant that additional cultural and political influences would not need to be considered within this review. Although there are differences between wildfires and hurricanes, there are many similarities that makes their focus in this review a reasonable exercise, e.g.:

- the movement of wildfires and the track of hurricanes are dependent on many factors, making prediction difficult
- both hazards provide similar timeframes for notification—including public alerts and warnings, in that they begin in one location and have the potential (over time) to negatively impact communities in its path
- both hazards have the capacity to displace large groups of people
- both hurricanes and wildfires have the potential to change course or direction without warning, therefore potentially decreasing the time available to make protective action decisions

The purpose of this literature review is to identify the factors that have an impact on household protective action decision-making in the context of WUI fires. This is done by looking both at U.S. and Australian wildfire research,[24] as well as U.S. hurricane literature. The factors

[24] Wildfire research include that which referred to bushfires and forest fires.

identified by this review are organized according to the Protective Action Decision Model (PADM) to better understand what factors affect the different stages of the decision-making process [28]. From these factors, and their organization in the PADM, the authors have developed a conceptual model of protective action decision-making for WUI fires. It is the intent that the collection and analysis of this information, and the development of the conceptual model, will help to inform the development of broad and all-inclusive WUI fire evacuation models.

D.3 Background

D.3.1 Evacuation Modelling

In any WUI evacuation model, certain key components need to be addressed in order to simulate WUI fire scenarios to an acceptable degree of detail. In reference to the evacuation model, vehicle evacuation, including both private vehicles and public transportation, is the primary transport mode for affected populations during WUI fire incidents. This reliance on vehicles is often due to the scale of these incidents, the distances that need to be covered, the trend in household units to evacuate together, and the fact that the transport of goods/provisions (in addition to the residents) are often required during evacuations. Therefore, WUI evacuation models should be capable of simulating the movement, route choice, and route destination of vehicles of varying capacities, which is covered in depth by the field of traffic modelling (see [21] for more details).

It is important to understand that traffic performance (and modelling) is not independent of the actions of individuals (referred to here as pedestrians). Pedestrian decision-making and preparation will determine the time at which household units decide to initiate their evacuation as well as the time that they move from their starting location (e.g., home, business, hospital, school, etc.) and eventually enter the traffic system. This aspect of individual/household decision-making in WUI fire events is less developed, and in turn, not well represented in current large-scale WUI (or disaster-based) evacuation models. What is required are largescale evacuation models that account for individual/household protective action decision-making before vehicular evacuation begins. Protective action decision-making is defined here as the process by which people make decisions based on the cues/information available (i.e., threat conditions) to protect themselves, others, and/or their property in the event of a WUI fire. Furthermore, current evacuation and traffic models such as those reviewed by Ronchi et al. [21] would be significantly improved if they were better able to account for behavioural choices of individuals/households based not only on threat conditions, but the interactions between individuals as well. A number of studies have previously explored the benefits of including such components into existing models [27], [29]–[33].

The first step in accounting for individual/household decision-making during WUI fires is made in this paper. From a review of WUI fire and hurricane literature, the authors have developed a conceptual model of decision-making for WUI fires. The PADM is used as the foundation for the development of this model, and is discussed in the following section.

D.3.2 Behavioural Modelling

Over the last 50 years, numerous empirical studies have sought to systematically chart the social processes involved in human response to emergency incidents [34]–[36]. Of these, the Protective Action Decision Model (PADM) is selected here as it provides a framework to understand how people protect themselves and one another in response to cues from a disaster event [28], [37]. This model was deemed most appropriate for the task of categorizing the factors affecting the different stages of the decision-making process in an attempt to create a behavioural conceptual model for WUI fire evacuations.

The PADM asserts that the process of protective action decision-making begins when people are first presented with any kind of environmental cue, including physical and social cues and information. The introduction of these cues initiates a series of stages through which an individual passes prior to performing protective actions; e.g., initiating evacuation or deciding to stay and protect one's home. These stages are split into pre-decisional processes, which determine whether a decision-making process commences (PRE-DECISION in Figure D.1), and into the key components of the decision-making process itself (CREDIBLE THREAT, RISK ASSESSMENT and PROTECTIVE ACTION DECISION in Figure D.1).

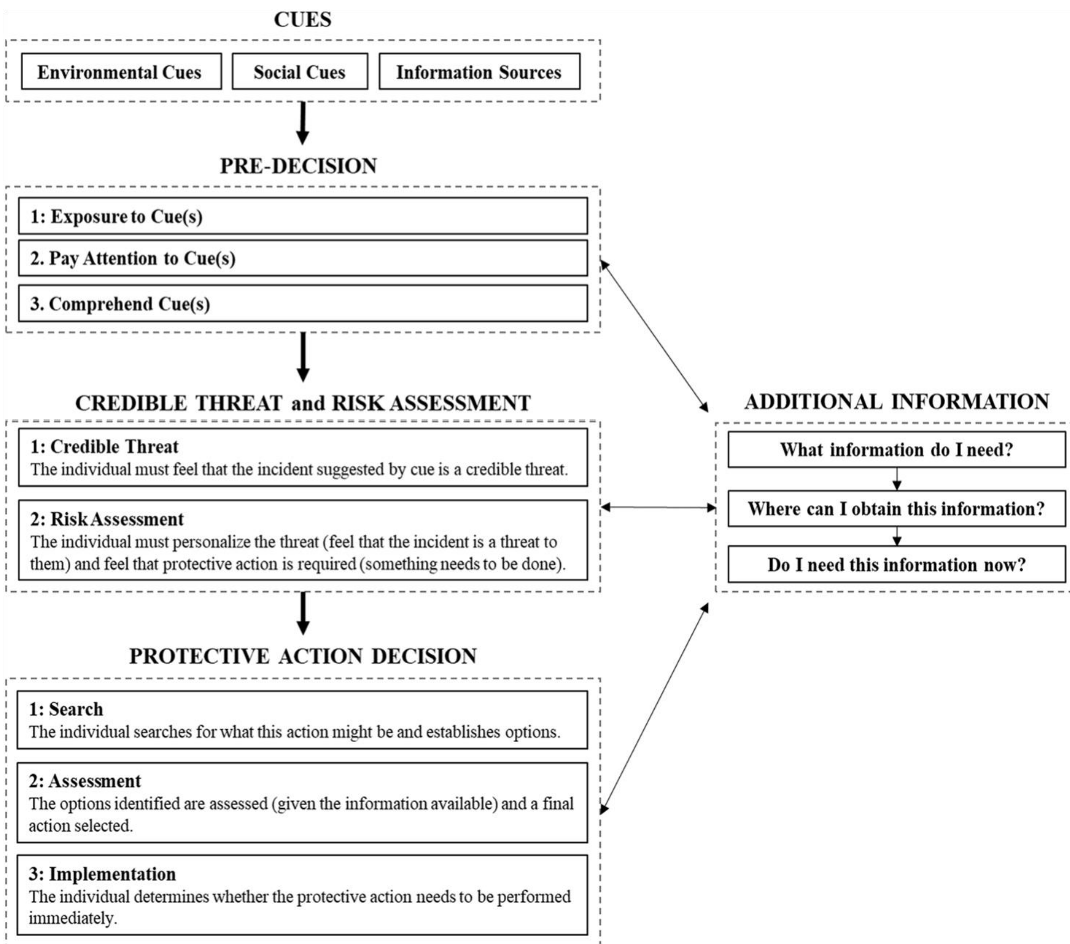

Figure D.1: Protective Action Decision Model Framework (adapted from [28]).

Initially, the individual needs to receive a cue, pay attention to it, and comprehend the meaning associated with the cue (e.g., hearing an alerting signal, seeing flames, or smelling smoke). These represent the three pre-decisional stages of the PADM (PRE-DECISION 1–3 in Figure D.1), the stages that determine whether external information is processed such that it can inform the decision-making process [28]. Given that this information is processed, it then needs to be assessed to determine whether the information provided is credible (CREDIBLE THREAT in Figure D.1). At this stage, the individual decides if there is actually something occurring that may require action.

If the individual considers there to be a threat, they next determine whether the threat is relevant to him/her (RISK ASSESSMENT in Figure D.1), known as personalizing the threat (or risk). Research has shown that a person's perception of personal risk, or ‘‘the individual's expectation of personal exposure to death, injury, or property damage’’ is highly correlated with taking protective action [28], [35], [38], [39]. The individual tries to gain insight on the potential outcomes of the disaster and what those potential outcomes mean to his or her safety. If the cues are deemed to relate to them, the individual then determines whether it is relevant and pressing. This then requires the individual to determine the nature of the response required at that point in time.

At this stage (PROTECTIVE ACTION DECISION in Figure D.1), the individual engages in a decision-making process to identify a set of possible protective actions from which to choose. When it comes to taking protective actions in response to a WUI fire threat, there are ultimately two choices, to stay or to leave. Within the option of staying, households may choose to actively defend their home and property, or passively shelter in place (SIP), i.e., in their home, another location on their property or in their community. After establishing at least one protective action option, an individual engages in protective action assessment of these options and their current action.

If at any stage the individual is uncertain about the situation, the individual engages in additional information-seeking actions or they simply wait until additional information is provided to them. If seeking information, they may search for other sources of information (e.g., websites, media, etc.) and/or reach out to other people to discuss the situation and what to do (also known as the milling process) [40], [41]. The greater the ambiguity involved in the situation, the more likely that individuals will search for additional information that can guide their actions [42], [43]. Information seeking is especially likely to occur when individuals think that time is available to gain additional insight. The individual continues in this action until sufficient information is available or time runs out (the threat reaches them) [28]. During an incident, information received can be incomplete, ambiguous, or contradictory, causing uncertainty in understanding the nature of the event and the actions necessary [44], [45]. In these cases, progress in the stages of the PADM can be significantly delayed and/or promote inefficient or unsafe protective action behaviour.

D.4 Methodology

This paper is based on a review of literature related to evacuation decision-making during WUI fires and hurricanes. It includes literature from various databases including Web of Science, Google Scholar, the NIST Research Library, and the Carleton University Library. The literature was obtained from peer-reviewed journal articles, conference proceedings, book chapters, government agency and university reports. A set of key search terms was identified, and additional terms were added as the research progressed. These terms include: Wildfire, Bushfire, Forest Fire, Wildland Urban Interface, WUI, Hurricane, Evacuation Behaviour/Decisions/Actions/ Alternatives, Decision Making, Evacuation Modelling, Shelter-In-Place, Protective Actions, Affecting/ Influencing, and Risk Perception. The review includes primarily post-2000 literature as the majority of related research for WUI fires and hurricanes was conducted during this time, however, a small number of commonly referenced hurricane research papers from the 1990s were also included. The selected studies were reviewed to identify the factors deemed influential in the protective action decision-making process. The literature includes both qualitative and quantitative studies, as well as related literature reviews and compendiums.

WUI fire literature from both the United States and Australia has been included, while the hurricane literature was limited to the United States. It is important to note that Australia and the United States have historically had very different approaches to wildfire policy. Australia's policy of ''prepare, stay and defend or leave early'' and later ''Prepare. Act. Survive,'' allows for the practice of staying and defending one's home. Conversely, in the United States, evacuating all people threatened by wildfires has been the long-accepted practice. Given these differences between Australian and U.S. wildfire policies, it is acknowledged that the findings given in the respective literature would have been influenced by the varying perspectives about wildfire safety and the role of evacuations. It is also understood that additional factors, both technical and non-technical, may exist that have an impact on the protective action decision-making process. This is beyond the scope of this paper.

The methodologies employed in the reviewed material differed, as some studies collected purely qualitative data, quantitative data, or a combination of both. Within these studies, some conducted correlation analysis, while others also utilized regression analysis. Varying sampling techniques and strategies were used, including surveys, questionnaires, interviews and focus groups. The size and nature of the samples also varied, with some sample groups having a greater awareness and interest in the risk posed to them by the hazard in question. Some studies collected post-disaster data, whereas others looked at intended actions. The definition of terms such as evacuation, as well as other aspects of the process, may have been different and in turn, measured differently between the studies. In addition, each paper discussed its own limitations within the context of the individual study. Commonly mentioned limitations included the accurate representation of a target population, survey response rate, hindsight bias, and issues related to the reliability of behavioural intention studies.

The factors included in this paper are those that were found by the authors of the reviewed literature to be significant based on each study's own criteria. In the case of quantitative studies, these include factors that were deemed statistically significant. For the qualitative studies, these factors included those that were deemed notable by the researchers, based on the analysis methods employed. The identified factors for WUI fires and hurricanes are presented in Sects. 4 and 5 respectively. Each section is broken up into the stages of the PADM discussed in Sect. 2.2. In addition to these, individual/household delay and actions processes relevant to the proposed conceptual model were also identified and incorporated in each section. The presented factors are discussed in greater detail in Sect. 6, along with conceptual model considerations and recommendations for future work. The paper is concluded in Sect. 7.

D.5 Factors Influencing Protective Action Decision-Making During WUI Fires

This section details the factors identified in the literature relating to protective action decision-making during WUI fire events. A summary of the identified factors can be seen in Sect. 6.1, Table D.1. Section 4.1 focuses solely on the factors affecting threat identification and risk assessment, since minimal to no data was found relating to the pre-decisional phases of the PADM (i.e., perception, attention, and comprehension). Next, Sect. 4.2 addresses factors affecting the decision to evacuate (or not). Finally, Sect. 4.3 details additional factors relevant to delay, delay time and the specific types of actions undertaken.

D.5.1 Credible Threat and Risk Assessment

WUI fire literature was identified that discussed factors that affect the following PADM processes: identification of a credible threat and risk assessment. A few studies identified sociodemographic and cue-related factors, but the majority of factors were related to location, preparation and experience.

One WUI fire study identified sociodemographic factors and their impact on threat and risk identification. Mozumder et al. [46] found that having a higher income or level of education was related to an increased level of concern that one's home may be threatened by a wildfire. Additional studies explored the role of environmental and social cues in decision-making. In several studies, a fire cue was often noted to be a trigger that indicated a credible threat and high level of risk inciting evacuation. This trigger could be the sight of others leaving [47]; sensory cues such as visible smoke, embers or flames; or information from trusted sources about the location and intensity of the fire [47], [48].

Studies also identified residence, location, knowledge and experience with WUI fires as influential to threat identification and risk assessment. First, the length of time a household lived in the area; i.e., residence time, was found to relate to the level of perceived wildfire risk. Newer residents were more likely to be concerned that their home was endangered, whereas long-term residents were more likely to feel that their property was safe [46], [49]. However, if a household had experienced previous property damage due to a wildfire, they were more likely to be concerned that their home would be endangered again [46]. Similarly, a household's knowledge of previous fires in their community and area led to greater concern that wildfire may endanger their own home, impacting their assessment of risk and leading to a higher likelihood of evacuation [46], [50]. In a review looking at post-Black Saturday Fires research, it was noted that one's location had an impact on risk perception, as many people living in suburban locations had not considered themselves at risk to wildfire [51].

D.5.2 Protective Action Decision

The vast majority of WUI fire literature focused on identifying the factors that influence the protective action decision itself; i.e., the decision to stay or go. These factors were grouped into categories relating to sociodemographic factors, environmental and social cues, experience and preparation, familial and societal responsibilities, place/location, and credible threat and risk assessment.

Sociodemographic Factors

One of the most commonly cited demographic factors affecting the likelihood of evacuation was gender. Numerous pre-and post-disaster studies indicated that women were more likely than men to decide to evacuate, and that men were more likely than women to stay in place [46], [51]–[57]. On a similar note, Proudley [58] found that the roles people play within a family had a large role in how people respond and behave during a WUI fire event. With respect to reasons for wanting to stay, Benight et al. [49] found that women were significantly more likely than men to report that their ‘‘love for the forest’’ made it difficult to leave. Among those who chose to stay, women were more likely to report that they thought it was too dangerous to leave or that their attempt to leave had been unsuccessful [54]. The study found that protecting property was more often cited by men as their reason for staying, however, this was also a major reason for women as well.

Additional sociodemographic factors that influenced evacuation decisions include political leaning, age, income and occupation. Mozumder et al. [46] found that in the United States, Democrats were more likely than Republicans to evacuate under both voluntary and mandatory evacuation orders. The average age of those who chose to stay and defend during the 2009 Black Saturday Fires was slightly higher than those who evacuated (51.5 years vs. 48.4 years), suggesting that age could be a potential factor [57]. One study found that people with a higher income were more likely to evacuate, and those employed by the wood products and insurance industries were more likely to stay and defend (implied by the authors as being potentially a result of having greater knowledge or skills related to wildfire management or damage) [56].

Environmental and Social Cues

The nature and number of cues received about a wildfire threat have been found to influence the protective action decision made. Rates of evacuation have been found to be higher when people receive multiple warnings from more than one source [50], and receiving advice to leave from friends, family, neighbours and emergency services was also found to influence evacuation (more so for women than men) [54]. However, Strawderman et al. [50] found that these sources had less impact than a more formal warning from authorities. McLennan et al. [57] found that a greater percentage of those who chose to evacuate had received information about the fire from neighbours or emergency personnel in a face-to-face setting. Similarly, receiving a voluntary or mandatory evacuation order was found to increase the likelihood of evacuating, with the latter having a greater effect [46]; however, this may not always be the case [59].

Preparation and Experience

Preparation for WUI fires and experience with these events can also influence protective action decisions. Commitment to a previously developed plan to stay and defend, coupled with a belief that preparations taken were sufficient to meet the perceived level of risk, was a principal factor in staying and defending [47], [48], [57], [60]. Similarly, a lack of preparedness and planning to stay has been found as influential on evacuation decisions, showing that levels of wildfire preparedness and knowledge were higher among those who chose to stay and defend versus those who evacuated [57]. Taking this further, having a plan to evacuate made people less likely to consider staying and defending and more likely to evacuate [56], [61]. Additionally, studies found that those who intended to stay and defend had greater confidence in their perceived physical readiness and ability to successfully defend their homes than did those who intended to evacuate [57], [62], [63].

In reference to previous experience, Whittaker and Handmer [51] found that previous false alarms—i.e., evacuations or evacuation orders later deemed unnecessary—led people to be less likely to evacuate in the future, while Benight et al. [49] found that such experience did not have a negative impact on future evacuation intentions. Other studies found that those who had evacuated in previous WUI fire events were more likely than those without such experience to evacuate in the future [50]. This variation in the influence of previous evacuations was also noted by Cohn et al. [52], who found that for some, previous experience motivated immediate evacuation; for others, it resulted in evacuation after a longer period of time, and for others still, it made them less inclined to evacuate at all as they deemed it unnecessary.

Familial and Societal Responsibilities

Various studies show that there are a number of factors related to familial and social roles and responsibilities that influence protective action decisions. It was found that having children in a household not only influenced evacuation behaviour, but it also prompted a quicker response—either immediately upon threat awareness or under a voluntary evacuation order [57], [63]. Conversely, those with pets or livestock were more likely to wait and see or stay and defend than those without [46], [57], [63]. The impact that having livestock had on decisions to stay was found to be stronger than the impact of pets [46]. As noted by Tibbits and Whittaker [60], focus groups revealed that for many farmers and people whose livelihoods depend on their livestock, there was a feeling that they had no choice but to stay and defend, for economic reasons as well as for the welfare of their animals.

For those who choose to stay and defend, connections to their community and emotional attachment to their property were found to be motivating factors [48], [57], [61]. Studies found that concerns about personal and family safety were motivating factors for people intending to evacuate [61], [63], whereas a desire to protect property with the acceptance of some personal risk was found to motivate those intending to stay and defend [52]. Another reason Cohn et al. [52] identified for staying was the concern about an inability to return for an extended period of time. According to Tibbits and Whittaker [60], people's confidence in their own ability to defend their property was influenced by active emergency and firefighting officials in the area, as well as by having more than one able-bodied person in the home to help defend; however, other studies found no such evidence [57]. Paveglio et al. [56] found that the belief that residents who live near forests should accept the likelihood of some level of potential property damage was found more commonly among those who choose to stay and defend [56]. Similarly, McLennan et al. [48] found that some of those who chose to stay and defend during the Black Saturday Fires of 2009 were more likely to believe that they were to some extent responsible for protecting their own property, as opposed to relying entirely on emergency personnel.

Place/Location

The decision to evacuate has been shown to be influenced by the location and length/frequency of residence. Some residents of rural areas have been found to decide to stay in place as they deem it impractical given the time and distance required to reach a safe area [56], [60]; however, other studies found no effect of property location on protective action decision-making [57]. In a more general sense, the belief that evacuation was no longer safe was found by McLennan et al. [47] to be a factor contributing to the decision to stay and defend in some cases. Conversely, Strawderman et al. [50] found that those living in a rural area or on a farm were more likely to evacuate than those living in subdivisions or urban areas. Paveglio et al. [56] noted that full-time residents were less likely to evacuate than part-time residents.

Credible Threat and Risk Assessment

The assessment of risk was identified by various studies as being an important factor in the decision to evacuate [46], [50], [61], though not universally across all studies [56], [62]. For those who intended to evacuate, ‘‘risk’’ could be defined as a concern that one’s life and home would be endangered [46], [61]; for those who intended to wait and see or stay and defend, ‘‘risk’’ corresponded to danger associated with leaving unnecessarily and having to drive through hazardous conditions [61], [64]. McLennan et al. [61] noted that while those intending to leave were more likely to report higher levels of concern about wildfire danger, they were no more likely than those intending to stay to believe that they were at greater risk than others.

D.5.3 Delay and Actions

A number of factors have been identified which affect the time it takes to make a decision. It has been indicated by Paveglio et al. [56] that in the United States, those planning on employing shelter in place are likely to 'wait and see' how bad the fire gets, and potentially evacuate if conditions degrade. McNeill et al. [66] found that the biggest cause for decision delay is a lack of distinct attractiveness of one decision option over another. That is, both the option of evacuating or staying and defending are similarly appealing. They found this to have more of an impact on decision delay than a lack of perceived risk, sociodemographic or responsibility avoidance. Additionally, Rhodes [64] notes that 'waiting and then leaving when threatened' is seen by some to be an acceptable strategy that allows for the increased chances of protecting property and life safety. Individuals who 'wait and see' do not necessarily see their actions as being risky [65]. In their review of literature from the United States, Canada and Australia, McLennan et al. [67] found that many people are likely to delay leaving (because they want to protect their property or avoid the costs of evacuating—financial burden, dangers during evacuation) and therefore it should not be assumed that all those threatened by a WUI fire will evacuate immediately upon receiving an evacuation order or warning.

There are also a number of factors that influence the actions people take once they have decided to evacuate. Often times people prepare, including collecting their belongings and packing vehicles, before evacuating. This is seen even among those who originally chose to stay and defend, but considered evacuation as a last-minute possibility [60]. Having to manage belongs has been found to slow down an evacuee's response time [49]. Also, families tend to leave together as a group, sometimes with neighbours and extended family as well (the authors did not specify what was meant by extended family) [52]. Evacuees will often search for others and inquire about what they have heard about the event before packing up and leaving [52]. These actions have the potential to increase the time it takes to evacuate.

D.6 Factors Influencing Protective Action Decision-Making During Hurricanes

This section details factors influencing protective action decision-making during hurricanes as found in the related literature. Table D.1 in Sect. 6.1 provides a summary of these factors in comparison to those identified in the WUI fire literature. As with the WUI fire data discussed in Sect. 4, there was no discussion of factors affecting the pre-decisional phases of the PADM, and because of this, only those factors that influence threat identification and risk assessment are discussed (Sect. 5.1). Additionally, Sect. 5.2 discusses factors that influence the decision to take action, i.e., stay or go (Sect. 5.2). Finally, factors relating to delay, delay time, and specific types of actions taken are discussed in Sect. 5.3.

D.6.1 Credible Threat and Risk Assessment

Literature was found that identified factors that influence threat identification and risk assessment. These factors include sociodemographic factors, as well as those relating to environmental and social cues, place/location, and experience.

First, sociodemographic factors were identified as influential to threat identification and risk assessment. In their analysis of gender roles in hurricane evacuations, Bateman and Edwards [68] found that women were more likely than men to perceive higher levels of risk. Even more complicated is that studies have found perception of risk to be a mediating variable between gender and evacuation behaviour—in that while men were less likely to perceive risk, men who did perceive risk were more likely than women (with comparable levels of risk) to evacuate.

Environmental and social cues have been identified by several studies as playing a role in the identification of a credible threat and assessment of risk. Storm intensity and severity were found to be of primary concern and were seen as key indicators of personal risk [69], [70]. Additionally, the perceived potential for flooding was found to influence perception of risk more than forecasts for high winds [70]. Huang et al. [72] found that in addition to environmental cues, social cues also had an impact on risk assessment. Official warnings were determined to have a positive effect on both the identification of a credible threat and risk assessment.

Studies also identified location and experience in hurricanes as influential to threat identification and risk assessment. The location of those threatened by a hurricane can influence how the threat is perceived. Surprisingly, it was found that those farther from the coast perceive more severe storm characteristics, potentially as a result of the types of environmental cues faced by residents in different locations [72]. For example, Stein et al. [71] found that there was a heightened perception of risk due to wind rather than flooding or storm surge for residents outside of the evacuation zone. Additionally, having previous hurricane experience has been shown to increase perception of credible threat and risk [72]. However, experience with unnecessary evacuation was found to have an impact on lowered risk levels, leading to the belief that previous positive outcomes indicated perceived positive outcomes in the future.

D.6.2 Protective Action Decision

As was found when looking at the WUI fire literature, the majority of the factors discussed in the hurricane literature were found to influence the actual protective action decision. These included sociodemographic factors, and those relating to environmental and social cues, experience and preparation, familial and societal responsibilities, place/location, and credible threat and risk assessment.

Sociodemographic Factors

It was noted by a number of researchers that females were more likely than males to evacuate [73]–[76]. However, other studies found that when other factors, such as roles and responsibilities within the family and location within the risk areas were taken into account, the effect of gender on evacuation decision was insignificant [68], [72]. In general, the likelihood of evacuating has been found to be higher among younger individuals [68], [74], with the exception of those who classified themselves as retirees who have been found to be more likely to evacuate [68], [77] (even more so with women than with men [68]). It should be noted that other studies found no significant association between age and evacuation [77], [78]. Conflicting results have been found for other socio-demographic factors such as income, education, marital status, and race. Some studies have found these factors to have a significant influence on evacuation [70], [73], [78]– [81], while other studies have found that these factors do not play a significant role [68], [77], [82].

Environmental and Social Cues

Receiving information about a hurricane threat or an evacuation notice from a trusted source, particularly from family, peers or authorities, tended to lead to a higher likelihood of evacuation [74], [80]. Other sources of information such as national television stations, were also identified as influential and, depending on the situation, could have a greater impact on evacuation decisions than other information sources [82]. One of the most influential social cues on the decision to evacuate was receiving an official evacuation order or warning [72], [74], [77]. Both voluntary and mandatory evacuation orders have been found to increase the likelihood of evacuation, with the latter having a greater effect [70], [79], [80], [83], [84].

It has been found that one's location inside or outside of an evacuation zone can impact the outcome of such evacuation orders. For example, those located outside of the evacuation zone were less likely to evacuate, unless they received information about the evacuation order from the media, which then prompted them to evacuate unnecessarily [71]. The effect of the news media was found to have a minimal impact on those inside evacuation zones. Conversely, Lazo et al. [75] noted that perceived evacuation zone did not have a significant impact on evacuation behaviour.

The type of information disseminated about the storm was also found to play an important role in the decision to evacuate. Dow and Cutter [83] noted that the probability and location of hurricane landfall were important factors affecting evacuation decisions. Information on wind speeds [84], storm strength [76], [79], [82] and storm severity [77], [83] were also identified as influential to the decision to evacuate. However, location, such as coastal proximity, and the fact that public officials tend to disseminate stronger messages during stronger storms, can mediate the influence of such storm indicators [74], [77]. The mediation effect caused by other factors was also noted when it came to the effect of observing others. Observing neighbours and peers leaving, or the absence of neighbours who have already left, has been shown to increase the likelihood of evacuating [68], [74], particularly in the case of residents in non-evacuation zones [71]. However, other research found that neighbourhood evacuation was strongly related to high-risk areas and with actions taken by officials, therefore making it difficult to identify the independent strength of this factor [77].

Preparation and Experience

Previous experience with hurricanes and hurricane evacuations is a potentially influential factor in hurricane evacuation decisions [73]. Numerous studies have found such experience to lead to increased likelihood of evacuation [69], [75], [78], [81], [82]. Petrolia and Bhattacharjee

[84] found that past storm experience had a significant impact on future evacuation intention; however, the nature of the experience determined whether the person was inclined to stay or go. For example, past experience has been found to negatively impact evacuation in instances where past evacuations were viewed as unnecessary [72], [80]. It should be noted that other studies have found the impact of past experience to be insignificant [74], though others point out that it can contribute to awareness of the hazard and potentially produce a greater appreciation for the danger it may pose [77]. Murray-Tuite et al. [78] noted a level of consistency between previous evacuation actions, with 70% of study respondents making the same protective action decisions for both Hurricane Katrina and Hurricane Ivan.

People who had created a household evacuation plan were more likely to evacuate [68], [75] and those who had spent more money on household storm preparation and planning were less likely to evacuate [82]. An increased knowledge about hurricanes was not found to impact evacuation decisions [77].

Familial and Societal Responsibilities

The strength and viability of one's social network has been found to have an impact on evacuation decisions, with those who have stronger social support being more likely and able to evacuate [81], [85]. Riad et al. [81] noted that it was a weaker social network, and not poverty, that was the greatest obstacle to evacuation for those with fewer resources.

The desire to keep one's family safe was identified as being one of the strongest influences on evacuation intention [75]. In line with this, research has found family size and the presence of children to impact the decision to evacuate. However, this impact varies. Studies have found that having children in the household can positively impact evacuation [74], [76], [80], [82], negatively impact evacuation [78], or have no effect at all [68], [77]. Similarly, the impact of family size is unclear [68], [78], [82].

Work responsibilities (requiring people to stay) and the potential loss of income due to evacuating have been found to significantly impact the decision to stay [80], [83]. Additionally, wanting to protect property from the storm and/or from looters [77], [79] and having pets or livestock decreased the likelihood of evacuation [70], [79], [82]. Concerns regarding perceived evacuation impediments, including traffic congestion, reduced the likelihood of evacuation [72], [83]. In line with this, people tended to consider a wide variety of indirect costs associated with evacuation such as travel costs, care for pets, and potential difficulties with re-entering the evacuation zone [83].

Place/Location

The vulnerability of one's home to hurricanes has been shown to impact the likelihood of evacuation, though the strength of this factor varies depending on the study. In the case of hurricanes, vulnerability is most often classified as living in a mobile home, and for those who do, studies show that they are more likely to evacuate [68], [76]–[78], [82], [84]. Conversely, some research indicated an insignificant correlation between evacuation and mobile home residence [74].

Other research on place and location has found that living in multi-family dwellings can increase the likelihood of evacuation [78]; however, not all studies agree [79]. Homeownership, compared with renting, is also identified as an influential factor for non-evacuation in some studies [76], [80], [82], with longer-term residents being less likely to evacuate than shorter-term residents [81]. However, not all studies found significant results [77]. The belief that one's home was a safe place was identified by Dow and Cutter [83] as being the first consideration in deciding to stay, followed by traffic, work responsibilities and the likelihood that landfall would be nearby. In line with this, living near the coast or bodies of inland water, or in flood areas has been shown to lead to increased levels of evacuation [68], [72], [74], [77], [82]. However, context matters here, of course. The factors of the population within the coastal communities, e.g., income and other demographics, should also be taken into account [78].

Credible Threat and Risk Perception

As the PADM model shows, risk perception is a critical factor that influences protective action decisions. Those who feel safe in their home are more likely to stay, and those who feel unsafe were more likely to leave [69], [77], [81]. Individuals who were concerned about costly damages favoured evacuation [77], [79], as did those who perceived personal vulnerability to wind and storm surge [75].

D.6.3 Delay and Actions

Some research found that those living farther from the coast were more likely to wait before making their decision to evacuate compared to those closer to the coast [84]; however, they were more likely to take less time to prepare—i.e., spending less time protecting their property, packing and securing their home [74], [86]. Not having an evacuation destination identified ahead of time (pre-storm) was identified as contributing to added confusion and subsequent delay as a result of not knowing what protective action decision to make [84]. Additionally, large households tended to evacuate later and took more vehicles, whereas older adults tended to evacuate earlier [86].

D.7 Discussion

D.7.1 Similarities and Differences Between WUI Fire and Hurricane Factors

For this paper, the factors mentioned in Sects. 4 and 5 above, for WUI fire and hurricane events respectively, are structured according to the PADM framework. This allows for a more comprehensive understanding of how a given factor will affect the evacuee decision-making process and how this effect might propagate through this process, potentially affecting the time it takes to respond and the outcome of the response. As will be shown in the discussion below, it was often found that a particular factor influenced more than one stage of this process. A summary of the identified factors is presented in Table D.1. Factors that were identified solely in qualitative studies are denoted with an asterisk (*), all other factors were found in quantitative studies or in both qualitative and quantitative studies. For detailed information about the methodologies used in each study, readers are directed to the sources noted in the table beside the respective factors.

For both hurricanes and WUI fires, very little research was found that identified the factors affecting the pre-decisional phases (i.e., receipt of, attention paid to, and comprehension of cues and information). The only study identified discussed how hot weather may have prevented awareness of the Black Saturday Fires as the heat prompted some people to stay indoors [53]. Identifying additional factors that affect the pre-decisional phases will enable WUI evacuation models to more effectively and comprehensively represent potential obstacles to resident fire threat awareness.

With respect to the threat identification and risk assessment stages of the PADM, similar factors were identified in the hurricane and WUI fire case studies. Within the sociodemographic factor category, income, education and gender were identified as having potential impacts on the assessment of threat and risk in both the WUI fire and hurricane literature. Similarly, within the environmental and social cue category, triggers were important factors identified for both hazards. For instance, for WUI fires, environmental cues consisted of seeing or feeling the heat from flames and embers, and seeing or smelling smoke; and for hurricanes, environmental and social cues consisted of storm intensity and severity, as well as the risk of flooding due to heavy rain or storm surge. Both data sets found that social cues, such as observing others leaving, receiving information from trusted sources, or receiving an evacuation order increased the credibility of a threat and the perception of risk. Place and location as well as preparation and experience were also factor categories found to play a role in threat and risk assessment in both hazards. However, in both cases, it is important to note that previous experience alone was not sufficient to influence behaviour. This factor is more nuanced in that the type of experience (e.g., positive or negative), is what actually influenced threat identification and/or risk assessment.

The vast majority of the factors identified in this literature review played a role in the protective action decision-making stage of the PADM. With respect to sociodemographic factors, gender was found to be the most commonly discussed factor for both WUI fires and hurricanes. In both cases, it was predominantly the case that women were identified as being more likely than men to evacuate. These findings must be put into context; however, when other factors associated with gender roles were taken into account (e.g., roles and responsibilities within the home), the impact of gender became insignificant. Moving forward, it would be beneficial to delve further into the role of gender in evacuation decision-making and response. Additional sociodemographic factors such as age and income were mentioned in both WUI fire and hurricane research, but they were identified less often and/or their influence was often contradicted by findings from other studies.

Table D.1: Hurricane and WUI Fire PADM Factors

PADM stage	Wildfire	Hurricane
Pre-decision	Weather [53]*	Not Applicable
Credible threat and risk assessment	Income/Education [46] Trusted sources [47], [48]* Length of time lived in area [46], [49] Location [51] * Observe others [47]* Previous experience with wildfires, knowledge of other fires [46], [50] Sensory-environmental [47], [48]*	Coastal proximity [71], [72] Environmental cues [69]–[71] Gender [68] Previous hurricane experience, unnecessary evacuations [72] Social cues [72] Trusted sources [72]
Protective action decision	**Sociodemographic Factors** [46], [49], [51]–[58] Age Gender Income Occupation Political leaning	**Sociodemographic Factors** [68], [70], [72]–[82] Education Gender Income Marital status Race Retired
	Environmental/social cues [46], [50], [54], [57], [59] Evacuation order Multiple sources Telling other people Trusted source Wait and see	**Environmental/social cues** [68], [70]–[72], [74]–[77], [79], [80], [82]–[84] Environmental cues Evacuation order Observing neighbours Trusted source
	Preparation/experience [47], [48], [50]–[52], [56], [57], [60]–[63] Belief in capacity/survivability Commitment to plan Preparation and knowledge Previous evacuation/fire experience	**Preparation/experience** [68], [69], [72]–[75], [77], [78], [80]–[82], [84] Plan Previous experience (hurricane and/or evacuations)
	Familial and societal responsibilities [46], [48], [52], [56], [57], [60], [61], [63] Attachment to home/community/ desire to protect property Children Pets/livestock	**Familial and societal responsibilities** [68], [70], [72], [74]–[83], [85] Keep family safe (children, family size) Pets/livestock Protect property (from storm and looters) Social network Work responsibilities

*Indicate factors identified solely in qualitative studies

Table D.1: Hurricane and WUI Fire PADM Factors (continued)

PADM stage	Wildfire	Hurricane
Protective action decision (continued)	**Place/location** [50], [56], [57], [60] Distance to neighbours Full time vs. part time residents Rural vs. suburban	**Place/location** [68], [72], [74], [76]–[84] Dwelling type (mobile home, multi-family) Coastal/water proximity Home as a safe place Home ownership and length of residence
	Risk assessment/credible threat [46], [50], [56], [61], [62], [64] Assessment of effectiveness Concern Risk/danger (staying or leaving)	**Risk assessment/credible threat** [69], [75], [77], [79], [81] Risk of flooding, high cost damages
Delay and actions	Families stay together [52] * Gathering physical possessions [49], [60] Indecision [66] Wait and see [56], [64], [65], [67]	Age [86] Evacuation destination [84] Household size [86] Location [74], [84], [86]

*Indicate factors identified solely in qualitative studies

In a general sense, environmental and social factors that influenced evacuation decision-making were similar in both the WUI fire and hurricane literature; i.e., observing others; receiving warnings from multiple sources, especially from trusted sources; and receiving evacuation orders (especially those mandatory in nature) tended to result in a decision to evacuate. Another category, i.e., place and location, was identified in both data sets as influential to evacuation decision-making. Influential factors identified were locations (i.e., rural versus suburban), residency, neighbour proximity, home vulnerability (i.e., home type), home ownership, length of residence, and proximity to the hazard (i.e., the coast in reference to the hurricane studies and proximity to the fire front in a WUI fire). It is important to note; however, that the findings were not consistent across the studies, making it ever more important for additional research to be performed on evacuation behaviour in response to hazards.

Researchers identified that preparation and previous experience influenced protective action decision-making for both WUI fires and hurricanes. Similar to its impact on threat identification and risk assessment, the effect of previous experience is more complicated, requiring understanding of the type or nature of the experience (i.e., positive or negative) and its impact on future behaviour (i.e., evacuating or staying). Familial and societal responsibilities also affected decision-making in both WUI fires and hurricanes. Having children, a need to protect the family, family size, and owning pets and livestock were found to influence evacuation behaviour. The influence of pets and livestock on staying (or sheltering in place) might be further influenced by restrictive shelter policies on accepting pets and/or boarding facilities requirements of proof of vaccination (which evacuees are unlikely to have with them). Additionally, having a connection to one's community, wanting to protect property, and believing that one could successfully do so were also factors that were discussed along with the impact of one's social network and work responsibilities. Similarly, factors highlighting the important role of threat credibility and risk perception in evacuation decision-making was found in both data sets. The risk to life versus property, as well as the likelihood of evacuation being the safest option (versus being potentially dangerous), were examples of risk assessment impacts on WUI fire evacuation. The hurricane data showed that the risk of varying types of storm-related impacts such as flooding, storm surge and wind influenced people's likelihood of evacuating.

Lastly, factors influencing delay, delay time, and specific types of actions included confidence in one's capability to defend one's home in the face of a WUI fire, coastal proximity, age, family size and having (or lacking) a destination choice. Post-decision actions were identified by a few WUI fire papers and these included collecting belongings, checking on and waiting for family/friends, and deciding on the evacuation destination and travel routes to get there.

The factors identified in Table D.1 aid in the development of a conceptual model of protective action decision-making in WUI fires. Factors have been linked with various stages of the PADM to create the framework for a model that can conceptually explain eventual decisions to evacuate or stay in place (either to defend the home or to shelter in place). The factors identified from the hurricane studies fill in gaps left behind by the WUI fire studies to develop a more comprehensive model. The framework, or conceptual model presented in Table D.1, can be further developed, quantified, calibrated and validated with additional data on protective action response from a WUI fire event to eventually create a computer simulation model of WUI fire evacuation.

D.7.2 Conceptual Model Considerations

The conceptual model presented here has several limitations. First, individual study conditions can vary by hazard conditions, populations, and community environment, which in turn, can affect the factors identified as influential to evacuation decision-making and response. Also, the WUI fire studies reviewed focused on U.S. and Australian populations, which can differ greatly by evacuation policy, preparedness and experience. Within both Australia's former wildfire evacuation policy (Prepare, Stay and Defend) and its current one (Prepare. Act. Survive.), there is a greater acceptance of staying and defending, while in the U.S., community officials almost exclusively disseminate mandatory (and sometimes voluntary) evacuation orders to threatened communities.[25] Delays (or ‘‘wait and see’’ behaviours) still occur in U.S. fire evacuations; however, issues of data applicability lie in the final decision to stay or go. Policies in one country may affect evacuee perception of viable evacuation alternatives and/or their experience or

[25] Despite the practiced policy of evacuation in the United States, a number of studies suggest a growing number of people do not want or intend to evacuate automatically in the event of a wildfire and a small number of communities have looked into implementing a version of evacuation alternatives, primarily shelter in place [46], [59], [88], [89]. With that said, such cases are rare and such methods are still typically seen as a last resort if evacuation is not a possibility.

knowledge with such evacuation alternatives (which then influences the eventual decision). Little data is available on evacuation decision-making and behaviour during WUI fires in countries other than the United States and Australia. Studies of WUI fires in other countries would strengthen and broaden the scope of the conceptual model developed here.

D.7.3 Future Model Development and Research Needs

As mentioned earlier, Table D.1 provides the framework or conceptual model of protective action decision-making in WUI fire (and hurricane) events. Factors are identified as influential to each step of the PADM (noting that there is little research that identifies influential factors of the pre-decisional phases). The next step in conceptual model development is to identify the ways in which the factors that influence the same decision-making phase interact with one another in a more integrated manner. In reality, many of these factors are highly coupled and this may affect the outcome in complex ways (i.e. additive, counteractive and multiplicative). Reconciling these interactions is not a trivial task (and one that requires additional empirical support), but it is necessary for the continued development of this type of conceptual model. For instance, Dash and Gladwin [73] identified risk perception as having a greater impact on hurricane evacuation than negative past experience such as traffic delays. Similarly, it was found that risk perception could have a bigger impact than evacuation warnings if people believed their homes were safe as they were less likely to interpret such warnings or orders as being directly applicable to them and their situation [77]. This was also shown to apply in the reverse where environmental cues led people to evacuate even when they were not under an evacuation order [71]. For these reasons, understanding factor interactions at each decision-making phase of the PADM will be vital when translating these concepts into a quantitative model.

This work has focused on establishing a qualitative framework identifying the social and environmental factors to be considered within a WUI evacuation model. For implementation within a computational platform, this framework would need to be quantified. Work is currently underway to create a quantitative modelling framework (based on the framework adopted and developed here) to simulate householder risk perception given a WUI fire event and to predict householder protective actions [87]. Such predictions could be embedded within a simulation tool to make time-based estimations of the consequences of the decisions made by residents in conjunction with the resources available, the fire incident conditions and the existing physical infrastructure. An understanding of such consequences would be of great benefit in planning and design, in emergency response, and in post-incident investigations when attempting to assess the effectiveness of the emergency plans enacted. Provided here is a list of research gaps that need to be addressed to facilitate the development and validation of the conceptual model described above and the subsequent implementation within a simulation tool:

1. The factors that influence the three pre-decisional phases, including perception, attention, and comprehension.
2. The relationship between previous experience and PADM processes (e.g., threat identification, risk perception, and the protective action decision), and mediating factors.
3. A more current representation of the relationship between gender and PADM processes (e.g., threat identification, risk perception, and the protective action decision), and mediating factors.
4. The factors that influence specific actions taken before evacuation movement begins, as well as the time to complete these actions.

5. The factors that influence evacuation decisions, such as route choice and choice of final evacuation destination.
6. An understanding of the interaction of factors and their resulting outcomes.
7. Data from studies on WUI fires from populations in countries outside of the U.S. and Australia.
8. The influence of changing demographics of people living in the WUI on evacuation decision-making and response (e.g. new WUI residents and long-term aging WUI residents).
9. The influence of a changing WUI landscape (e.g. environmental conditions) on evacuation decision-making and response, especially where communities are now vulnerable to WUI fires for the first time.

D.8 Conclusion

The increasing prevalence of large and destructive wildfires is an issue of growing concern. With more people living in the wildland urban interface, being able to evacuate potentially large groups of people with little warning and in a short period of time will continue to become a more pressing and challenging task. One of the ways to address this more credibly and effectively is through the development of comprehensive WUI fire evacuation models.

A key component that must be considered in these models is protective action decision-making and behaviour in the WUI; i.e. what people do in response to the fire. Choosing to evacuate or taking another protective action is a complex process influenced by a number of diverse factors including sociodemographic factors, social and environmental cues, preparation and experience, familial responsibilities, location, and credible threat and risk assessment. Although challenging, it is important to represent these factors within WUI fire evacuation models, as they influence if/when people choose to evacuate and where they will go. At this stage, identifying the factors that influence evacuee decision-making during WUI fire events and characterizing the nature of this impact is a key step—a step that has been addressed in this article. The authors collected and categorized the factors identified as influencing evacuee decision-making and response to WUI fires and hurricanes according to the PADM framework. The conceptual model developed represents a qualitative description of the evacuation decision, delay and actions taken before vehicular movement begins. This represents an important foundation on which to build.

Overall, the development of a comprehensive and credible conceptual model of resident response to WUI fire incidents has a number of important benefits. It will allow us to develop simulation tools that better account for resident response and to quantify the impact of this response. Such tools could be used by urban and emergency planners to assess the impact of new construction and mitigate against such impacts. Similarly, first responder training may be updated to address the implications of such a conceptual model, enabling their interventions to be sensitive to expected resident responses. An understanding of resident response will allow authorities to better prepare guidance and allocate resources to meet current population's expectations, vulnerabilities, and capabilities. Additionally, regulations regarding WUI safety can be updated to account for expected resident response.

Broadening the scope of this conceptual model to include research from WUI fires and hurricanes was necessary given the limited information available; it also generated ideas for future research into the factors influencing the decision to evacuate or not in WUI fires. This approach provided the opportunity to see how factors might vary given different incident scenarios, strengthened the findings that some factors were particularly influential, and identified gaps in our current understanding that should be explored in future research.

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Appendix E: Approach to Using Human Behaviour in Fire to Inform WUI Community Evacuations

E.1 Introduction

The increasing number of fires impacting the wildland urban interface (WUI) and the growth of WUI communities in recent years has highlighted the importance of being able to safely evacuate at-risk communities [1]. Incidents such as the 2016 Fort McMurray fire and the 2017 British Columbia fires forced the evacuation of tens of thousands of people. The recent California wildfires resulted in the evacuation of hundreds of thousands of people and numerous fatalities. WUI fire evacuations are challenging as they often need to take place in a short period of time with little advanced warning. Recent international fires have shown that these challenges can result in last-minute evacuations and substantial loss of life [2]. WUI evacuations are complex, requiring the collaboration of numerous agencies and adaptability to the nature of the fire and the environment, as well as the characteristics and number of people who need to evacuate [3]. Given this complexity, it is necessary for all the influential elements to be understood, and for people from various disciplines (engineering, policy, social science, fire services, etc.) to work together to tackle the challenges posed by such evacuations.

One important component that can be overlooked when striving to improve WUI fire evacuations is the role and impact that human behaviour can have on the success of an evacuation. Human behaviour in fire (HBiF) is a multidisciplinary field of study that looks at human response to fire events [4], [5]. Though historically undervalued, the acceptance of HBiF as one of the key pillars of fire safety engineering has grown in recent years [6]. While typically associated with fires in the built environment (office buildings, apartments, houses, etc.), the study of HBiF is closely related to the field of disaster research, where researchers have sought to understand the ways people respond to natural and technological disasters such as tornados, volcanos, hurricanes, floods and more recently, wildfires. The way that people respond to these events will impact their evacuation decisions. With a more thorough understanding of the decision-making process and the factors that impact how people behave and act, researchers and practitioners can design systems, messages, procedures and communities that are better able to support safer and effective WUI evacuations.

The study of human response and decision-making during wildfires has grown over the past few decades, primarily in the United States and Australia [7]. Despite this growing momentum, there are few Canadian studies looking at the impact of human behaviour on WUI fire evacuations. Given the importance of understanding human responses to wildfires, this study seeks to build on existing research in the field, create a survey for WUI communities informed by this research, and gather information about the factors impacting people's decision to evacuate in a Canadian WUI context. This survey will be tailored to look at a specific type of WUI community found in Canada: seasonal communities.

E.2 Study Approach

This project is in progress and consists of three primary stages. Stage One was completed last year and is currently subject to peer review, Stage Two is the underway presented herein as the focus of this paper and presentation, and Stage Three will take place over the coming years involving field studies. Each stage is summarized below for context. Stage Two is the basis of this current study.

E.2.1 Stage One: Understanding HBiF during WUI Fires

Stage One consisted of conducting a review of existing literature looking at evacuation decision-making. This review included wildfire and hurricane literature so as to gain insight from understanding and comparing decision-making findings from both disaster types. Using the factors identified in the research, a first-stage conceptual model for evacuation decision-making during wildfires was created using the Protective Action Decision Model (PADM) as a framework [8]. This conceptual model improves our understanding of the factors that have the greatest impact on the different stages of the decision-making process: pre-decision, credible threat and risk assessment, and protective action decision. This literature review and the conceptual model is currently in final peer review and is expected to be published in 2019.

E.2.2 Stage Two: Survey Creation and Data Collection Preparation

Stage Two of the project consists of the creation of a survey to collect further information about the factors influencing protective action decision-making during wildfires. This survey is created based on the conceptual model developed in Stage One, the factors found to have an impact on evacuation decision-making, and the gaps in knowledge identified during the literature review. For example, it was found that most of the factors in the studied research focused on the third stage of the PADM, the protective action decision itself. Therefore, in addition to seeking information about the decision to evacuate or not, the survey seeks to gain more information about the factors that influence the pre-decision phase and the credible threat and risk assessment phase of the PADM. Furthermore, the study seeks to gain information about the amount of time people anticipate spending on pre-evacuation tasks. The survey is specifically tailored to collect data about the indented evacuation actions of residents in seasonal communities without a recent history of wildfire threat (Stage Three), however, it could be modified for use in other types of communities (non-seasonal, indigenous etc.).

E.2.3 Stage Three: Canadian Case Study

The third stage of the project will involve the piloting of the survey followed by its broader distribution within a seasonal Canadian case study community and the subsequent analysis of the collected data. Given the variable Canadian climate, seasonal communities are generally comprised of cabins and cottages where people spend time during the warmer summer months, which corresponds to the Canadian fire season. These communities, often located in the WUI, are popular with local and foreign tourists alike and can see large population fluctuations over the course of the year. As the Canadian fire season is changing and more of these communities become vulnerable to a wildfire threat [9], there is a growing interest in better understanding the intended evacuation actions of residents and the factors influencing these decisions.

E.3 Survey Creation

E.3.1 Methodology

The goal of the survey is to gain insight into the anticipated actions of residents in seasonal Canadian WUI communities. Questions were created using best principles from The Tailored Design Method [10] and inspiration was drawn from the 2016 Canadian Census [11] and the 2009 Bushfire CRC Survey [12]. The survey herein is divided into five main sections seeking to gain different types of information. These include: Cabin Information and Visits; Previous Experience; Warnings and Information Sources; Intended Actions; and Household Information.

A quantitative survey method was chosen to allow for statistical analysis to be performed on the collected data. A combination of closed-ended questions with unordered and order response were used in addition to a few partially closed-ended questions allowing respondents to specify an alternative answer. Space is provided at the end of the survey to allow participants to provide additional information that they feel is important, such as expected evacuation responses, additional previous experience or evacuation constraints.

The survey is designed with the understanding that the first case study community to be studied has not been impacted by a wildfire in recent history. Given the history of wildfire response and policy in Canada, more questions focus on information about evacuation intentions and experience than staying and defending. This decision was also influenced by findings from previous studies that have shown that people are less likely to stay and defend if the property threatened is not their primary residence.

E.3.2 Filling in Knowledge Gaps

It was noted in Stage One of the project that there were a limited number of factors identified in previous research that were shown to affect the first stage of the PADM, the pre-decisional stage. This stage has three main components: being exposed to a cue; paying attention to a cue; and comprehending a cue. Figures D.1 and D.2 show two questions in the survey that seek to gain more information about factors that could potentially affect this stage.

Figure E.1 shows a question seeking to understand if respondents have reliable access to services that could impact their ability to receive or be exposed to a cue. Given the remoteness of many seasonal WUI communities in Canada, it is important to understand if people would be able to receive a message or cue delivered via a means requiring one of the services listed. For example, Alert Ready, Canada’s national alerting system, can distribute messages about a threat or emergency such as a wildfire or WUI evacuation via radio, television, or LTE-connected devices

[13]. If a person does not have reliable access to the listed services, they could be unable to receive an Alert Ready alert. It could also impact their ability to search the internet or receive news updates. It is important to note that a wildfire can further impact these services. This question acts as a means of establishing a baseline for service accessibility in the surveyed communities.

Do you have reliable access to these services at your cabin?

	More than 90% of the time	50 – 75% of the time	25 – 50% of the time	0 – 25% of the time	Do not have access
Electricity	☐	☐	☐	☐	☐
Internet	☐	☐	☐	☐	☐
Television	☐	☐	☐	☐	☐
Radio	☐	☐	☐	☐	☐
Cellular Service	☐	☐	☐	☐	☐
Cellular Data	☐	☐	☐	☐	☐
Water	☐	☐	☐	☐	☐

Figure E.1: Survey question asking about access to services that could impact being able to receive an alert about a wildfire threat or evacuation notice

Another factor that has the potential to impact the pre-decisional phase of the PADM is language comprehension. In Canada, there are two official languages, French and English. It is therefore required by law that all official emergency messages be distributed in both languages. Canada is also a very multicultural country, and seasonal WUI communities are also popular with international tourists. Therefore, Figure E.2 shows one of the language questions asked by the survey with the aim of gaining information about the ability of respondents to understand a message delivered in one of the official languages.

Do feel confident conducting a conversation in French and/or English?	
English only	◻
French only	◻
Both French and English	◻
Neither English or French	◻

Figure E.2: Survey question asking if respondents feel comfortable conducting a conversation in French and/or English, Canada's two official languages

E.3.3 Time to Complete Pre-Movement Tasks

In addition to asking about intended evacuation actions and responses, the survey seeks to understand how long people think that they will spend on certain pre-evacuation tasks. Figure E.3 is an example of one question seeking to do this, specifically in the context of the respondent having decided to evacuate immediately (other timeframes/levels of urgency are also explored). The categories of pre-evacuation tasks were created after looking at similar questions asked in previous disaster research studies. In the case of nuclear power plant incidents, the categories used included: warning receipt, preparation to leave work; return from work; and prepare to leave home [14]. In hurricane literature, studies have asked residents in hurricane-prone areas about their intended evacuation actions, asking about the amount of time they anticipate spending on preparing to leave work, travel from work to home, gathering household members, pack travel items, protect property from storm damage (ex. install storm shutters), and secure their homes before evacuating [15], [16]. Such information is important when trying to understand potential trip generation time (TGT) which affects how long it will take people to evacuate an area. It is, however, important to understand the limitations of this question. The amount of time people expect to take is not necessarily the same as the amount of time they will actually take to complete pre-evacuation tasks during an evacuation. Given the current lack of time estimates (expected and recollected) from “identical” or similar communities, this information should be seen as exploratory and not used quantifiably.

If preparing to ***evacuate immediately***: How much time do you anticipate you would spend on the following pre-evacuation tasks? If you would not do the task or it does not apply to you, then write “0” as the estimated time. **(# minutes, # hours)**

Action	Estimated Time
Gather household members (people at cabin who you would evacuate with)	______
Gathering belongings to take with you	______
Loading belongings into vehicle/s	______
Secure cabin (turn off utilities, close windows, lock door, etc.)	______
Other (please specify) ____ ____ ____	______

Figure E.3: Survey question asking about how much time people anticipate that they would spend on pre-evacuation actions if they were planning to evacuate immediately

E.4 Next Steps

The authors plan a small pilot study distribution of the survey for user assessment, followed by the distribution of the survey in the case study community in 2019. This will be followed by the subsequent analysis of the collected data and development of a risk-based framework which will be influenced upon the results. Non-seasonal community evaluation and adaptation of the survey will follow in 2020.

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Appendix F: Emergency Egress for the Elderly in Care Home Fire Situations

F.1 Abstract

Practitioners are continuing to develop egress modelling software for the design of the built environment. These models require data about human behaviour and factors for calibration, validation, and verification. This study aims to address the specific data and knowledge gap: emergency egress of the elderly. Such data is difficult to collect given privacy and consent concerns, with strong relationships generally being required between residences and researchers. Through the observation of nine fire drills at six Canadian long term care and retirement homes, specific evacuation actions and behaviour were observed for 37 staff members and information about the evacuation of 56 residents was collected. These drills demonstrated that emergency egress in long term care and retirement homes is highly staff dependent with 72% of residents recorded requiring full assistance at all stages of movement in evacuation, and that the type of announced/unannounced drill and level of resident care will affect the type of data collected. Specific attention is given to understanding the considerations that must be made when using fire drills as data sources, and the impact that these can have on using such data for modelling.

F.2 Introduction

A demographic factor that has potential to have significant impact on the time required for emergency egress is that the global population is aging [1]. In Canada, the 2016 census showed that seniors outnumbered children for the first time in the country's history [2]. By 2036, seniors are projected to comprise 23%-25% of Canada's population [3]. This change will affect the requirements of the built environment. Aging and elderly populations require more time and assistance to evacuate in emergencies due to the increased prevalence of physical and mental disabilities [4], [5]. The Society of Fire Protection Engineers (SFPE) identified the collection of data relating to demographics, specifically vulnerable populations, as the priority theme in its 2018 Research Roadmap [6]. This demonstrates that there is a need for understanding of the behaviour, actions and dependencies of vulnerable populations, such as the elderly, in fire events.

In places such as long term care (LTC) and retirement homes, which specifically cater to this demographic, the role played by care staff can have a substantial impact on the nature of the evacuation process [7]. This can be seen in a number of prominent and deadly fires in LTC and retirement-type homes. Devastating fires (ex. Rosepark Care Home in Scotland in 2004 and in the L'Isle-Verte Senior's Residence in Canada in 2014) have resulted in significant loss of life [8], [9]. There have been over eight fires in Canadian residences dedicated to the care of the elderly within the last nine years alone with life loss (Table F.1).

Table F.1 Recent fires in Canadian long term care, retirement and seniors homes [10] – [19]

Date	Place	Location	Fatalities
Mar-18	R J Brooks Living Centre	Bancroft, Ontario	1
Sep-17	Extendicare Port Hope Long Term Care Centre	Port Hope, Ontario	0
Jul-17	Oasis Residence	Terrebonne, Quebec	1
Nov-16	Domaine des Trembles	Gatineau, Quebec	0
Mar-16	Villa Carital	Vancouver, British Columbia	0
Dec-15	Medicine Tree Manor	High River, Alberta	0
Jun-14	Extendicare Starwood	Ottawa, Ontario	0
Jan-14	L'Isle-Verte Seniors Residence	L'Isle-Verte, Quebec	32
Aug-12	Retirement Home	Edmonton, Alberta	1
May-12	Place Mont-Roc home	Hawkesbury, Ontario	2
Apr-12	Long Term Care Home	Langley, British Columbia	1
Apr-11	Rainbow Suites Retirement Home	Timmins, Ontario	1
Apr-10	St. Joseph's Residence	Winnipeg, Manitoba	0
Jan-09	Muskoka Heights Retirement Home	Orillia, Ontario	4

In order to be representative of real-life emergency situations that can inform building design, egress models must represent various elements of human behaviour and take into account the wide range of factors that can influence how and when people will evacuate in diverse situations and environments. These models require calibration, validation and verification. They rely upon access to data covering a range of populations and environments. Data of this nature can come from a variety of settings, can include a wide spectrum of demographics, and can represent varying levels of credibility for using and developing egress models and subsequent design. Herein, quantitative and qualitative behavioural data was collected through the observation of nine fire drills at six different LTC and retirement homes in Ontario, Canada. Data relates to the actions and behaviours of the residents and most specifically the dependencies on staff and caretaker members. This study discusses the limitations to be taken into account when using fire drills as a data collection method. The study is Canadian focused but certain conclusions and material will extend and have use broadly.

This manuscript is the first in a series by the authors which is intended to be followed by a modelling verification and validation study which is beyond this current manuscript's scope.

F.3 Theory

F.3.1 Legal Fire Drill Requirements

In this study, the observed retirement homes had three levels of care. These levels range from independent, assisted and memory care. In independent care, there is little to no supervisory staff needed for residents. Assisted care offers staff assistance with day-to-day activities. Memory care assistance offers extended care for residents with neuro-diverse requirements such as early stage dementia or derivatives. These residents often have difficulty with recognition and can easily be confused. For their safety, these residents receiving memory care assistance are located on a secured floor, with staff assistance available. LTC home residents tend to require physical or cognitive assistance and have restricted mobility. Enhanced monitoring and care is provided with 24-hour nursing.

The two types of care homes are both required to have fire safety training and procedures per the National Fire and Building Code of Canada (NBC and NFC herein) in addition to the provincial codes [20], [21]. The procedure of a fire drill is the responsibility of the building management [22]. The procedure should address the potential building fire hazards with respect to the residing occupants, note building safety features, indicate the target number for non-staff occupant participation during the drill and the number of trained staff involved. Procedure should follow the fire department regulations and confirm that the emergency systems comply with the NBC [22]. The NFC also addresses that the frequency of the fire drills depends on the occupancy type. For elderly care homes, the staff are required to participate in a fire drill once a month and the staff participation must be recorded. In LTC homes, three fire drills are required every month, one on every shift (morning, afternoon, night) [21], [23]. Both LTC and retirement homes are required to have one fire drill per year observed by a city fire marshal. This drill must represent the worst-case timing scenario - the least number of staff that would be present in the home - the night shift. It also requires that all residents in the fire drill wing be evacuated to a place of relative safety e.g. to an adjacent fire compartment, and not necessarily to outside the building. The code allows staff members to stand in and act in the place of residents [21], [23].

F.3.2 The Role and Purpose of Fire Drills

A drill can be defined as "an exercise involving a credible simulated emergency that requires personnel to perform emergency response operations for the purpose of evaluating the effectiveness of the training and education programs and the competence of personnel in performing required response duties and functions" [24]. Drills are often used to evaluate the performance of individuals in a simulated emergency environment so as to gauge how they could perform during a realistic emergency. Drills can also be seen as training and educational activities to teach people how they should act in an emergency situation [22]. In both cases, drills provide the opportunity to address performance, be it an individual act, role or procedure, or the interactions between different groups, individuals, environments, and emergency scenarios. Drills can also provide opportunities to gather valuable information about evacuee behaviour and procedural design [25]. Given that conducting "experiments" in the traditional sense of the word is generally not possible for ethical and safety concerns – particularly with vulnerable populations – drills, along with other models, can provide a limited opportunity to better understand aging populations' behaviour in fire. Egress drills are commonly used tools. However, their benefit, effectiveness and limitations are not widely understood as discussed in depth elsewhere [22]. This is a critical consideration when using drills as a means of data collection for research. It is important to understand that drills are a simulation, a model of an emergency situation. Practicality, safety, cost and ethics can limit their value [22]. Researcher influence can also impact the realism of a drill and the quality of the data collected and should therefore be managed carefully to minimize its impact [26]. For the modeller using this data it is critical to know the limitation and applicability of the data to keep it within context and understand its impact on the practitioner's uncertainty.

F.3.3 Egress Data and Evacuation Modelling

Over the past few decades, evacuation modelling software has been developed for applications in crowd dynamics, pedestrian movement and evacuation processes [27]. These models are used by various fields and disciplines, and as such they play an important role in understanding and representing human movement and evacuation behaviour. There exist many different egress models, ranging from hydraulic calculations to adaptive agent-based approaches [28]. These models vary in the way that they configure buildings, populations, and procedures [29]. Practitioners have reviewed and summarized the features and capabilities of current egress modelling software [30], [31].

Models rely on an understanding of the situation being simulated and appropriate data input. This data is not only used for creating egress model simulations, it is also necessary for the verification and validation of the tools themselves [32]. Data can come from a variety of sources including simulated emergency evacuations such as fire drills. Much of the data collected available in publicly accessible literature has been compiled and can be found in the fifth edition SFPE Handbook [33]. An understanding of human behaviour in fire and the dependencies between groups and their care takers are important when using and interpreting the data available. Additionally, data collection context, techniques and processes can have a large impact on the nature of the data collected and therefore need to be considered when looking to use the data in a computer model specifically when dependent behaviour is sought to be understood.

F.4 Methodology

Data relating to fire drills and procedures was collected in collaboration with three LTC homes and three retirement homes. The characterization of the buildings used for the nine drills is summarized in Table F.2 and E.3. The drills are numbered in the order that they were observed. Early research focused on LTC homes (Drills 1-4, 6) while the more recent studies focused on retirement homes (Drills 5, 7-9). The first four drills were monthly drills in which resident participation was not mandatory while the latter five drills were legally required annual fire marshal-observed drills.

Table F.2 Summary of participating long term care and retirement home locations where data was collected

	Drill 1[a]	**Drill 2**	**Drill 3[a]**	**Drill 4**	**Drill 5[b]**	**Drill 6[a]**	**Drill 7[b]**	**Drill 8**	**Drill 9**
Number of Storeys	3	3	7	2	5	3	5	5	6
Number of Residents	161	193	180	192	127	190	125	N/A [c]	N/A [c]
Long Term Care Home	X	X	X	X	-	X	-	-	-
Retirement Home	-	-	-	-	X	-	X	X	X

[a] Drills 1, 3 and 6 were observed in different wings at the same location at the same level of care but at different dates so occupancy differs.
[b] Drills 5 and 7 was observed at the same location at different levels of care location at the same level of care but at different dates so occupancy differs.
[c] Exact occupancy not available but > 100.

Table F.3 Summary of fire drill conditions

	Drill 1	**Drill 2**	**Drill 3**	**Drill 4**	**Drill 5**	**Drill 6**	**Drill 7**	**Drill 8**	**Drill 9**
Type of Drill Observed	Monthly	Monthly	Monthly	Monthly	Annual	Annual	Annual	Annual	Annual
Working Shift	Day	Evening	Evening	Evening	Night	Night	Night	Night	Night
Number of Staff	15	7	9	7	3	8[a]	3[b]	3	3
Number of Staff Stand-Ins	0	0	0	0	3	11[c]	1	0	4
Number of residents participating	3	1	2	2	10	14	22	14	6
Number of residents that did not evacuate	0	1	0	0	0	0	0	4	0
Number of residents recorded	3	0	2	2	10	5	18	10	6
Autonomous residents recorded [e]	3	0	0	0	1[e]	0	11	1	0
Drill Timing to “all clear” (mm:ss)	6:00	5:00	4:52	3:23	13:33	9:08	14:28	15:05	7:38

[a] 8 staff participated in the drill, data was collected for 3 of them
[b] 3 staff participated in the drill, data was collected for 2 of them
[c] 11 staff stand-ins participated in the drill, data was collected about 7 of them
[d] Resident evacuated on their own, but were returned to their room and then evacuated by staff
[e] Autonomous is defined as residents who left their rom on their own ability and moved to the safe zone on their own ability, with or without prompting, with or without walkers, wheel chairs etc.

F.4.1 Building Connections and Conducting Interviews

The first stage of the research involved building a relationship of trust with LTC and retirement homes. Four rounds of written requests were sent out to managerial staff at various homes describing the project and inquiring about their willingness to be interviewed about the home's fire safety practices, policies and evacuation procedures. It was made clear that the authors would answer questions or discuss any concerns that the home representatives had prior to agreeing to an interview. Table F.4 details the response rate for each round of interview requests. Interviews were conducted and transcribed in person with managerial staff. The pre-determined questions focused on general building information, fire detection systems, active and passive systems, fire strategies and staff procedures, resident level of care as well as general demographics and resident population characteristics.

Table F.4 Response rate for each round of interview requests

Round of Interview Email Requests	Request Timeframe	Type of Home	Number of Homes Contacted	Number of Homes that Responded	Number of Homes that Agreed to Participate	Number of Homes Where Interviews Were Conducted	Number of Homes Where Drills Were Observed
1	Sept. 2014	Long Term Care	8	4	3	2	1
2	Sept. 2015	Long Term Care	7	4	4	4	3
3	Jan. 2016	Retirement	7	2	1	1	1
4	May 2017	Retirement	15	6	4	3	3

F.4.2 Fire Drill Observation and Data Collection

Following the interviews, the participating homes were asked if they would be willing to allow members of the research team to observe one of the homes' required fire drills as part of this research study; six different homes agreed. The authors were invited to observed drills that were pre-arranged by the different homes based on monthly or yearly fire drill requirements. Information such as floorplans, staff fire safety procedures and anticipated number of participants were acquired in advance of each drill and were used to prepare a guide which was given to each observer. Drill conditions can be seen in Table F.3.

The method of observing each fire drill followed a similar process so as to maintain compatibility and allow for comparisons to be made. Each drill was observed in person from within the designated fire wing (outside the room compartments). An in-person observer method for data collection was necessary given that informed consent of residents living with dementia could not practically be obtained for using cameras for data collection. Additionally, filming nursing staff during the fire drills was forbidden as third-party evaluation by film was prohibited by their unions. Research ethics were also more easily obtained in this method of data collection. It is acknowledged by the authors that this method of observation does not allow for all events that may occur during a drill to be recorded and analyzed. While the authors acknowledge this can and does result in a loss of important data, the willingness of the homes to allow the drills to be observed in the first place was in part due to the fact that cameras were not being used.

At each home, the authors met with the drill coordinator for a pre-drill discussion on the details of the drill. If the drill was a worst-case scenario annual drill, the drill coordinator would also hold a pre-drill discussion with the staff members participating to review procedures, assign roles, and answer questions. The drill observations took place within the building wing where the evacuation was taking place. Three to four researchers (led by at least one of the authors, but also including those on their research team) attended each fire drill and were positioned along the corridors of the fire drill area to limit interference with staff procedures. The number of researchers in attendance at each drill was determined based on maximizing the amount and quality of data collected, and by minimizing the impact of the observers on the drill (based largely on the geometry of the floorplan).

The information collected evolved as the project progressed to collect more specific information. For the first four drills which took place at LTC homes, each observer was responsible for recording general observations of participating staff and residents along with the corresponding times. For Drills 5 – 9, the timestamps of specific actions, including when staff members entered the wing and when residents or staff entered a room, left a room, and entered the safe zone, were the focus of the observation. Behaviours exhibited and actions undertaken by both staff and residents were also noted, along with the times that they were observed. For these later drills, the observation task distribution between the researchers depended on several factors including the geometry of the building wing being evacuated, the level of care being provided (and corresponding level of resident dependency), and the number of participating staff and residents.

For Drills 5, 6 and 9, each researcher recorded the actions of one staff member. This was deemed the most effective method given that the residents in Drill 5 and 6 had a high dependency on staff (memory care floor or long term care home) and would therefore not evacuate on their own, and for Drill 9 there were only a few residents living on the evacuation floor. It should be noted that in contrast to Drills 5 and 9 where the number of observers equalled the number of participating staff members (3:3), there were more staff participating in Drill 6 than there were observers (8:3). It was determined that in order to collect data to the degree of specificity required while not unduly interfering with the drill by having too many observers present, it was necessary to focus closely on a select number of staff. Therefore, each researcher observed one staff member. This meant that the same amount of data was collected as in the other drills, but the proportion of data collected to potential data was smaller.

For Drills 7 and 8, researchers focused on recording actions observed in specific sections of the wing. This was deemed the most effective method as the drills took place on floors where residents were more independent and autonomous and therefore were expected to evacuate without extensive staff assistance. This method allowed the researchers to observe and record the actions of both the staff and the residents (both autonomous and non, herein we define autonomous as residents who left their room on their own ability and moved to the safe zone on their own ability, with or without prompting, with or without walkers, wheel chairs etc). Given the floorplan geometry, this method also allowed the researchers to remain in one place throughout the drill, limiting their impact on the drill. Following each drill, the researchers observed the post-drill discussion held by the drill coordinator with the participating staff (and the fire marshals if present). After leaving the homes, the researchers then met to discuss the drill and to consolidate the raw data each person had collected.

F.5 Results

F.5.1 Interview Data

Though each home had different architectural designs and features, the buildings were typically organized in the same way. In the LTC homes, this meant that each floor was compartmentalized into wings or units, which were straight hallways that generally branched off a central core. The elevators were centrally located, and fire rated stairwells were located at the end of each unit. The wings were separated by fire rated doors, creating compartmentalized units. This enabled horizontal evacuation to take place during emergency situations. In the retirement homes, this compartmentalization was only seen if the home had a floor or wing designated for the care of residents with dementia. Most floors of the retirement homes consisted of rooms branching off a main hallway. Horizontal evacuations were still the first stage of an evacuation in the retirement homes, however residents could be evacuated to the stairwells.

In the LTC homes, the average age of residents was 75 to 88 years. Based on their knowledge about the residents, it was estimated by the interviewed staff members that between 88-100% of residents would require some form of assistance to evacuate horizontally given the number of residents with cognitive and/or physical disabilities. While the need for assistance was less than in the retirement homes, in one building for example, over 90% of the residents would still require assistance to go down the stairs. Staffing levels were consistent among both the LTC and retirement homes - that the least number of staff were present during the night shifts.

The interviews provided information on the fire evacuation procedures and practices at each home. Each home had a fire plan that was updated annually and reviewed by the fire department. The official procedures varied from home to home, however they were similar in nature and are published in publicly available policy literature. REACT was the most popular fire response procedure (Remove those in danger, Ensure door is closed, Activate alarm, Call 911, Try to extinguish the fire), with one home using the RACE method (Rescue, Alarm, Contain the fire, Extinguish) and another using the SCATEE method (Save, Contain, Alarm, Telephone, Evacuate, Extinguish). A few home representatives did not cite a specific reaction acronym, however the approach they described closely resembled the REACT method.

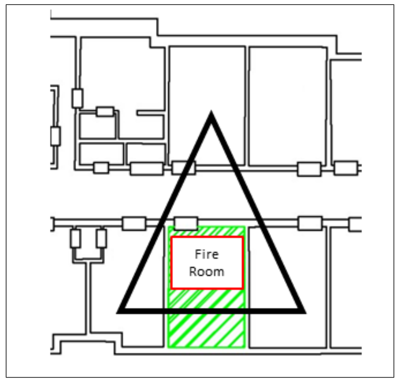

Figure F.1: Visualization of the "critical triangle" that determine what are weighted to be evacuated first.

In addition to the initial fire safety training they received as part of their orientation upon being hired, employees were required to participate in annual training and fire drills. During the monthly fire drills, the residents were not required to participate as it was viewed more as a way for the staff to practice the steps that they would need to go through in an actual fire evacuation. In both the LTC and retirement homes, this involved locating and evacuating the fire room (and any connecting rooms) followed by the rooms on either side and the one directly across the hall from the fire room: these occupants are considered most at risk during the initial stages of a fire. This was referred to as the critical triangle (Figure F.1). The rooms were then to be progressively evacuated, starting with those in closest proximity to the fire room. All doors were to be closed after each room was evacuated. Each home had a way of designating which rooms had already been evacuated. Some homes used Evacuchecks which were tabs attached to the doorframe of each room that could be flipped once the room had been checked, other homes hung a tag on the door handle (Figure F.2a and F.2b).

Figure F.2: (a) Evacucheck before evacuation (b) after evacuation

In the LTC homes, where some residents were bedridden, several different methods of physically assisting residents during real evacuations were described. One home could use mechanical lifts to move bedridden residents into a wheelchair, another home moved the beds themselves into the hallway and into the safe zone. The two other interviewed LTC homes used what was known as the blanket method, where bedridden residents were wrapped in their sheets, guided to the floor and then pulled into the safe zone. As the participating retirement homes did not have any bedridden residents given the level of care they provided, such methods were not necessary. Additionally, it was also expressed by the LTC home interviewees that while the staff were searching for the fire, they were supposed to close any open resident room doors as well as clear the hallway of all obstacles (wheelchairs, nursing carts, etc.). In the LTC homes, the staff were also expected to make a "Code Red" announcement over the intercom at the start of the drill to inform all staff in the building that a fire had been detected. In contrast, staff at the retirement homes were notified of the fire emergency via handheld radios instead of over the intercom system. During both LTC and retirement home fire drills, one staff member was expected to simulate calling emergency services and one staff member was required to remain on a floor or wing that provided physical and/or cognitive assistance.

F.5.2 Drill Observations

Sections 4.2.1 – 4.2.9 provide summaries of the nine observed drills, where only critical information is provided. The significant times recorded for each observed action and behaviour are written in mm:ss format. The drill floorplans (Figures E.3 – E.11) may show more residents and staff stand-ins than are noted in the description as the location of all participating residents and staff stand-ins were disclosed prior to some drills. Rooms labelled "Room #" represent resident rooms that were or would normally be occupied by a resident (including rooms from which residents were not evacuated during the drill). Rooms labelled "Vacant Room #" indicate rooms where residents were not living at the time. Research observer locations are shown in each drill figure. Tables E.1 through E.3 summarize parameters for each drill.

F.5.2.1 Drill 1 (Long Term Care Home – Day time working shift)

Fifteen staff members participated in the drill. Three residents participated and evacuated without any assistance from staff. The other residents in the wing either remained in their rooms or had left just before the drill started.

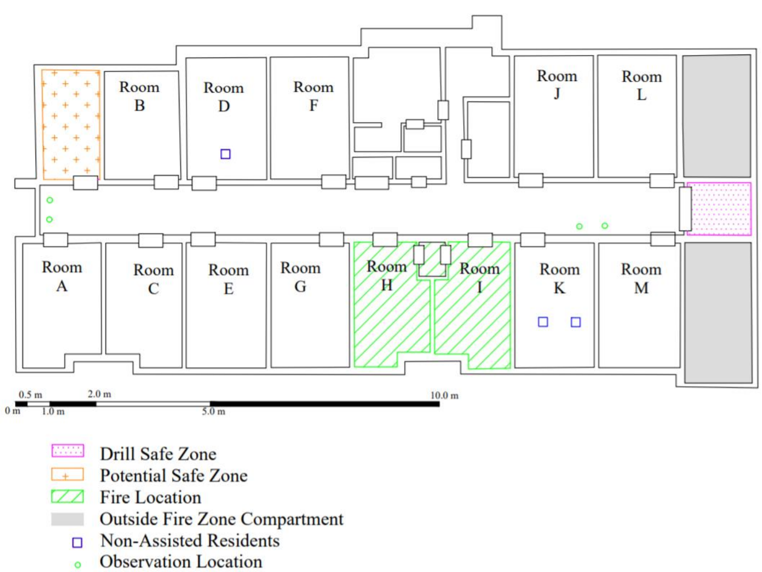

Figure F.3: Drill 1 Floorplan

The floorplan of the wing where the drill took place can be seen in Figure F.3. The drill started with the activation of the fire alarm and an announcement over the intercom indicating "Code Red". After 30 seconds, the staff at the nursing centre began discussing if they should call emergency services. They were told by another staff member not to as it was "just a drill". At 0:50, one resident evacuated the wing through the main exit instead of the one adjacent to their room. The fire room was located after 1:20 and staff begin to clear the hallway. At 2:20, a staff member was assigned to simulate calling emergency services. Once the hallway was cleared, the staff began checking resident rooms, closing doors and marking the rooms as clear. Two residents from the same room evacuated the wing at 3:39. Ten seconds later, one of those residents returned to their room. Staff announced that the evacuation was complete at 4:15 and “all clear” was announced at 6:00. The post-drill debriefing followed. During the debriefing, staff members discussed their confusion about what they should do during an evacuation (when to call emergency services, which exits to use, what to do at night when they are short-staffed). The drill coordinator then reviewed the steps according to the home's fire safety plan with the staff.

F.5.2.2 Drill 2 (Long Term Care Home – Evening time working shift)

The second fire drill took place on the evening staffing shift. It was expected that three to four residents would participate, though none did. According to the home's fire safety plan, the residents who were bedridden would be kept in their beds and then moved out of the wing. However, this was not something that was intended to be simulated during fire drills.

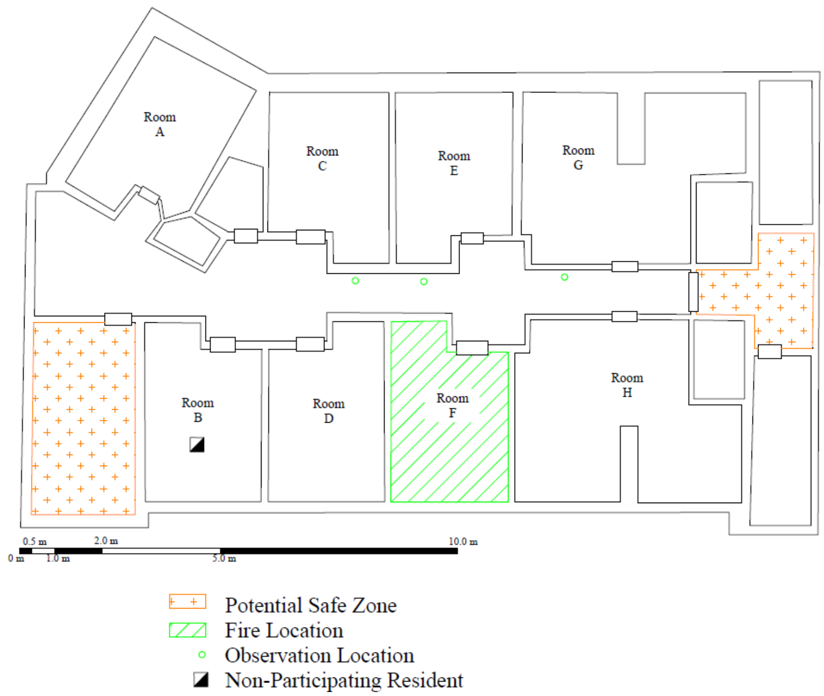

Figure F.4: Drill 2 Floorplan

The floorplan of the evacuated wing can be seen in Figure F.4. The fire alarm indicated the start of the drill, after which "Code Red" was announced over the intercom. The first staff member entered the wing at 0:19 and entered the designated fire room at 0:32. During the 24 seconds that the first staff member was in the fire room, two additional staff entered the wing. Upon leaving the fire room (not closing the door to the room all the way), the first staff member moved back down the hallway. Ten seconds later, a second staff member checked the fire room, leaving 10 seconds later and closing the door. At 2:00, a green checkmark was placed on the fire room door and the door of the room next to it, and a fourth staff member entered the wing. Three additional staff members entered the wing at 2:12, with one asking if the fire room had been checked. At 3:00, one staff member said that all the residents were in bed and another staff member finished checking a room and stood outside the room with the door open (a resident was inside the room). At 3:11, the drill coordinator announced the end of the drill and the staff began to move into the hallway outside of the wing. The post-drill debriefing began soon afterwards, and "all clear" was announced over the intercom at 5:00. A key point that the staff discussed during the post-drill debriefing was that there needed to be a better way for staff within the fire wing to communicate with those outside the wing as there was no way to know how many staff should be sent to assist with the evacuation.

F.5.2.3 Drill 3 (Long Term Care Home- Evening time working shift)

The floorplan of the wing where the third drill took place can be seen in Figure F.5. The drill coordinator activated the fire alarm in the room that was to act as the fire room. The coordinator remained in the room until located by one of the participating staff members, as their presence indicated that it was the fire room.

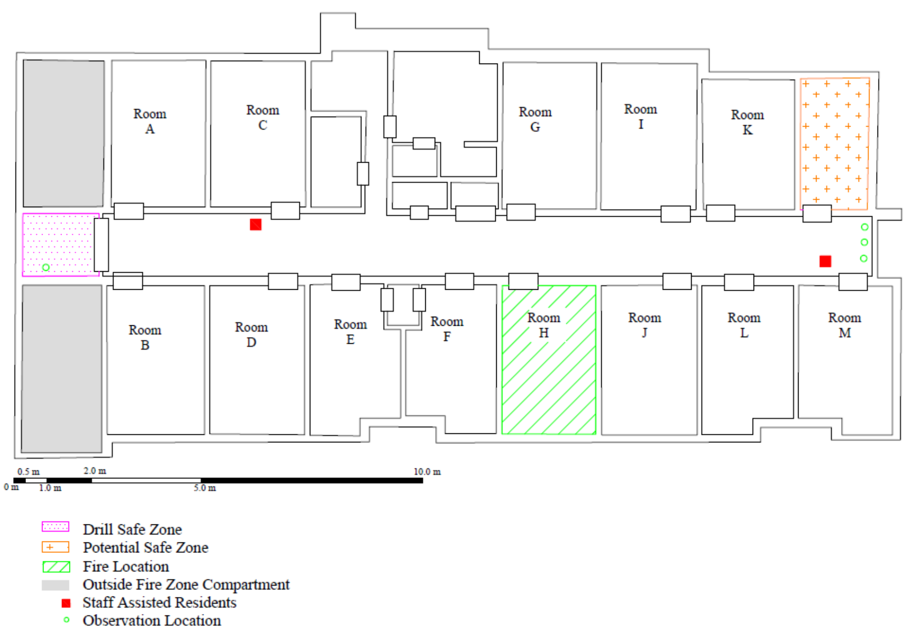

Figure F.5: Drill 3 Floorplan

When the alarm sounded, one staff member was already in the wing. "Code Red" along with the fire wing location was announced over the intercom at 0:20. A second staff member entered the wing 10 seconds later. Seven more staff entered near 1:00. At 1:10, a staff member began moving a resident toward the main safe zone (1:31) and a resident at the far end of the hall was moved back into their room to allow staff to conduct the complete egress procedure for all rooms. At 1:27, the fire room was identified by one of the staff members. At 2:00, the staff started clearing the hallway in the fire wing, and soon after the door to the fire room was closed. During the drill, two non-participating residents in the safe zone tried to enter the fire wing and were stopped by staff members outside the wing. Two staff members re-entered the fire room at 2:30, leaving soon after and closing the door as another staff member asked if they checked to see if anyone was in the room. Soon after, a custodial staff member (not part of the drill), moved a cleaning cart from the hallway and into the safety zone, leaving it directly on the other side of the fire doors. The hallway was clear at 3:00, and 15 seconds later, a staff member opened the fire room door again. At 4:00, the Evacucheck was flipped on the fire room door, after which staff members began flipping Evacuchecks on other resident room doors. The drill ended with "all clear" announced at 4:52, 20 seconds after the drill coordinator ended the drill. The drill was followed by a staff debriefing. A participating staff member discussed her confusion on how to use the Evacuchecks.

F.5.2.4 Drill 4 (Long Term Care Home – Evening time working shift)

It was the home's policy that mechanical lifts be used for bedridden residents as the home had a no-lift policy for the employees. During the fourth drill, the staff were expected to simulate using the lifts (taking one to the resident room but leaving it outside the door). The drill coordinator mentioned that the home had adopted a new procedure approximately one and a half years ago, and that the staff were still adapting to it. Specifically, the staff were now expected to check and evacuate all rooms in the wing as opposed to just the critical triangle. The drill coordinator also mentioned that fire drills were being used as both a training and evaluation tool. The floorplan of the wing where the drill took place can be seen in Figure F.6.

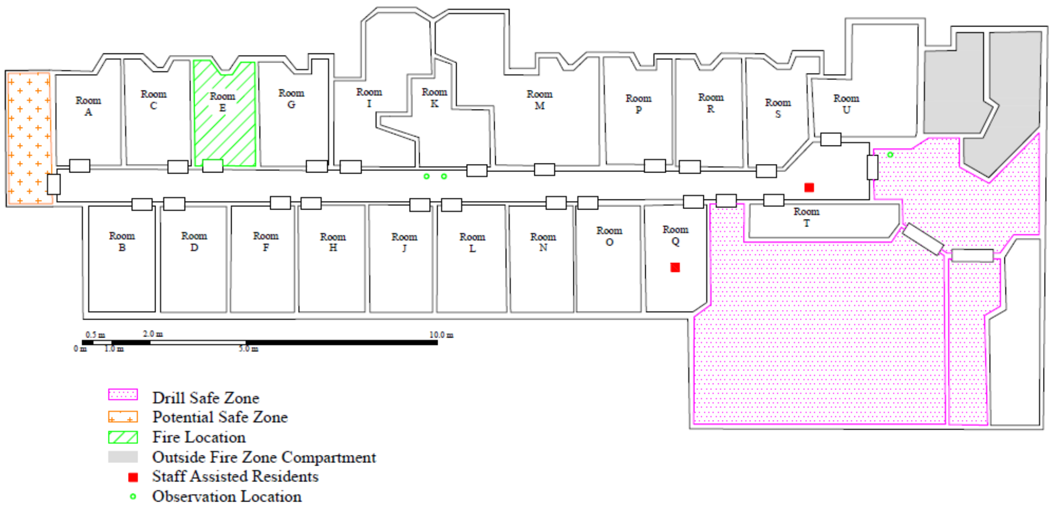

Figure F.6: Drill 4 Floorplan

The fire alarm signaled the start of the drill and 15 seconds later a resident in a wheelchair was moved from the hallway to the safe zone. A second resident was also evacuated from the hallway to the safe zone at 1:00 after two staff members spent 15 seconds debating where to take the resident. The door next to the fire room was closed at 1:41, followed by the door to the room across from the fire room. At 1:50, a third staff member entered the wing, and 12 seconds later a towel was placed at the base of the fire room door. During the following minute, four additional staff members entered the wing, standing around and waiting for something to do. At 3:12, a staff member left the wing to say that everything was done. At 3:23 "Code Red All Clear" was announced. During the drill it was noted that key elements of the home's fire emergency procedures were not executed. Examples included not simulating lift use and neglecting to close the doors and evacuate all resident rooms. In the post drill debriefing, the staff expressed that the drill generally went well. The drill coordinator briefly discussed a few things that were missed, and the staff asked a few questions.

F.5.2.5 Drill 5 (Retirement Home – Night time working shift)

In addition to the three staff, ten residents participated in the fifth drill along with three additional staff members standing in place of residents. The floorplan of the wing where the drill took place can be seen in Figure F.7. All participating residents were evacuated to the section of the hallway separated by the fire doors; the stairwell at the other end of the hall was not used.

There were initial difficulties with the staff's hand-held notification system, so the fire room was not located nor entered until 2:02. During that time, a resident left their room independently and made their way towards the safe zone before being prompted by one of the observing staff members to go back to their room. Two staff members initially entered the fire room, but one left 30 seconds later to begin evacuating the room beside it. At 3:45, the first resident in the fire room was assisted into the hallway but tried to get back into the room. The second resident in the fire room entered the hallway at 4:06 and both residents then travelled with a staff member to the safe zone. Two staff members continued to evacuate the rooms, starting with those in closer proximity to the fire room. The third staff member entered the wing at 5:44 (they had been on the main floor meeting the fire marshal as would happen during a real fire). Once all of the rooms had been checked and the residents had been evacuated, the rooms were then rechecked and tagged to show that the rooms were clear. During this second check, a resident was found hiding in their room, 10 minutes after the drill started. This resident was then evacuated, and the remaining rooms were double checked and tagged. The drill lasted a total of 13 minutes and 33 seconds.

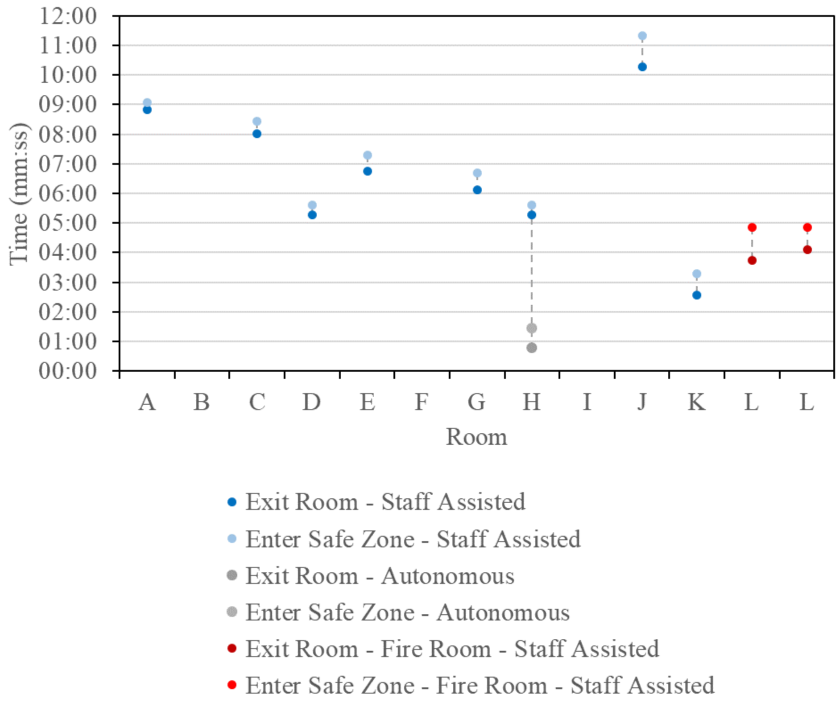

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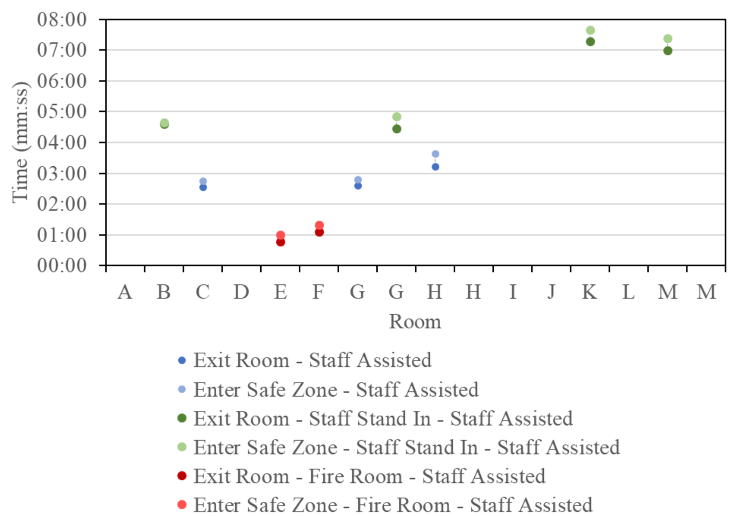
Figure F.7: (a) Drill 5 Evacuation Timeline (b) Floorplan

F.5.2.6 Drill 6 (Long Term Care Home – Night time working shift)

The sixth drill was observed in the same long term care home as the first and third drill, and was an annually required worst-case scenario drill. Each of the three observers were responsible for watching one staff member. As with the previous worst-case scenario drill, all the staff were aware that a drill would be taking place. During the pre-drill discussion with the drill coordinator and participating staff, the details of the evacuation were explained, roles were assigned, and staff questions were answered. Eight staff were assigned to evacuate the wing and 11 staff were designated to act as resident stand-ins. The residents chosen to be replaced by staff members were pre-determined based on their requiring a personal lift to get out of bed or their history of uncooperative behaviour. During the pre-drill discussion, the participating staff members were given the opportunity to practice the blanket evacuation method that was to be used to evacuate the staff stand-ins replacing bedridden residents. During this time, the research team selected three of the participating staff to focus on during the drill.



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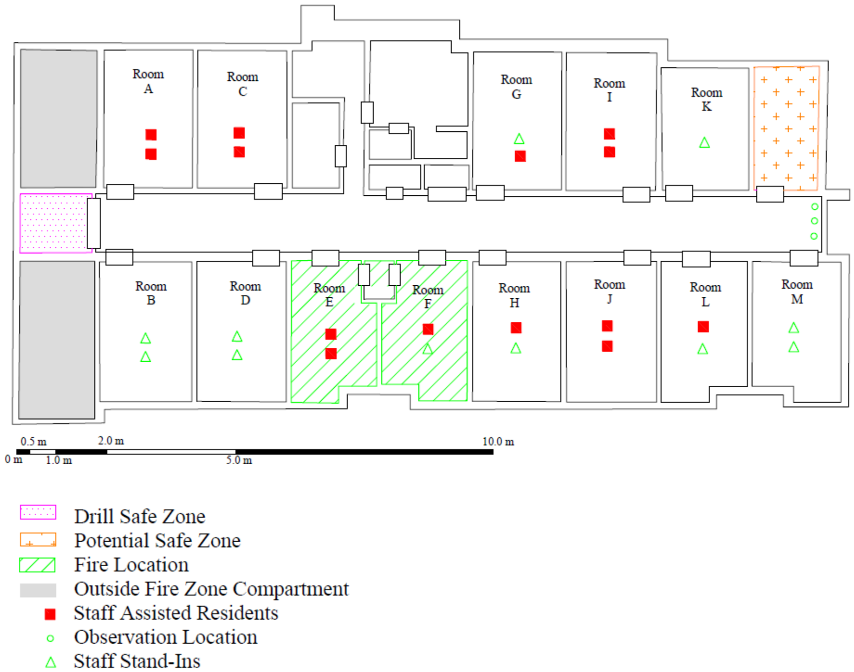

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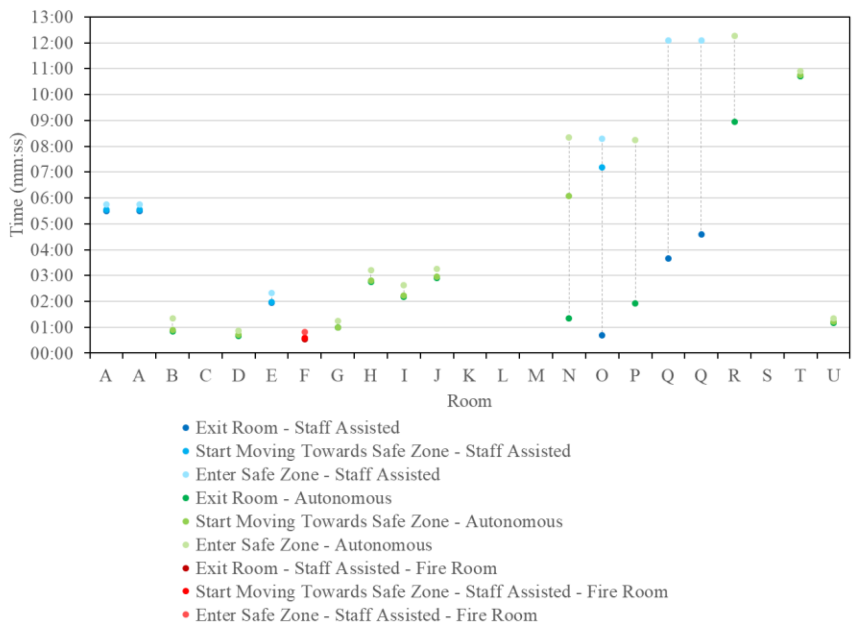
Figure F.8: Drill 6 (a) Evacuation Timeline (b) Floor plan.

The floorplan of the drill location can be seen in Figure F.8. The fire alarm was set off by the drill coordinator from within the designated fire room. The first staff members to respond started checking the rooms to locate the fire. Once the fire room was identified at 0:34, the evacuation started with that room and the one connected to it via a shared washroom, and then proceeded to the critical triangle. One staff member was the designated site manager and this person was in charge of directing all of the other staff. This person did not help with the physical checking of the rooms or the evacuation of residents, with the exception of assisting ambulatory residents who only needed guidance. After the evacuation of the critical triangle, the other rooms were also evacuated. From the start of the alarm to the drill being deemed complete by the organizer and the observing fire marshal, the drill lasted 9:08. In addition to the 11 staff members, 14 residents were evacuated from the wing. During the post-drill debriefing, one of the main points discussed was how physically strenuous the blanket method evacuation was, especially after it had been done several times. The staff expressed concern over the feasibility of the night staff being able to evacuate certain residents in this manner.

F.5.2.7 Drill 7 (Retirement Home – Night time working shift)

In contrast to the fifth drill which was observed on a memory care floor at the same home, this drill took place on an independent care floor without fire separation doors. This meant that all residents on the floor were meant to be evacuated to the stair-wells. Twenty-two residents and three on-duty staff members participated in the drill, although one staff member was required to stay on the memory care floor and did not participate in the evacuation. Four additional staff members were located in the safe zones for resident safety and supervision. The longer hallway was divided into two sections shown on the floorplan in Figure F.9. Residents on one half of the wing were evacuated to Stairwell 1 and residents from the other side were evacuated to Stairwell 2. The residents and staff were informed in advance of the date and time the fire drill would occur.

The alarm was sounded for 5 minutes at the start of the drill, then was silenced as to not disturb the rest of the building and occupants. The fire alarm was first sent to the responding nurses' communication phones, which they responded to before the audible alarm was heard by the fire marshal or observers. The evacuation followed the critical triangle method. The resident in the fire room required staff assistance and was observed to have exited the room at 0:32, pushed in a wheelchair by the staff member, and then entered the safe zone at 0:49. Two ambulatory residents evacuated on their own once the audible alarm began. Most other residents evacuated when instructed by the staff member, but some were confused about the procedure. Those residents exited their room and sat on their walkers, awaiting staff assistance to the safe zone. One room housed a married couple in which the spouse would not leave without the other resident who insisted they finish showering before evacuating. The second staff member, who had attended the fire command centre, entered the fire drill wing at 4:05. Occupied and vacant rooms underwent two checks before an "All Clear" marker was placed on the door handle, indicating the room was empty. There was one wheelchair-bound resident who independently initiated evacuation once the alarm sounded but was not observed to have entered the safe zone and was later seen re-entering the floor via elevators. The drill ended at 14:28. A key finding was that although this drill occurred on an independent care floor, a majority of residents still required verbal cues from staff to initiate evacuation and some even thought it was the staff's responsibility to guide each resident to the safe zone. This highlighted the important leadership role of staff in these establishments even if the residents were perceived as independent.



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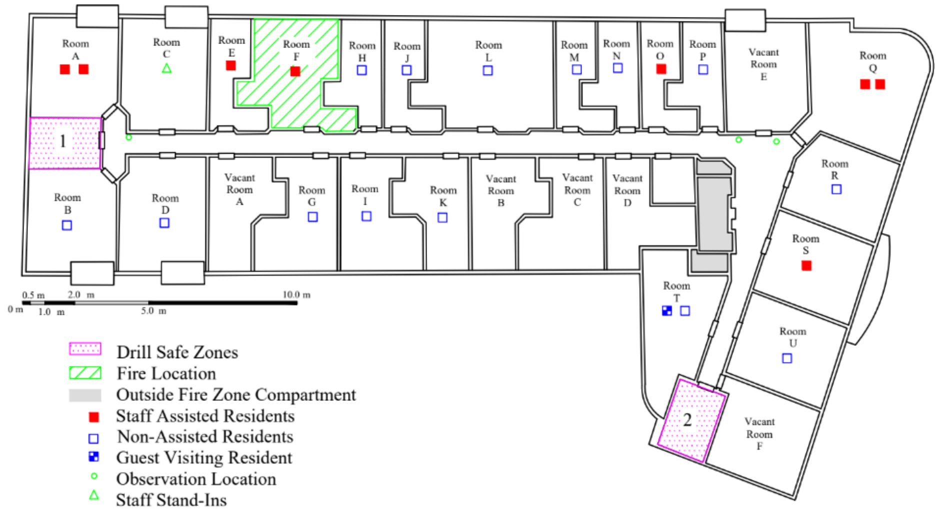


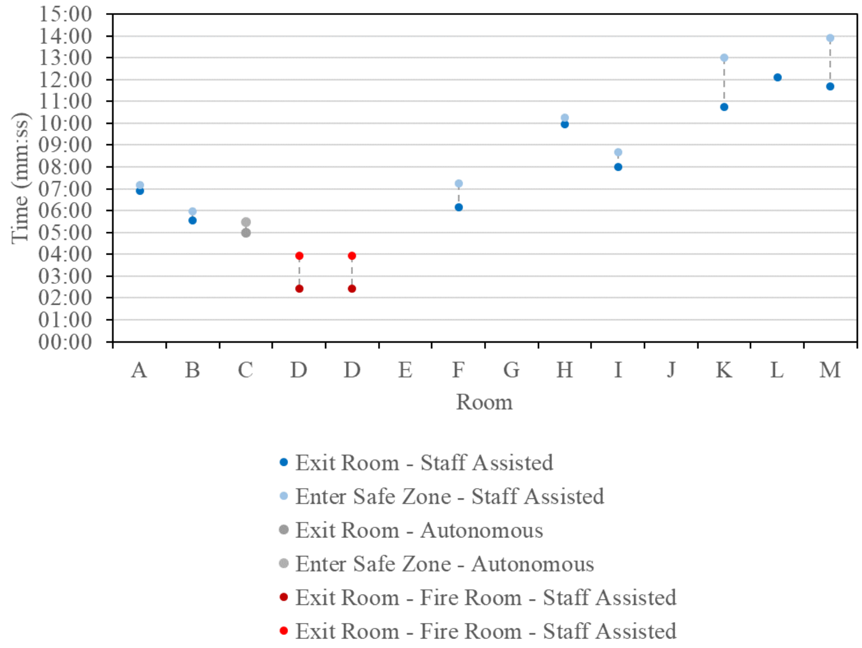
(b)

Figure F.9: Drill 7 (a) Evacuation Timeline (b) Floorplan

F.5.2.8 Drill 8 (Retirement Home – Night time working shift)

The eighth observed drill was held on an assisted living floor that was not secured; it had two wings separated by a fire door to create compartmentation shown in Figure F.10. As this was an annual worst-case scenario drill, the staff of the building were notified of the fire drill details in advance while the residents were notified of the date but not the time that the drill would occur. Three on-duty night staff and 14 of an expected seventeen residents participated, four of whom abstained from evacuating (two refused to evacuate, two were told by staff that they did not have to evacuate). Four observing administrative staff, two maintenance staff and two fire marshals were also in attendance on the fire floor in addition to the three research observers and the two drill coordinators. The floor was separated into two fire safety zones by a fire door to which the residents were evacuated past into the safe zone following the critical triangle method.

On arrival, staff members were overheard discussing the proper procedures for the drill. This was a silent drill therefore the fire marshal indicated the start of the drill. One staff member was required to go to the fire control centre to discover where the fire was located while the other two entered the fire wing and awaited the fire location. Once the location was known, the first staff member evacuated the fire room while the second staff member began notifying the resident in the adjacent room of the evacuation. The residents occupying the fire room were confused and exited the room at 2:25 and then entered the safe zone at 3:57. A resident who did not require assistance other than a verbal cue then evacuated to the safe zone. The third staff member re-entered the wing almost 8 minutes after the drill started. For both occupied and vacant rooms, one check was conducted before the room was declared empty of residents and a marker was hung on the door. One staff member was repeatedly reminded to properly close the door after exiting the room with a resident or after the check. The second staff member encountered two non-participating residents and instructed a third resident that participation was not necessary. This staff member then proceeded to jog with said resident's walker to the safe zone in an attempt to emulate the evacuation actions. At 11:30, visitors entered the fire drill zone via elevators and stood in the lobby area. The fire marshal did not require staff to evacuate a wheelchair-dependent resident to the safe zone if it caused undue stress to the resident. The last resident who entered the safe zone did so at 13:55 and the drill was deemed complete soon after. In the post-drill discussion, the fire marshals emphasized that the building was sprinklered and had compartmentation therefore firefighting actions by staff were not required.



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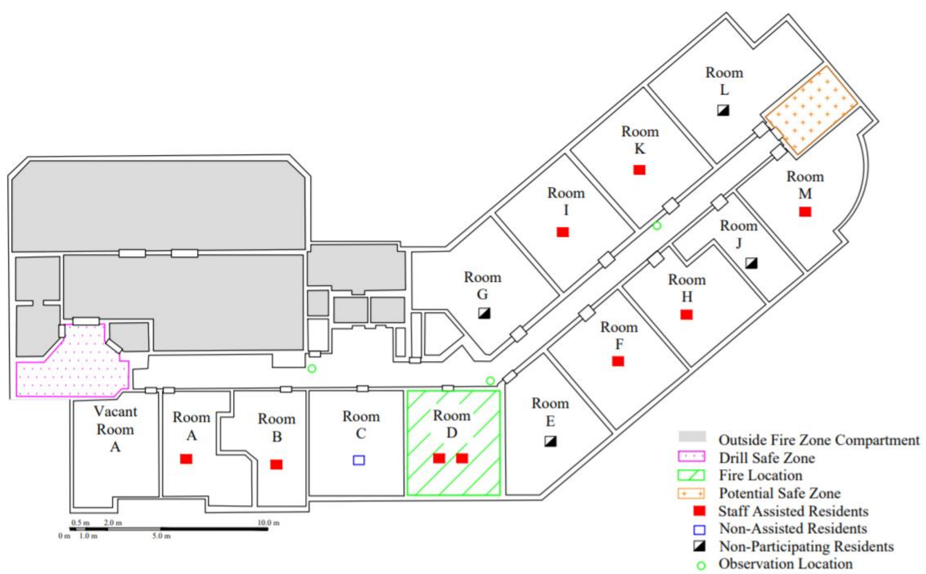

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Figure F.10: Drill 8 (a) Evacuation Timeline (b) Floorplan

F.5.2.9 Drill 9 (Retirement Home – Night time working shift)

Having just recently opened, this home had been receiving occupants two months before the fire drill was observed and had approximately 50% occupant capacity at the time of observation. This was the first annual fire marshal-attended drill the retirement home underwent with resident participation. This included three on-duty staff, four staff stand-ins and six residents on a secure memory care floor which required a pass code to exit into the stairwells, one of which was used as the safe zone. The floor had 33 rooms; only ten were occupied, as shown in Figure F.11. Some residents were notified in advance of the drill and were moved to alternate floors. Staff stand-ins were put in their place with the respective mobility assistance devices.

This was a silent drill where no audible alarms were used, but the staff went through the motions of going to the fire command centre (located at the Nurse's Office on the same floor) and using the mobile communication phones to relay the location of the fire. The fire room had a staff stand-in using a walker and was evacuated by staff at 0:21, entering the safe zone at 1:43. The second staff member began evacuating residents 59 seconds after the drill began. The third staff member realized they were supposed start the drill on a different level and went into the elevator lobby, then "re-entered" the fire wing at 1:19. The staff followed the critical triangle evacuation procedure similar to Drills 5 and 8. A couple of residents were in the communal lounge area at the time of the drill and exited the lounge at 5:32, entering the safe zone at 6:52 and 7:03. All residents required staff guidance from their initial locations to the safe zone. All the rooms were checked twice before an Evacucheck marker was flipped up, indicating that the room was cleared. The last resident was evacuated from their room and exited the wing at 7:32. The drill ended soon after, at 7:38. Observers noted issues with the room doors not fully closing and the lack of fire separation doors on all floors of the building. In the post-drill discussion, the fire marshal suggested that the residents in the fire wing should be evacuated but residents from the rest of the building could stay in place due to the building's compartmentation design. This highlighted the reliance on compartmentation from the building design for the fire safety plan.

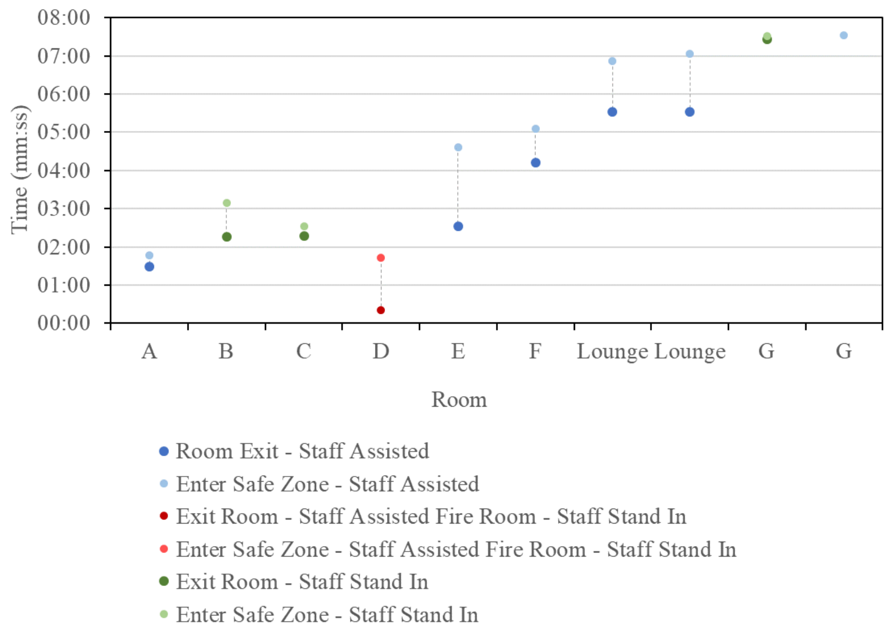

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Figure F.11: Drill 9 (a) Evacuation Timeline (b) Floorplan

F.6 Discussion

F.6.1 Observed Trends in Behaviour and Actions

Through the observation of the nine fire drills discussed above, several similarities and differences in resident and staff actions and behaviours were identified. A high level of staff dependence was observed. Table F.5 provides the types of staff actions and behaviours observed as well as their frequency and probability of occurrence. For consistency, only the actions of the staff members who were the primary focus of the observers are included. Drill 1 was excluded as the recorded actions were not associated with specific staff members and therefore could not be tallied. Table F.5 shows there are several actions that were observed in multiple drills and by numerous staff members. The observed actions were influenced by the type of drill being observed and in part due to the requirements of relevant legislation. For example, the number of staff members who evacuated residents was quite low in the first four drills (all monthly drills), especially compared to the percentage of overall staff participating in the drill. This is likely a reflection of the fact that during these drills the staff are not required to evacuate residents. While they are supposed to evacuate residents who are willing and able to participate, it was seen that this was not often done, be it for reasons of not disturbing the residents or because the staff were unaware that they were supposed to. As the staff during the worst-case scenario drills knew the location of the fire room prior to the drill, they were not observed spending time looking for the fire while the staff in the monthly drills generally did. It is also important to note that while Table F.5 groups the observed actions into categories and appears to follow a linear progression from drill start to drill end, there is evidence of observed actions occurring multiple times at various times during the drills. For example, staff seeking information from each other occurred at various times throughout the drills.

Less data was collected for residents as they did not egress independently for most instances and focus was instead on staff interactions. Some observations included residents seeking information by coming to stand at their doors prior to being evacuated, residents waiting for other residents before evacuating (e.g., couple), finishing tasks (e.g., showering), bringing belongings with them (e.g., tea), and hiding. The action of hiding requires more careful study to allow design to account for this in the future. It was also observed that many residents, even those in retirement homes where nursing care is not provided, required assistance to evacuate (40 of the 56 who were recorded). In some cases, this meant that the staff had to guide and walk with them to the safe zone. In other cases, this meant verbally prompting residents who were waiting at their bedroom doors. In both cases, the staff had a large impact on the evacuation of residents as the worst total egress times seemed to be most affected by low staff and high proportions of residents as per Table F.3.

Table F.5: Frequency and probability of observed staff actions and behaviour

Action or Behaviour	**Overall Frequency From All Nine Drills** # of Staff Observed (# of Drills Observed In)	**Probability Based on Total Number of Actions (%)**	**Probability Based on Total Number of Staff Observed (%)**
Pre-Drill Actions			
Normal (unaware of drill about to occur)	23 (3)	9.7%	62.2%
Staged (aware of drill about to occur)	14 (5)	5.9%	37.8%
Perception of Initial Stimulus (Drill Start)			
Ambiguous - Observe behaviour of others	0 (0)	0.0%	0.0%
Unambiguous - Alarm, intercom message, staff radio devices	37 (8)	15.7%	100.0%
Seek and Disseminate Information, Investigate			
Already in fire wing when drill starts	10 (6)	4.2%	27.0%
Travel to and enter wing where the fire is located	27 (7)	11.4%	73.0%
Search for the fire (checking rooms)	10 (2)	4.2%	27.0%
Go right to fire room (do not search other rooms)	6 (6)	2.5%	16.2%
Communicate location with collogues via handheld radios	5 (2)	2.1%	13.5%
Raise the Alarm / emergency message via intercom system	1 (1)	0.4%	2.7%
Seek information from other staff members	5 (3)	2.1%	13.5%
Seek information from fire marshal or drill coordinator	1 (1)	0.4%	2.7%
Initial Securing of Environment			
Bring fire extinguisher into wing	7 (5)	3.0%	18.9%
Locate/entire fire room	14 (7)	5.9%	37.8%
Simulate fighting fire using fire extinguisher	1 (1)	0.4%	2.7%
Place towels under fire room door	2 (2)	0.8%	5.4%
Clear all obstacles out of hallway	8 (1)	3.4%	21.6%
Close resident room doors (pre-evacuation)	2 (1)	0.8%	5.4%
Resident Evacuation			
Check rooms for residents (initial check)	16 (6)	6.8%	43.2%
Assist residents with pre-movement actions (in resident rooms)	3 (2)	1.3%	8.1%
Verbally prompt residents to evacuate (not req.to walk with)	2 (1)	0.8%	5.4%
Guide and walk with residents to safe zone	14 (7)	5.9%	37.8%
Guide/assist resident back into room (still within fire wing)	1 (1)	0.4%	2.7%
Aide another staff member in evacuating a resident	3 (2)	1.3%	8.1%
Close room doors upon exit of room	4 (3)	1.7%	10.8%
Do not close room doors upon exit of room	2 (2)	0.8%	5.4%
Re-Checking Rooms and Marking as Clear			
Use Evacucheck or hanging marker to indicate cleared room	9 (5)	3.8%	24.3%
Re-Check evacuated rooms (once)	5 (2)	2.1%	13.5%
Drill Closure			
Stand around	3 (1)	1.3%	8.1%
Say that all residents have been evacuated, in bed	1 (1)	0.4%	2.7%

F.6.2 Evacuation Timeline and Order

Figures E.7 – E.11 show the observed room exit and safe zone entrance times for Drills 5, through 9. Given the high dependency on staff, the pre-evacuation times were largely determined by when a staff member assisted or prompted a resident to evacuate. These figures show a general trend of evacuating residents based on their proximity to the fire room, which was in line with the critical triangle method and evacuation strategy mentioned earlier. The variation in time spent between exiting a room and entering the safe zone is also clearly visible in the graphed data. It is important to note, however, that this does not always correspond to the movement time and speed of an evacuee. As was observed during Drill 7 and can be seen depicted in Figure F.9, a number of residents exited their rooms independently or with prompting and then remained in the hallway outside of their rooms until they were prompted again or guided to the safe zone by a staff member. It is therefore important to make sure that when using data from a fire drill it is clear whether or not this is represented in the data. True autonomous behaviour is a very gray concept when considering elderly populations. Figures E.7 –E.11 show residents who required a staff member to walk with them to the safe zone (this was defined as staff-assisted for this study) and residents who reacted and evacuated entirely on their own or required only verbal prompting (defined as autonomous herein). The residents were classified this way to be able to see potential differences in the time spent walking from a resident room to the safe zone. This classification is useful for recording movement times (and therefore “agent” speeds when geometry is considered); however, it does not articulate the number of residents who relied upon any form of interaction with staff – which will also be important in modelling. In that case, the number of staff-assisted residents would be higher.

Table F.6 and Figure F.12 are provided with specific limitation, in that they implicitly include the movement of staff with the resident behaviour. Building geometry is not included and that they are only based on collected data. In all but two drills, staff were always present when the drill began. The latest time for the first staff member to enter the fire wing was 0:24. This tabulated information, based on drills with sufficient resident engagement may be useful in table form for practitioners developing first-stage models. The authors plan future work to study the generation of appropriate models. Figure F.12 provides the reader with a visualization of the evacuation timeline of Drill 5 through 9, though inherently does not include the effect of differences in architecture between each drill in different buildings which would be used for travel velocities. This information will be provided within future research and can be derived from the floor plan figures provided.

Table F.6: Drill evaluations of only recorded residents

Drill	**Pre-evacuation Times Avg [Min – Max]**	**Time which Percentage of People Evacuated [MM:SS]**			
		25	50	75	100
5	5:36[0:47 – 10:16]	4:52	5:37	8:27	11:19
6[a]	2:02[0:46-3:13]	1:19	2:45	2:47	3:38
7	3:09[0:32-10:39]	1:20	3:16	8:14	12:16
8	6:53[2:25-11:42]	5:28	7:10	10:15	13:55
9	3:53[1:29-5:32]	4:37	6:52	7:03	7:32
Average	4:18				

[a] only 5 residents of 14 are recorded.

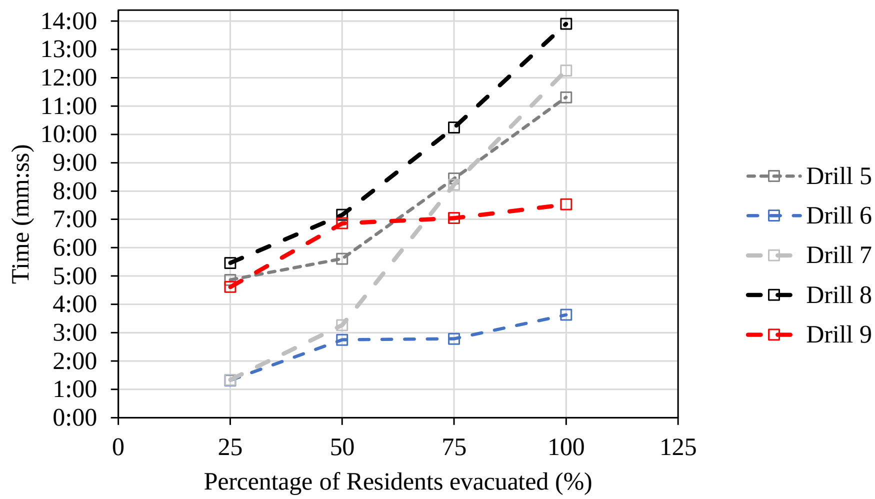

Figure F.12: Evacuation profile assuming implicit staff and resident behaviour (see Table F.6 for limitations)

F.6.3 Considerations for Using Fire Drill Data

It is evident in looking at these drills that there are numerous modifications that are made (intentionally or unintentionally) during a drill that would not be possible given an actual fire event. In some drills, more staff were noted to have played a role in the drill than were supposed to. These staff were observed closing doors to resident rooms, tagging doors and supervising residents in the safe zone. In reality, during the night shift which these drills were supposed to be simulating, these additional staff would not be present to assist. While it is understandable why these staff would be present during a drill for additional resident safety, it is not representative of a real fire. During such an event, the on-duty staff would be responsible for evacuating the residents as well as monitoring them within the safe zone. Additionally, the impact to pre-evacuation and preparation times, as well as the potential increase in resident resistance to evacuation as a result of being woken up and potentially wanting to get dressed or gather belongings, is not represented in these worst-case scenario drills.

Another trend that was seen during all but one of the observed fire drills was that of residents evacuating (either assisted or autonomous) to only one safe zone, regardless of their proximity to the second (typically the stairwell). While it makes sense why this would be done for ease and convenience during a simulation, given the mobility and mental state of many residents (e.g., having residents wait in a hallway is easier and more practical than a stairwell), it is not representative of all of the safe zones that residents would be evacuated to in an actual fire. Often not all residents were evacuated, even during worst-case scenario drills. In the observed monthly drills (Drills 1-4), it was seen that very few residents were evacuated at all. In the later drills where more residents did participate, staff stand-ins generally took the place of residents who would have greater difficulty evacuating (uncooperative, reduced mobility, etc.). As was seen in Drill 8, a staff member jogged from a resident room to the safe zone with a walker, "simulating" the evacuation of that resident. Given the mobility impairment of this resident, this was not an accurate representation of the resident's evacuation. These resident exemptions or replacements not only affect the time required to complete the drill (pre-evacuation time, walking speed) but also have a large impact on the realism of the drill. It is understandable why LTC and retirement homes do this, to better ensure the immediate safety of their residents and staff as well as reduce the level of disruption caused to both. However, this does have an impact on the credibility of potential data and the use of these drills for training and evaluation of staff in such homes.

The roles played by the drill coordinators and fire marshals present during the drills were also seen to impact the drills. During the worst-case scenario drills, the observing fire marshals and/or drill coordinators were observed to interact with or prompt the participating staff members. This ranged from telling staff that they should be tagging the evacuated rooms to telling staff that they did not have to evacuate residents to the safe zone, as was seen in Drill 8. In this specific case, the fire marshal said that the only important time that the staff were being evaluated on was the time required to prepare the residents and bring them into the wing hallway (not take them to the safe zone). This information not only impacted the subsequent actions of the staff who then did not finish evacuating a resident (therefore impacting the accuracy of the drill's representation of a "real" fire event), it also contradicted what had been observed during the other worst-case scenario drills. In most of the post-drill discussions with the staff, the fire marshals and/or the drill coordinators commented on the impact of fire compartmentalization and sprinklers, stating that in the case of a fire, the staff would have plenty of time based upon the fire rating of the structure (door rating for example) to evacuate residents. In relation to this, no comment about the impact of smoke on tenability in relation to the safe egress time, nor difference in real to standard fire was discussed. The impact of staff and resident actions, such as doors being left open or the fire room being entered multiple times, are not made clearly apparent.

Looking specifically at the considerations warranted by the differences between the earlier and later drills observed in this study, it can be seen that each have advantages and disadvantages. The first four drills in this study were largely influenced by their type (monthly drills not requiring resident participation) and the residence type (long term care homes where residents were highly dependent on staff). In the case of these four drills in this study, the observation style also had an impact (focused on general observations, less on evacuation timestamps). These four observed drills did not provide the type of data that could easily be incorporated into an egress model (pre-evacuation times, walking speeds, etc.). However, they did serve to provide an understanding of general fire evacuation procedures in these homes. Additionally, as the staff and residents were not informed of the drill prior to it occurring, the initial response to the alarm reflects more closely their response to an actual fire. This realism can fade once the drill coordinator and observers were observed and no fire or smoke is found.

Drills 5 through 9 in this study have their own set of opportunities and challenges that need to be understood when looking to use the collected data. While there were some autonomous resident evacuations observed, staff verbally prompting residents to evacuate or physically preparing them for evacuation and walking with them to the safe zone was a very prominent occurrence. This showed that even in retirement homes where residents do not require the same level of daily care as in LTC homes, staff still play an important role in fire evacuations. This information is valuable for models as it shows the importance of modelling the impact of staff and it provides examples of times associated with different staff actions. With respect to the general limitations of annual, fire marshal-observed, worst-case scenario drills, there are a couple key considerations. The staff who will be participating in the drill are aware of the drill before it happens. As these drills are being used for official evaluation by the fire department/province, the homes are also allowed to "practice" the drill before it is observed. While this is beneficial in that it ensures that staff (and potentially residents) are better prepared should a real fire occur, it reduces the realism of the drill (showing the conflict of using drills as training and evaluation tools). Staff stand-ins also affect the realism of the drill, given that they will not react or move in the same way as actual residents.

F.6.4 Future Work

Research into fire evacuations in LTC and retirement homes, and the inclusion of human behaviour in fire into egress models in general, needs to continue so as to further develop models that are more representative of actual evacuations. The use of the Protective Action Decision Model (PADM) developed by Lindell and Perry holds great potential for being used to create a conceptual model of human behaviour based on data such as that collected in this study [34], [35]. The PADM shows the process of decision-making during emergencies, describing the steps and factors that influence the adoption of protective actions (in the case of a building fire, evacuating or seeking refuge for example) [35], [36]. Such a conceptual model could then be used to support the creation of computational models for use within egress software, therefore creating more accurate and realistic models of evacuations of the built environment.

The authors intentionally do not provide a full agent profile for modelling herein. Such a full profile will be more beneficial to create along with validated and verified models which are intended to follow this study by the authors.

These models must also begin to incorporate the impact of toxicity and smoke as it has been shown to have a large impact on evacuees [37]. The presence of smoke can not only affect visibility, but also response time and movement speed [38]. Our understanding of toxicity and smoke plays a role in building compartmentalization, which, as seen in this study, is very much relied upon in residences such as LTC and retirement homes. Some studies have also shown that certain health conditions, such as cardiovascular disease, can impact one's susceptibility to smoke [39]. This may therefore have a great impact on residents of LTC and retirement homes and should be studied further.

F.7 Conclusion

This study of nine drills in Canadian LTC and retirement homes has shown that valuable data can be collected from the observation of fire drills. Information about residents, the interactions between staff and residents, the type of actions that are undertaken by staff during the evacuation process and the general procedures that are followed was collected. This information provides a better understanding of evacuations in such care homes and acts as a source of data that can be used to help inform egress modelling software. These drills demonstrated that emergency egress in long term care and retirement homes is highly staff dependent with over 72% of residents requiring full assistance in evacuation.

This study has also shown that there are a number of important considerations that must be made when choosing to conduct this type of data collection or when using data collected by such means. The use of in-person observation and written note-taking can be used in cases where cameras are not welcomed or allowed. When specific observation objectives are defined, and the observers can focus on specific staff and/or resident participants, valuable data can be collected from places that would otherwise not have allowed researchers access. However, if the scope of information sought is too broad or the situation overwhelms the observation and recording capacities of the observers, the completeness of the data collected can be reduced.

It is easy to see that data from actual fire events would provide the most accurate data, and that collecting data from such events is important in further developing our understanding of human behaviour during such events. However, this data can be very difficult to come by. Over the course of this study, the researchers made continual efforts to reach out to the owners of local LTC and retirement homes that had experienced real fires in recent years for camera based and real event data. To date, all of these invitations have gone unanswered. Given the difficulty of being able to access such data, fire drills pose a more readily available source of evacuee behaviour information of vulnerable populations. Through drill observation, important information about the behaviours and actions exhibited by staff and residents in care homes and the procedures that are supposed to be followed during fires can be obtained.

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