INVESTIGATING STRUCTURAL AND HUMAN FACTORS OF WILDLAND-URBAN INTERFACE FIRES

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Abstract

Wildfires are increasing in number and severity due to multiple factors including climate change and increased interactions between people and the wildland. This thesis investigates structural and human factors of wildland-urban interface (WUI) fires with the goal of informing the design and creation of wildfire resilient communities. A review of building survival post-wildfires found that there are many structural and landscape factors that contribute to building survival, which are impacted by the wildfire behaviour. There is a lack of post-wildfire data collection and data from diverse types of building performance in Canada. An ignition study of Eastern white cedar shingles found that increasing moisture content delays ignition. Video analysis of vehicular evacuations from the 2016 Fort McMurray Fire observed unusual traffic behaviour such as lane reversals, driving outside of marked lanes and bandwagon behaviour from other evacuees, which should be taken into account during evacuation planning.

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I want to thank my supervisor, Dr. John Gales, because without him, I would have never had gone into fire safety engineering. I can't thank him enough for his support, guidance, and mentorship throughout my academic career.

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Declaration

The contents presented herein is the work of Hannah Carton under the supervision of Dr. John Gales and Dr. Eric Kennedy. Some content has been modified from existing works written by the author and influenced by input and feedback from multiple colleagues and co-authors.

Chapter 3 is based on the following conference paper. The author conducted the literature review, analyzed the results, and drafted the paper. This paper is included in Appendix A of the thesis.

> Carton, H., Gales, J., and Kennedy, E.B. (2023). *Identifying Research Needs for Canadian Wildfire Building Code Development.* CSCE 2023: Canadian Society for Civil Engineering (CSCE) 2023 Annual Conference, Moncton, New Brunswick.

The author has also written or co-authored additional publications which were partially included and/or referenced within this thesis. For each of these publications, the author was involved in the drafting of the publication and the analysis. These publications are included in the thesis Appendices F and G:

> Guevara Arce, S., Carton, H., and Gales, J. (2022). *Fire Building Codes in Developed and Developing Countries: A Case Study Comparison Between Canada and Costa Rica*. CSCE 2022: Canadian Society for Civil Engineering (CSCE) 2022 Annual Conference, Whistler, British Columbia.

> Carton, H., Khan A., and Gales, J. (2020). *Wildfire Evacuation Modelling Coupling Traffic and Fire Behaviour*. NCUR 2020: National Conference on Undergraduate Research. Montana State University, Bozeman, Montana.

The author has written or co-authored the following publications, not directly related to the current thesis, during the course of her master's studies. The first publication is included in Appendix H, while the second has been excluded due to length.

> Carton, H., and Gales, J. (2023). *Experiential Assessment as an Alternative to Traditional Examinations in Engineering*. CEEA 2023: Canadian Engineering Education Association Conference, Kelowna, British Columbia.

Gales, J., Champagne, C., Harun, G., Carton H., Kinsey, M. (2022) Fire Evacuation and Exit Design in Heritage Cultural Centres. Springer Briefs in Architecture and Technology (Springer-Nature). 5 Chapters, 75 pp.

Table of Contents

List of Figures

List of Tables

Chapter 1: Introduction

1.1 General

Wildfires are increasing in number and severity, in Canada and globally. The increase is associated with climate change-associated factors as well as increased interactions between humans and the wildland through urbanization and seasonal recreation [1], [2]. Climate change is resulting in increased temperatures and drier summers. The number of lightning strikes which are responsible for 50% of wildfire ignitions in Canada are also forecasted to increase [3]. With an increasing population and urbanization, there are more communities and infrastructure in wildland areas, increasing the likelihood of wildfire impact. Increased human activity in wildland areas is also resulting in more human-caused wildfires [4]. Additionally, in North America, decades of fire suppression as the primary fire management strategy have led to increased fuel loads and changes in forest composition which increase the fire severity [4]. The fire management strategy to suppress all wildfires created the 'wildfire paradox' where the lack of wildfire caused forest stands to be older and more flammable and more fuel build up, which can increase the risk of severe wildfires [5], [6].

Between 1998-2017, it is estimated that wildfires caused $68 billion USD in economic damages globally, though only 41% of economic losses from wildfires is reported [7]. It is estimated that between 1998-2017 wildfires, dry mass movement and volcanic activity affected 6.2 million people and killed almost 2,400 [7]. It is forecasted that by 2100, the number of severe wildfire events will increase by a factor of 1.31 to 1.57, depending on climate mitigation efforts, though the change in number and severity of wildfires is expected to vary geographically [8].

The wildland-urban interface (WUI) is defined as "the area where built structures, such as homes, are meet or are dispersed within wildland vegetation" [1]. Canada's wildland-urban interface accounts for approximately 3.8% of its total land area, or 32.3 million hectares [1], with an estimated population of 4.1 million people [9]. This number is expected to increase as the population increases as well as due to seasonal recreation [2]. It should be noted, that this area does not include interface areas between industrial infrastructure or infrastructure used for transport and utilities, such as roads and powerlines, which are excluded from the WUI definition [1]. Since 2012, Canada has experienced an average of 5,700 wildfires per year, resulting in over

2.8 million hectares burned [10]. Due to climate change, it's predicted that the likelihood of extreme wildfires in Western Canada will increase between 1.5 and 6 times in the next ten years. The average fire season length in Canada is approximately two weeks longer than it has been historically [4]. The increase in wildland and WUI fires has also resulted in an increasing trend in the number of evacuations and amount of people evacuated (see Figure 1.1), where between 2013-2018 there was an average of almost 50 evacuations per year affecting almost 38,000 people [11]. The largest of those occurred in May 2016 during the Fort McMurray Wildfire which resulted in the evacuation of 88,000 residents and caused approximately $8.9 billion CAD in damages [12].

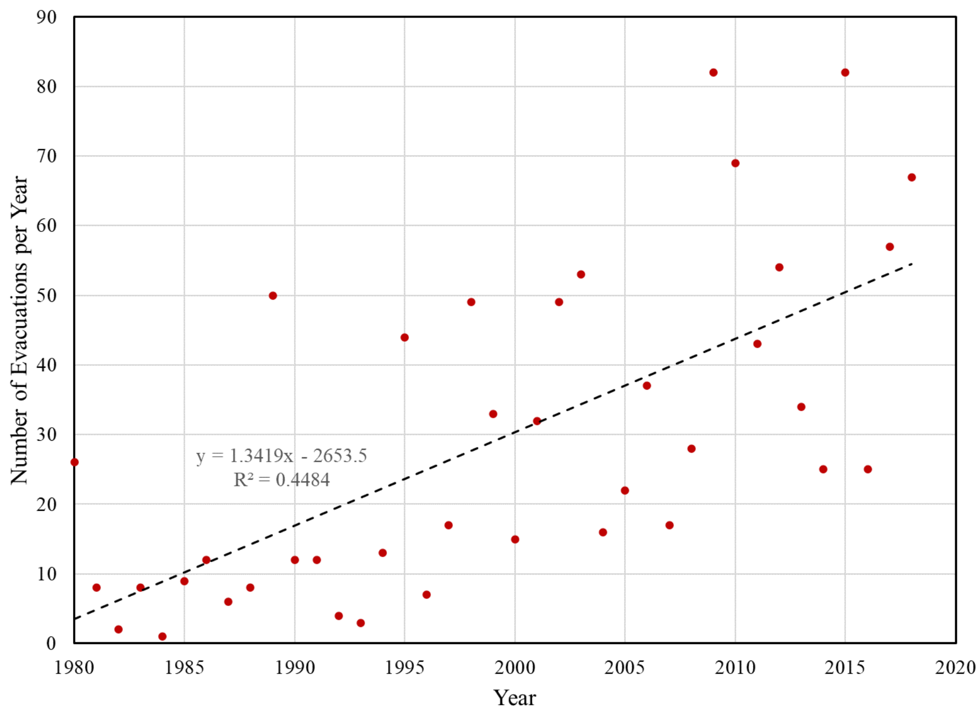


Figure 1.1: Number of evacuations per year in Canada from 1980-2018 (data is from [11]*)*

The 2023 wildfire season in Canada has been called "unprecedented" due to the number of wildfires and amount of area burned [13]. At the time of writing, over 12 million hectares of land has been burned and over 150,000 people have been evacuated in nine provinces and territories [14]–[16]. The wildfires have caused record-setting air quality alerts across Canada and the United States [17], [18]. The 2023 wildfires have the worst daily total cumulative wildfire carbon emissions since they began tracking it, 20 years ago [19]. Wildfires in Nova Scotia resulted in the evacuation of over 23,000 people and has destroyed over 350 structures, including 210 homes [20],

[21]. The wildfire season typically runs May to September though it has been estimated to have increased in length by almost two weeks since 1959 [3].

Figure 1.2: Wildfire smoke in Ottawa, Canada in June 2023 (Susanne Fletcher, with permission)

1.2 Motivation

Wildfire research has been identified internationally and locally as a critical research need in response to the increasing wildfire threat. The International Association of Fire Safety Science's (IAFSS) *Agenda 2030 for a Fire Safe World* identified wildfires and wildland-urban interface research as a key research priority [22], as have the Society of Fire Protection Engineers (SFPE) in their research roadmap [23]. Disaster risk reduction is also a key part of the United Nations (UN) Sustainable Development Goal (SDG) #11: Make cities and human settlements inclusive, safe, resilient and sustainable, where Target 11.5 specifically addresses the need to reduce impact to people and infrastructure related to disasters such as wildfires [24]. Canada has a number of initiatives, including but not limited to the *Blueprint for Wildland Fire Science in Canada (2019-2029)* [25], the *Canadian Council of Forest Ministers (CCFM) Wildland Fire Management Working Group Action Plan 2021-2026* [26] and the *Wildland Fire and Mitigation Plan* by the Canadian Interagency Forest Fire Centre (CIFFC) [27]. Within those initiatives, different aspects of wildfire research are also highlighted, such as structure and material responses to wildfires and wildfire evacuations and community planning.

With the risk from wildfires which is only expected to increase in the coming years, there is a need for wildfire research and data. While data from other countries and jurisdictions is needed and useful, due to differences in wildfire behaviour and impacts, attributed to differences in factors including but not limited to climate, vegetation and infrastructure, there is a need for Canadian-specific data. Canada is currently undergoing an "unprecedented" wildfire season which is only expected to get worse in the future [13]. The motivation of this research was to contribute to the growing need for wildfire research in order for communities to better prepared for severe wildfire events. The field of wildfire research is very broad, this thesis aims to address research gaps on structural and human factors in wildland-urban interface fires.

1.3 Scope of the Project

This project addresses wildland-urban interface (WUI) fires, which is a broad topic in of itself. The research can be sorted under two main categories: 1) structural factors and 2) human factors. Structural factors of WUI fires refers to characteristics of structures in the WUI and how they impact building ignition. This was investigated through a literature review of post-wildfire studies on building survival as well as through a material study of cedar shingles, a common roofing material in heritage buildings in southern Ontario [28]. The study used a cone calorimeter to evaluate how moisture content and heat exposure impacted ignition of the shingles. The human factors involve the analysis of videos from the 2016 Fort McMurray evacuation. The analysis investigated the behaviours of the evacuees as well as traffic observed during the evacuation.

1.4 Research Objectives

The overall goal of the thesis was to contribute to designing and creating wildfire resilient communities in Canada. This was done through research objectives, which each addressed a different issue in wildfire safety engineering. The research objectives of this thesis were as follows:

1. Identify and prioritize research gaps needed to develop a Canadian wildfire building code.
2. Investigate the material properties and ignition of a common roofing material under different heat fluxes and moisture conditions.
3. Evaluate human and traffic behaviour during a Canadian wildfire evacuation.

The information gathered from the objectives contribute to the need for Canadian-specific wildfire research and can be used to inform wildfire resilience in existing and future communities in Canada. The studies identify different research needs and recommendations that can be used to inform wildfire research priorities. Structural and landscape vulnerabilities are investigated, including the ignition risks of Eastern white cedar shingles, a common building material in older houses in southern Ontario. The behaviour of evacuees during an actual Canadian wildfire evacuation is observed and analyzed which can inform evacuation and emergency management strategies and plans.

1.5 Outline for the Thesis

This thesis is formatted manuscript style and is separated into six chapters and an appendix, where Chapter 1 is an introduction to the thesis, Chapter 2 provides theoretical background and context to subsequent chapters and Chapters 3 to 5 represent different studies relating to wildland-urban interface fires. Chapter 6 concludes the thesis and presents recommendations for future work. A graphical outline of the thesis is presented in Figure 1.3 below.

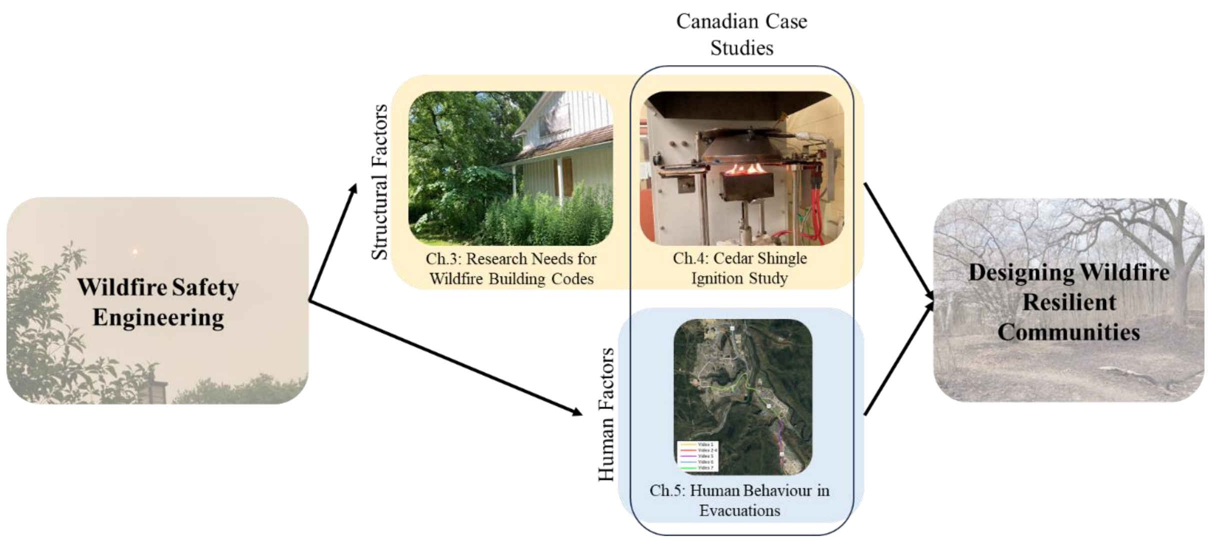


Figure 1.3: Graphical representation of the thesis outline

Chapter 2: A Review of Wildfire Science is a review which introduces key concepts and background used for this research. A brief overview of fire dynamics and what contributes to influencing wildfire behaviour is described. Structural ignition and the pyrolysis of wood is described. Theoretical background on human behaviour in emergencies and existing behavioural frameworks are provided.

Chapter 3: Research Needs to Develop a Canadian Wildfire Building Code is a literature review of post-wildfire studies on building survival in order to investigate what structural and landscape factors contribute to building damage after wildfires. It also identifies research needs to develop a Canadian wildfire building code. A preliminary version of this work was presented in a conference paper and was modified and updated to become the thesis chapter (see Appendix A). The author is the first author of the conference publication and was responsible for the research and analysis.

Chapter 4: Material Properties and Ignition of Cedar Shingles presents a material study of Eastern white cedar shingles, which are common roofing materials in older houses in southern Ontario, including heritage properties. The study investigates the effects of moisture content and radiant heat flux on ignition using a cone calorimeter. Parameters such as heat release rate, time to ignition and charring were recorded. The results of the testing and observed impacts of moisture content and heat flux are discussed therein.

Chapter 5: Human Behaviour in Wildfire Evacuations presents a case study of a Canadian wildfire evacuation. The human behaviour of evacuees and traffic decisions made during the 2016 Fort McMurray Fire were analyzed through videos collected from public websites such as YouTube and Facebook. Notable behaviours observed in the videos were summarized and discussed, with connections made to existing behavioural frameworks.

Chapter 6: Conclusions and Recommendations summarizes the main conclusions from the work presented herein and its novelty and relevance. Recommendations for future work based on the conclusions are also provided and how they can inform the wildland and WUI fire community.

Chapter 2: A Review of Wildfire Science

2.1 General

Wildland fires or wildfires are generally defined as an unplanned fire in a vegetative area. They are also referred to with the type of vegetation that is being burned (forest fire, bush fire, peat fire etc.) [8]. Wildland-urban interface fires refer to fires within the wildland-urban interface (WUI) which is defined as areas where built infrastructure meet the wildland [1]. These WUI fires are of particular concern as they are the wildfires most likely to negatively impact people and communities. Canada's wildland-urban interface (WUI) currently accounts for approximately 3.8% of its total land area, or 32.3 million hectares [1], with an estimated population of 4.1 million people [9]. This number is expected to grow as the population increases due to urbanization as well as recreational activities [2].

Wildfires are a complex phenomenon where many factors contribute to its behaviour. The Fire Triangle (Figure 2.1a) illustrates the conditions necessary for sustained fire. In the context of wildland fires, oxygen is provided through the surrounding air while the fuel source depends on the surrounding environment. In Canada, humans and lightning are the main causes of wildfire ignition, with each source accounting for approximately half the number of wildfires, however lightning-caused wildfires account for the majority of area burned [3]. The Fire Behaviour Triangle (Figure 2.1b) is commonly used to illustrate the primary factors which influence a wildfire's behaviour. The fire behaviour refers to how a wildfire starts and how and where it may spread. This behaviour can be described using characteristics such as but not limited to fire intensity, fire temperature flame height and rate and direction of fire spread [29].

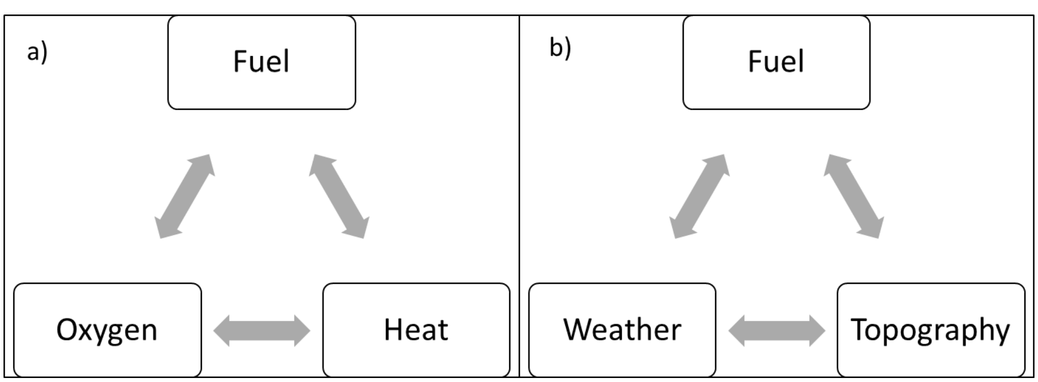


Figure 2.1: a) The Fire Triangle and b) The Fire Behaviour Triangle

Fuel, weather and topography are considered the main factors which influence a wildfire's behaviour. The type of fuel and its characteristics such as moisture content, amount and continuity can impact the fire behaviour. For example, coniferous trees are more flammable than deciduous trees due to their sap and growth density. However, deciduous trees are more flammable at the beginning of spring due to their low moisture content [30]. Weather can influence a wildfire's behaviour through the conditions present at the time of burning. Wind speed and direction, precipitation and humidity can all play a role in how the wildfire behaves [8]. Weather can also influence the fuel conditions, with hotter and drier weather producing drier fuels. Additionally, weather can impact the likelihood of a wildfire beginning in the first place. Topography is considered the third factor as wildfires travel faster on upward slopes as slopes are preheated by the rising heat and gases [31]. Additionally, burning materials falling downwards can increase the fire spread.

In addition to the factors listed in the triangle, it is also important to consider human factors on fuel, weather and topography which may impact fire behaviour. Through fuel management strategies such as fire breaks and defensible space around communities, and suppression activities, it is possible to alter wildfire behaviour. However, human's impact on the weather through climate change is considered one of the largest reasons driving the increase in number and severity of wildfires [8]. Global warming is expected to lead to more increased wildfire events through direct effects such as more extreme weather including stronger winds, higher temperatures as well indirectly through changing fuel types and availability [8]. It is forecasted that by 2100, the number of severe wildfire events will increase by a factor of 1.31 to 1.57, depending on climate mitigation efforts [8]. This is already being observed around the world, for example in British Columbia, a study found climate change increased the area burned in the 2017 fire season by a factor of 7-11 [32]. Land-use is also one of the largest drivers behind changing fire regimes, such as changing the natural landscape for agricultural use or deforestation for industrial uses can increase or decrease the number of wildfires depending on its original state. For example, land fragmentation in dense forests can increase the flammability and potential ignition points, whereas in a savannah, fragmentation can create fire breaks which may reduce the area burned [8].

An overview of wildfire research found that it can be categorized into five main categories: 1) forest ecology and climate science, 2) detection, modelling, and mapping, 3) community risk mitigation and planning, 4) soil and water and 5) atmospheric science. These categories can also be broken down into sub-categories [33]. It found that while some publications were found from the 1920s, consistent, published wildfire research began in the 1970s and has been increasing steadily, with over 1,000 articles published in 2019 and 2020 [33]. The majority of the research originates from the United States, Australia, Canada and Spain, though since 2014, other countries with wildfires such as China, India, Brazil and Norway have also contributed [33].

2.2 Structural Factors

When considering community structural resilience against wildfire, it can be viewed as primarily an issue of structural ignition [34]. Through increasing structural resistance to ignition (also known as hardening) structures and their surroundings against wildfire ignition and spread, then the risk of structural and property damage can be reduced as well as the risk of human injury or fatalities [35]. Community hardening largely addresses the "fuel" section of the Wildfire Behaviour Triangle as it is the easiest factor of the three to implement changes. Community hardening can be done at both the individual homeowner level, through vegetation treatments and structural design choices, as well as at the community level through urban planning and emergency strategies.

2.2.1 Ignition

There are three main pathways for structural ignition in a wildfire: 1) direct flame impingement, 2) radiant ignition and 3) firebrands [35]. Direct flame impingement is when the fire spreads through flame contact. Research into direct flame impingement in a wildfire or WUI context is largely understudied and generally not considered the primary mechanism for ignition and fire spread of wildfires, though post-fire reviews has shown that it can be responsible for structural damage [35], [36]. Radiant ignition is when materials are ignited by the heat from the fire at a distance and is considered fairly well-studied. Much of the early wildfire research on radiant ignition was characterizing the radiant energy from wildfires and determining the conditions required for radiant ignition of various fuels [35]. Radiant ignition research contributed to the determination of spatial separation between houses as well as the vegetation management guidance, such as recommending fuel treatments within 30 m of a structure [29], [37].

Firebrands or embers are smaller pieces of burning fuels (commonly vegetation or wooden structures) that are generated when the larger fuels decompose [38]. They are considered a primary driver of structural ignition and wildfire spread as they can travel long distances and ignite fuels where they land [35]. In some fires, they are considered the primary form of wildfire spread [39]. Firebrand research is largely categorized into 1) generation, 2) transport and 3) ignition of structures. A review of firebrand research found that ignition via firebrand is a critical research need, while firebrand transport is more studied. While firebrand generation is less studied that firebrand transport, efforts are being made to characterize firebrand generation from a variety of wildland fuels [38].

2.2.2 Fire Dynamics

In order to fully understand some of the content of this thesis, some scientific concepts are explained herein. Fire dynamics is the study of how a fire behaves, using principles of chemistry and physics such as material sciences and thermodynamics [40]. A fire is a chemical reaction where a fuel reacts with oxygen to produce heat and light (see Figure 2.1a)). A fire can be described using characteristics such as temperature, heat energy, heat release rate (HRR) and heat flux. The temperature is a measure of the molecular activity in a material from a reference point [41]. In Celsius (℃), 0℃ is the temperature at which water freezes, while 100℃ is the temperature at which water boils. The temperature of wildfires can vary significantly, however, a study of crown fires found that peak air temperatures could reach over 1300℃ [42]. Heat energy is defined as the amount of energy needed to change its state and is measured in Joules (J). Heat release rate (HRR) is the rate at which a fire releases energy which is measured units of power such as J/s or Watts (W). HRR can also be reported incorporating burning area (W/m^2) [41]. The heat flux is a measure of heat energy transferred per surface area unit (W/m^2) [41]. The radiative heat flux of wildfires can vary, but crown fire experiments found peak heat fluxes over 100 kW/m^2 at a 10 m distance [43].

As mentioned previously, there are three main pathways for structural ignition in a wildfire: 1) direct flame impingement, 2) radiant ignition and 3) firebrands [35]. Ignition itself is defined as "the process by which a rapid, exothermic reaction is initiated" [44]. More broadly, it is the process by which a fire starts. Ignition can be separated into two categories: 1) piloted, where an external factor initiates the process such as a spark or firebrand, and 2) spontaneous ignition, where the conditions of the material creates a flame, such as radiative heat [44]. There are many different factors which can impact the ability of a material to ignite (also known as ignitability). The critical heat flux is defined as the minimum heat flux at which ignition can occur whereas the critical temperature is defined as the minimum temperature at which ignition can occur. These values are not solely a material property as they can be impacted by many factors including material condition, shape and configuration [44].

2.2.3 Structural Wood and Wildfires

Wood has long been used as a structural building material for elements such as roofing, exterior siding, frame, and attachments such as porches and decking. In recent years, there has been a push for more use of timber in buildings due to its potential as a sustainable material [45]. However, it is considered an increased fire risk due to its combustible nature. In wildfires, it has been found that having wooden structural features increases the risk of building damage [35]. When wood is burned, it undergoes the following processes:

Pyrolysis: Pyrolysis is the process of chemical decomposition of a solid fuel into a gaseous state when exposed to heat [46]. It is also considered the start of ignition as the wood volatilizes into a combustible gas [47]. During pyrolysis, there is also the movement of moisture as water is evaporated nearest the heat source and some moisture will also move away from the heat.

Charring: Pyrolysis and charring are sometimes used interchangeably, though charring is when the organic material in the wood, such as cellulose and lignin, decompose to form char (see Figure 2.2) [48]. The formation of a char layer can impact the pyrolysis and heat transfer between the wood [46]. The char layer can also act as an insulating layer between the heat exposure and unburnt wood, where using pre-charred wood is a technique for wood protection [49].

Figure 2.2: Charring on an Eastern white cedar sample (author's photo)

Ignition: As mentioned above, ignition is defined as "the process by which a rapid, exothermic reaction is initiated" [44]. For wood, critical heat fluxes can vary from 11 to 13 kW/m^2 and 25 to 33 kW/m^2 for piloted and spontaneous ignition respectively, depending on the wood species as well as many other parameters including but not limited to wood condition, orientation, ambient temperature and gas temperature [46].

Combustion: Flaming combustion or fire is the oxidation of the volatilized fuel which releases heat and light [46]. In addition to flaming combustion, there is also smouldering or glowing combustion (see Figure 2.3a). Smouldering or glowing combustion occurs when the char is oxidized and creates the characteristic fine, white ash [48].

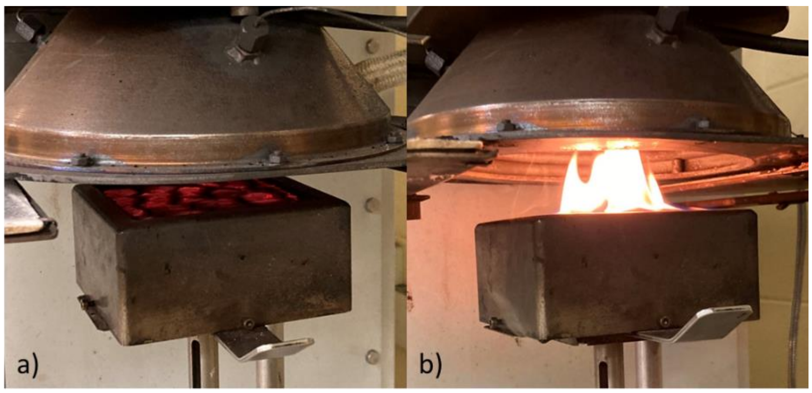


Figure 2.3: a) Smouldering combustion and b) flaming combustion (author's photos)

2.2.4 Cone Calorimeter

The cone calorimeter is a bench-scale, fire testing tool used to evaluate materials under a heat flux and their burning characteristics. The basic set-up of a cone test has a small sample on a load cell to measure mass under a cone heater and an exhaust hood, which can be oriented horizontally or vertically (see Figure 2.4). There are a number of standards regulating the use of a cone calorimeter, including ISO[1]-5660-1 and ASTM[2] E1354 [50]. The cone heater temperature can be set to a specific heat flux for testing. The cone calorimeter can directly measure parameters such heat release rate, smoke production, time to ignition, mass loss and gas concentrations (carbon dioxide, carbon monoxide and oxygen) [51]. Cone calorimeters are also equipped with a spark igniter so both piloted and spontaneous ignition of materials can be measured [50]. In wildfire contexts, cone

[1] International Organization for Standardization
[2] ASTM International, formerly known as the American Society for Testing and Materials

calorimeters are often used to examine the ignitability and flammability characteristics of fuels such as pine needles [52], foliage and twigs [53] as well as ornamental vegetation [54]. Cone calorimetry has also been used to study wood burning and ignition characteristics [55]–[57].

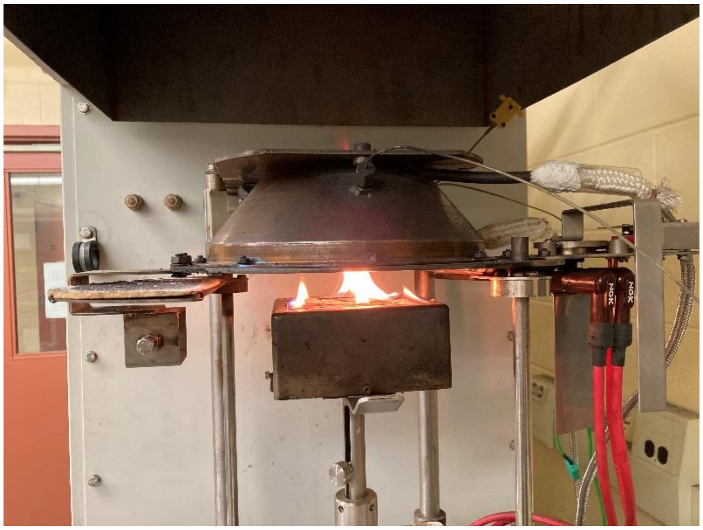


Figure 2.4: Cone calorimeter test in progress (author's photo)

2.3 Human Factors

Data on human behaviour in fire and wildland fires have been identified as a critical research need by multiple international organizations in order to design and create wildfire-resilient communities and prepare effective evacuation strategies [22], [23], [25], [58]. There has also been a call specifically for more research on wildfire evacuation decision-making and behaviour [33], [59]. Human behaviour in wildfire research has largely been focused on the pre-evacuation stage and what factors affect residents' choice to evacuate or stay and defend their property, along with what actions they may take prior to evacuating [60]. Some studies have been done looking at the behaviours during evacuation such as wayfinding [61], and transportation mode and intermediate actions [62], [63]. Kuligowski (2020) has also identified three main areas of research needs within the field: 1) more information on evacuation decision-making, 2) more evacuation movement data and 3) more behavioural research [59].

In addition to being used to inform evacuation management strategies and community planning, these behaviours are used to inform evacuation models in order to better prepare for and mitigate human damages and loss during wildfire events. These evacuation models can separated into three main categories: 1) fire behaviour, 2) traffic behaviour and 3) human/pedestrian behaviour. However, these models are often implemented independently with limited coupling between them. The lack of coupling results in the loss of information about key interactions and influences that inform decision-making in response to wildfires [64]. There is an international movement to develop frameworks for the coupling of models and the first coupled modelling platform has been proposed, WUI-NITY [65]. The platform underwent verification and validation testing, using traffic data collected from traffic detectors located on highways during the 2019 Kincade Fire in California [66]. It also went under additional calibration using data collected from a community wildfire evacuation drill [67].

2.3.1 Existing Behavioural Frameworks

There are a number of behavioural frameworks and models that have been applied to emergency contexts. ASET/RSET analysis uses a linear, chronological approach to describe behavioural actions, where each action is assigned a duration of time. Newer frameworks have expanded on to incorporate the decision-making process itself and not just the resulting action. The Protective Action Decision Model (PADM) is a behavioural model that has been applied to wildland fires and WUI fires and other disasters such as hurricanes as a framework for decision-making [68]. The conceptual model divides decision-making behaviour into three main stages of decision-making: 1) pre-decision making where perceived threats and cues are observed and understood, 2) credible threat and risk assessment, where the cues are evaluated to determine if they pose a credible threat and its associated level of risk and 3) protective action, decision options are created, evaluated, and implemented. Throughout all three stages, additional information is sought after and evaluated.

Cognitive biases is another behavioural theory that has been applied to human behaviour in fires, though not wildland fires specifically [69]. Cognitive biases provide short behavioural statements that can be used to describe people's behaviours and provide context. However, they also create the risk of oversimplifying behaviours resulting in potentially critical information being overlooked. A recent framework has also emerged regarding the role of social identity in decision-making during mass gatherings [70]. This framework suggests that during emergency events, a shared identity can emerge among those impacted and lead to more collective decision-making.

There are also many other behavioural frameworks currently being examined and those presented herein are only a select few.

These behavioural models can provide useful frameworks to contextualize people's behaviours, however, many of them lack validation due to insufficient data, which has previously been identified as a critical research need [71]. Additionally, the theories were largely created without considering specific wildfire contexts, though the PADM has been applied to wildfire contexts [68], [72]. However, the PADM has largely been applied to pre-evacuation decisions and not decision-making during the evacuation itself. As every wildfire event and community is different, the factors affecting decision-making and what actions are taken may also be different [60].

2.4 Summary

This chapter outlined background concepts and context to the content of the following chapters. Wildfires are introduced as complex phenomena whose behaviour is impacted by many different factors. Climate change is increasing the number and severity of wildfires and the number of people living in WUI interface areas is also growing. An overview of structural factors provided some fire dynamics concepts such as characterizing fires and ignition. The process of wood burning was also introduced. The cone calorimeter fire test was described. A brief introduction to human behaviour in wildfires and how the information is needed and used was given. Some existing behavioural theories and frameworks used to describe human behaviour in emergencies were provided.

Chapter 3: Research Needs to Develop a Canadian Wildfire Building Code

3.1 General

Wildfires are growing in number and severity. In Canada, while the overall number of wildfires appears to be decreasing, the number of wildfires categorized as “disastrous” is increasing [73]. The amount of area burned has increased, as well as the number of evacuations and evacuees [74]. The economic cost of wildfires is also expected to increase, as prior to 2003, no wildfire event has cost more than $10 million, but there have been a number of costly wildfires in the last decade, including the Fort McMurray Fire in 2016 which was the costliest disaster in Canadian history at an estimated $10.9 billion [75]. Approximately $4.11 billion of that amount was attributed to the direct damage to homes and businesses [75]. Canada’s 2023 wildfire season has been called “unprecedented” with over 2.7 million hectares burned in May 2023 alone [13]. The 2023 wildfires have the worst daily total cumulative wildfire carbon emissions since they began tracking it, 20 years ago and has set the record for most area burned with over 12 million hectares burned at the time of writing [14], [19]. In Nova Scotia, a wildfire outside of Halifax is estimated to have destroyed 200 structures, including 150 homes, and caused the evacuation of 16,400 residents [76]. It’s estimated that the wildfire caused $165 million in insured damages, with 90% of the claims related to personal property [77].

Figure 3.1: Wildfire smoke over Halifax covering the sun (red dot) in May 2023 (Austin Martins-Robalino, with permission)

In light of the growing wildfire issue, the protection and resilience of communities against wildfires has been identified as a critical research need. Canada's *Blueprint for Wildland Fire Science in Canada (2019-2029)* specifically calls for research in protecting communities through construction, management and mitigation strategies under Theme 3: Building Resilient Communities and Infrastructure [25]. It also calls for research into the development of codes and regulations for built structures in the wildland-urban interface for wildfire resilience. In response, the National Research Council of Canada recently published its first *National Guide for Wildland-Urban-Interface Fires*, henceforth referred to as the National Guide or Guide, with the goal of improving the resilience of Canada's buildings through guidance on interrupting wildland fire spread through structural and vegetative methods [29]. While this is only a guide and is currently voluntary and non-enforceable, unlike existing wildfire guidance such as FireSmart Canada, the guide was designed with the potential to become a future code [29]. The guide was developed based on existing international wildfire reference documents, such as codes, standards, and guidelines.

3.2 Wildfire Codes and Guidance

3.2.1 Canada

In Canada, fire and building codes are regulated provincially, where provinces and territories can develop their own codes or choose to adopt or adapt national model codes [78]. National model codes are developed by the federal government in order to provide the different building code jurisdictions with a model to follow and encourage consistency and compatibility across the jurisdictions [78]. At the time of writing, Canada has five model codes addressing different aspects of building safety, but the National Building Code (NBCC) and the National Fire Code (NFCC) are the two that primarily concern the fire safety of newly constructed and existing buildings. They are designed to complement each other, with the NBCC covering fire safety requirements at the time of construction, versus the NFCC covering the operation and maintenance of fire safety systems of buildings [78]. The model codes are objectives-based codes which list the minimum acceptable measures that must be present [78].

The code advancement process for the national model codes followed a broad-based consensus process where the codes are updated every five years. Proposed changes are submitted to the Canadian Board for Harmonized Construction Codes (CBHCC), formerly known as the Canadian

Commission on Building and Fire Codes (CCBFC). Those proposed changes undergo a series of reviews, both private and public, before being approved for the next code edition (see Figure 3.2) [79].

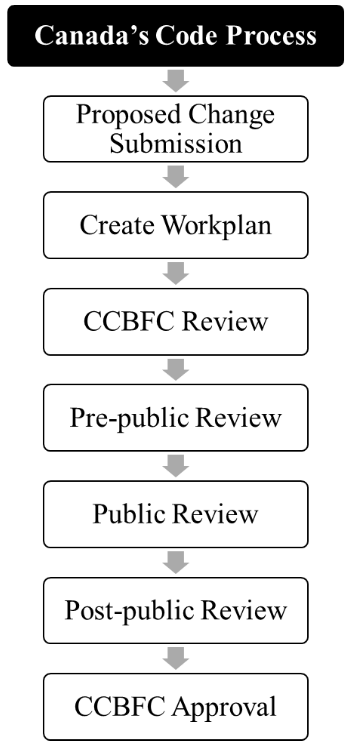


Figure 3.2: Overview of code advancement process before the 2025 code cycle

In November 2022, it was announced that the federal government was changing the national code development process to better integrate the provinces and territories, respond to priorities from different jurisdictions and harmonize the construction codes [80]. The CCBFC was replaced with the CBHCC, comprising of federal and provincial/territorial representatives. The current code development process with CCBFC will remain in place until the next code development cycle in 2025 [80].

Canada does not have a specific wildfire or WUI code or wildfire-related standards, and wildfire is not explicitly addressed in the NBCC or NFCC, though some provisions inherently contribute to wildfire resistance such as those relating to spatial separation and reducing fire exposure from adjacent buildings (NBCC 3.2.3, 9.10.14 and 9.10.15) [29], [78]. The FireSmart Canada program, originally published 20 years ago, prior to the publication of the National Guide, was one of the main resources for community guidance on protection against wildfires [81]. The guidance includes identifying priority zones, vegetation management strategies and structural materials guidance [82]. FireSmart is not limited to homeowners and provides guidance and recommendations at the community-level through infrastructure and utility planning guidance and emergency management strategies [82]. A review of wildfire standards and guidelines from around the world found that Canada's FireSmart guidance was strong in identifying wildfire risk and providing clear land management strategies and accessibility of utilities. However, they also determined it lacked detail in describing building protection measures, fire protection systems and environmental factors [83].

Recently, the National Research Council of Canada published its first *National Guide for Wildland-Urban-Interface Fires* with the potential for it to serve as the basis for code in the future [29]. The guide was developed using existing wildfire codes, standards, and guidelines, with many from the National Fire Protection Association (NFPA) which issues codes and standards in the United States. The risk mitigation guidance provided largely falls under three categories: 1) vegetation management, 2) structural materials and 3) community planning. Vegetation management guidance includes identifying priority zones surrounding a structure and strategies to reduce fuel loading in those zones including but not limited to vegetation thinning, pruning and removed dead litter. Structural materials guidance outlines construction guidance and materials selection to minimize the risk of building ignition through recommending less combustible or non-combustible building materials and design recommendation such as reducing openings or penetrations. Community planning guidance is largely centred around land use, access routes, resource capabilities and emergency planning [29].

However, this guide is currently voluntary and non-enforceable. It has not undergone the intensive review associated with code development, nor has it been reviewed for potential conflicts with other regulatory requirements [29]. While the guide drew on FireSmart, the objectives of FireSmart and the guide are not identical, as FireSmart is more focused on increasing the wildfire resilience of existing communities whereas the Guide is broader "with the potential for eventually being considered for code provisions" [29].

3.2.2 International

There is precedence for a wildfire-specific building code in countries prone to wildfires and these documents have been used as references for the creation of Canada's National Guide [29]. Notably, both the United States and Australia have wildfire-specific codes at the national level as well as the state level. *NFPA 1144: Standard for Reducing Structure Ignition Hazards from Wildland Fire* in the United States specifically addresses building design and construction as well as vegetation management, as does the Australian standard *AS 3959: Construction of Buildings in Bushfire-Prone Areas* [37], [83], [84]. Other wildfire-prone countries such as France and Italy do not have specific wildfire codes, but parts of their fire code are applicable to wildfires in addition to regional guidance [83]. In addition to individual countries' codes, there is also the International Wildland-Urban Interface Code (IWUIC) developed by the International Code Council (ICC) [85]. The IWUIC is a model code and designed to be adapted for use in other jurisdictions' building and fire codes [86].

The review of wildfire codes and guides found that both the standards and guidance available in the United States (not only NFPA 1144), and the IWUIC found that while both documents were strong in addressing categories relating to land management around properties and building construction, they were weaker when describing requirements relating to resources around fire suppression, such as water supply and firefighting capacities [83]. The Australian standard AS 3959, while also strong in land management and building construction, was also weaker in addressing resources, fire protection and environmental factors in its code requirements [83].

3.3 Objectives and Methodology

The aim of the literature was to find studies investigating structural and landscape factors which contribute to building survival after a wildfire. The inclusion criteria for the publications were as follows: 1) the paper must be in English, 2) the paper must be investigating building survival and/or damage after a wildfire, and 3) the methodology must use post-wildfire data, not solely risk-based modelling or an experimental test. The decision to exclude modelling and experimental studies was done as pre- and post-wildfire data collection has been identified as a key research need and can be used to validate and improve laboratory and modelling methodologies [87]. Additionally, while both are critical to furthering our understanding of wildfires and material performance, due to the complexity of wildfires and their interactions with infrastructure, it is difficult to replicate actual wildfire conditions at smaller scales [88].

The literature review was conducted using the Web of Science database in May 2023. The queries used were chosen in order to best capture studies relating to building survival. “Wildfires” was included in the search query or as a keyword in order to ensure that the studies were related to wildfires and not another mechanism of building damage, such as other severe weather events. Defensible space was chosen as its own search query as it is considered one of the primary tools recommended and used to increase the wildfire resistance of a property. When the query was searched for, the results were exported into Excel. The results were then filtered based on the title and then the abstract as to whether they meet the inclusion criteria. The publications were then reviewed for general information such as the location of the study and the year published. The contents of the paper were reviewed for the types of factors identified as impacting building damage and survival.

3.4 Results

3.4.1 Paper Yield and Statistics

The search terms yielded a total of 1,053 papers, which included duplicate results (see Table 3.1). When the papers were screened based on the inclusion criteria, there were 67 papers, however, 37 of the papers were duplicate results. Therefore, the search yielded 24 papers. One additional paper was included to bring the total to 25 papers, as it was found as part of an exploratory review completed previously [89].

Table 3.1: Search terms and number of results

Search Query	Keywords	# Results	# Useful Results	#Duplicates of Useful	# Useful Unique
building survival wildfire	-	49	11	0	11
building survival	wildfire	8	1	1	0
structural damage wildfire	-	58	1	1	0
structural damage	wildfire	9	0	0	0
defensible space wildfire	-	80	12	7	5
defensible space	wildfire	17	1	1	0
post-wildfire building	-	41	0	0	0
post-wildfire structure	-	58	0	0	0

Search Query	Keywords	# Results	# Useful Results	#Duplicates of Useful	# Useful Unique
building damage wildfire	-	168	12	6	6
building damage	wildfire	26	2	2	0
structure damage wildfire	-	275	9	7	2
structure damage	wildfire	70	3	3	0
structure survival wildfire	-	157	8	8	0
structure survival	wildfire	37	1	1	0
	Totals	**1,053**	**61**	**37**	**24**

The studies occurred in six different countries, with the majority taking place in the United States, specifically California. More than half of the articles were published after 2019. Most of the papers (23 papers) focused on landscape factors, such as the surrounding vegetation and defensible space, while 10 papers examined structural factors. It should be noted that nine of the papers looked at both structural and landscape factors. A full list of articles included in the review is available in Appendix B.

3.4.2 Structural Factors

The National Guide provides recommendations on building design and materials, largely directed at using non-combustible materials or combustible materials of certain dimensions to reduce ignition likelihood and reducing gaps or openings in the structure, adjusting for ember exposure level [29].

3.4.2.1 Building Materials and Design

Wood has long been considered a risk for fire safety due to its combustible nature [35], which was supported by a study of the 2018 Camp Fire in California which found that wooden features increased the likelihood of damage [90]. A study of the 2016 Fort McMurray Fire also found that that combustible decking, porches and fences increased the likelihood of building damage, where surviving homes had on average less than two combustible attachments [39]. A study of the 2017 Knysna fires in South Africa found that homes with timber walls and thatch were at a higher risk [91]. A study surveying building survival after the 2017 Pedrógão Grande Fire in Portugal, found that while there were not many identifed buildings of wooden construction, all were destroyed [92].

However, depending on the fire behaviour, the building factors which have the most impact can change. Studies found that in extreme fire weather conditions with firebrands, it was points of entry such as windows and eaves that have the most impact on building damage [93]. Firebrands have been found to be responsible for over 50% of structural ignitions [35], which was supported by studies where 60% of structure ignitions were attributed to firebrands [91], [92]. Where firebrands are the primary driver of ignition, windows and eaves had a larger impact over building materials. A study of building survival in California found that homes using dual paned windows and vinyl window framing survived at a higher rate than single-paned windows or window framing using metal or wood [94]. This was supported by other studies examining building survival in California [90], [93]. In addition to eaves, vent screens were also found to impact building survival as they prevent entry to firebrands [95].

It should be noted that there were geographical differences between the results of the studies. A study in California noted differences between regions, where roofing and exterior siding had a larger impact in the Bay Area than in other regions of the state [93]. Another study compared the 2018 Camp Fire in California and the 2017 Pedrógão Grande Fire in Portugal found differences in severity of damage and building construction [95].

3.4.2.2 Building Characteristics

The age of the building was found to be a contributing factor to building survival, where older buildings were more likely to be destroyed. This was observed in studies in California, Australia and Portugal, which indicates that it is not necessarily dependent on specific types of building construction. Ribeiro et. al (2020) found that over 86% of impacted structures in the 2017 Pedrógão Grande Fire were over 30 years old and had the highest percentage of highly damaged and totally destroyed structures [92]. Older structures were also more likely to have higher risk building features such as single-paned windows and vegetation cover [94], [96]. A study of building survival after the 2013 Linksview Fire in Australia found that housing built after the state introduced “Planning for Bushfire Protection” code in 2002, survived more often than older houses, where 27.3% of houses built in the 2000s were impacted compared to 69.6% of pre-1990s houses impacted. They also observed that the year of construction was a better indicator than the year of modification for building survival [96]. A study of the 2018 Camp Fire in California did not find statistical significance between homes built pre- and post- updates to California’s building code in

2008 incorporating wildfire-specific provisions such as more fire resistant exterior building materials, though, they did notice a slight improvement [97]. By contrast, Price and Roberts (2022) did find an impact of Australian standards on building survival, though not the exact mechanism. They did find, however, that in zones categorized as the highest risk (Flame Zone), building still remained 2.5 times more likely to be impacted than those outside the Flame Zone [96].

Building age may also be considered a proxy for building material quality assuming that older buildings' materials are more weathered and of a lower quality than new buildings, however, this was not explored in many of the studies. Two studies categorized the preservation level of the structures prior to the 2017 Pedrógão Grande Fire. One study concluded that the degree of maintenance had a limited impact on building survival, though, it was observed that better preserved structures fared slightly better [92]. The other study found that the preservation level did have an impact on building survival, however, it was less important than other construction characteristics such as decking and exterior materials [95].

3.4.3 Landscape Factors

The National Guide also provides recommendations on vegetation management surrounding the property. The guide defines priority zones around the house, accounting for slopes, and recommendations on managing the vegetation to reduce the fuel loads surrounding the house [29]. The Guide defines three priority zones, with Priority Zone 1, split into 1A and 1. The zones extend up to 100 m away from the property (or adjusted for slope), with the majority of the vegetation management recommendations occurring within Priority Zones 1A, 1 and 2, within 30 m of the property [29].

3.4.3.1 Defensible Space

When examining building survival, creating defensible space is considered one of the primary tools that communities can employ to reduce wildfire damage to structural properties. Defensible space in wildfire contexts has been defined as "an area where material capable of allowing a fire to spread unchecked has been treated, cleared or modified to slow the rate and intensity of an advancing wildfire" (Section 202, IWUIC) [98]. The distance required for effective defensible space is still being studied. Syphard et. al (2014) after reviewing fires from 2001-2010 in San Diego County, California concluded that the effective defensible space could be less than 30 m, with 4-5 m on shallow slopes and 20-25 m on steep slopes. They also found that the effective clearance was between 31-40% [99]. Another study in California found that in areas with housing density under 54 structures per km^2 if the clearance was over 30%, building were more likely to survive [94]. By contrast, a study in Colorado after the 2020 East Troublesome Fire found that there may be benefit for extending the defensible space up to 45 m (150 ft) [100].

While some studies did not characterize the defensible space itself, they did find that it was effective at reducing building damage. A study of the 2017 Lousã Fire in Portugal found that the presence of trees and bushes within 30 m accounted for 77.60% of the variance in the degree of damage/destruction of buildings [101]. A study in Sweden found that having a defensible space over 5 m, increased the likelihood of building survival [36]. They also found that landscape characteristics had a larger impact than structural characteristics, though, they note that the majority of the buildings surveyed were of similar characteristics with combustible exteriors. A study examining building survival after the 2016 Fort McMurray Fire assessed buildings using FireSmart Canada's hazard ratings, where the presence of hazard factors such as combustible building materials, surrounding fuels earned points. Based on the number of points, buildings could be categorized under Low, Moderate, High, and Extreme FireSmart Hazard levels. A "FireSmart" building were those whose hazard was considered Low or Moderate. The study found that surviving buildings were more likely to have been "FireSmart" and vegetation accounted for the majority of their hazard ratings [39].

Within defensible space, the area directly adjacent to the structure was often found to be the most important. Vegetation directly touching the structures increased the risk of building damage, which included ornamental vegetation, which was supported by studies in the United States [94], [99], [100]. Studies in both Sweden and Canada also supported the importance of landscape management directly adjacent to the structure, with the study of Fort McMurray noting that buildings that were considered "FireSmart" but were still damaged, there were easily flammable ornamental shrubs within 3 m of the home or there were substantial fuel sources such as wooden sheds, firewood or petroleum products within 5 m [39]. A study of Australian wildfires found that vegetation touching the structure or overhanging the structure have more of an impact than nearby forest cover [102].

Figure 3.3: Vegetation directly adjacent to a heritage property in Toronto, Canada (author's photo)

It should be noted, however, that there are some studies that did not find defensible space to have a significant impact. A study examining California wildfires between 2013-18 and building survival found that structural characteristics had more of an impact on building survival than vegetation characteristics. The authors propose that it was due to firebrand ignition as firebrands can be transported over large distances [93]. Another study of the 2018 Camp Fire found that the impact of defensible space was inconclusive based on their logistic regression models. They also posited that it may be due to the high intensity nature of the Camp Fire and exposure to firebrands [90]. Firebrands can be transported over large distances and "jump" over defensible spaces, resulting in an increased reliance on structural resistance to ignition.

3.4.3.2 Housing Density and Distance to the Wildland

Housing density was found to have an impact on building survival. A study in California found that buildings that were in lower density areas were more likely to be destroyed [103]. Another review of San Diego county found that between 2000-2010, buildings under 30 years of age and in areas with a density of 54 structures per km^2 all survived and structure density was one of the key contributors to building survival [94]. It was posited that this was due to houses in less dense areas are more likely to have surrounding vegetation and are more difficult to carry out defensive actions due to their distance and potential lack of resources [104]. By contrast, a study of the 2018 Camp Fire found that increased proximity to other destroyed homes also increased the risk of damage. They concluded that while denser neighbourhoods may offer some protection against ignition, once adjacent structures are ignited, the proximity becomes a disadvantage [97]. This was also supported by a study in Australia which also noted that the likelihood of impact increased when the distance between houses decreased [102]. A study in Sweden found little correlation between housing density and building damage, though, they note that there was little housing density variation in their sample size [36].

The distance between the wildland and the structure has also been found to impact building survival as it increases exposure risk. A study of building damage from wildfires across the United States found that the majority of houses destroyed were located in the wildland-urban interface (WUI) or just barely out of the housing density threshold to be classified as WUI. Many of the destroyed buildings outside of the WUI were in close proximity, less than 2.5 km away from the WUI [105]. A review of California specifically also supported that destruction rates of buildings by wildfire were higher in the WUI, though the WUI accounts for little of wildfires' overall burned area [106]. A study after the 2007 Witch and Guejito Fires in California found that 40% of homes on the perimeter of the community were destroyed, in comparison to 20% of homes in the interior [107]. A study of the 2009 Black Saturday fires in Kinglake and Marysville, Australia noted that 90% of buildings destroyed were within 100 m of the wildland, while 60% of destroyed buildings were within 10 m [108].

3.4.3.3 Other Landscape Features

In addition to the landscape factors listed above, the studies also mentioned a number of other landscape features which impacted building survival as the type of fire behaviour can affect what factors have the most impact. A study reviewing house loss in Australia from 1957-2009 found correlations between the Forest Fire Danger Index (FFDI) as well as maximum wind speeds, indicating that house loss increases with severity of fire weather [109]. A review of fires in California between 2013-2018 found that in the North Interior of the state, the maximum annual temperature was an indicator of weather or not a building was destroyed [104]. Another study, also examining Australian wildfires between 1925-2009 concluded that increased building damage and loss is largely attributed to increased population and structures in wildfire prone areas [108].

Slope is considered a risk factor as wildfires are known to travel faster uphill due to preheating from radiant heat and gases [31]. In guidance, it is common for the priority zones to be shifted to account for the slope [29]. In a review of the 2018 Camp Fire, having a slope near the property increased the risk of damage [90]. Steep slopes were also found to increase the distance of effective defensible space as well as the effective clearance required, where it was 4-5 m and 31% clearance on shallow slopes compared with 20-25 m and 37% clearance on steep slopes [99].

3.4.4 Other Factors

It should be noted that in addition to structural and landscape factors, the studies noted other factors which also impacted building survival. Defensive actions are one factor where studies found that had a positive impact on building survival, where defensive actions are defined as actions taken by an individual or firefighter(s) to affect the behaviour of the fire. A study of the 2007 Witch and Guejito Fires in California observed that 30% of homes were defended and it was estimated that defensive actions reduced the losses from 37% to 30% [107]. A study of the 2013 Linksview and Mt. York Fires in New South Wales, Australia observed that defensive actions were one of the most important factors and houses that were undefended were 3 times as likely to be impacted [110]. Proximity to a fire station was observed to decrease the risk of damage, which may be attributed to defensive actions [111]. It should be noted that the objective of the literature review was to focus on landscape and structural factors and as such, studies specifically on defensive actions in wildfires were not explicitly searched for.

3.5 Discussion

3.5.1 Location

The vast majority of the 25 studies included as part of this review were conducted outside of Canada, with only one study taking place in Fort McMurray, Alberta. The remaining studies took place in the United States, Australia, Portugal, Sweden and South Africa. 12 of the studies were done using data from wildfires in California. This highlights the need for Canadian- and region-specific data as wildfire data is not easily transferred between countries or regions due to differences in climate, vegetation, infrastructure, and materials. While data from other countries is useful, the lack of Canadian data means it is unknown at how applicable the information is to Canadian communities. This was evident in the studies as a few of them highlighted differences between regions and countries for both structural and landscape factors. One study compared California and Portugal building survival after wildfires and observed differences in severity of damage and building construction in the datasets. Venting systems played a larger role in California wildfires attributed to firebrands whereas exterior walls in Portugal were observed to have more of an impact on building survival [95]. However, even within California, there were regional differences observed in building survival factors [93].

The geographical differences have a number of implications for a national wildfire building code. In Canada, the national model code advancement process is being changed for the next 2025 code cycle in order to better harmonize with the provincial and territorial codes. However, this research highlights the need for region-specific data and that a "one-size-fits-all" approach may not be appropriate. More research is needed to determine what location-specific, if any, provisions may be recommended. The National Guide does include provisions based on hazard exposure levels and construction classes [29].

3.5.2 Building and Building Material Quality

The studies reviewed focused on the impact building materials and vegetation characteristics on survival post-wildfires as per the objective. However, this does exclude characterizing the building condition/quality prior to the wildfire event and how the building condition itself may impact building performance in wildfires. There were two studies done in Portugal which did include the overall preservation status of the building, however, their results indicated that while its status did have an impact, it was less than other structural factors such as building materials [92], [95]. More information is needed on how a building's condition and the condition of its materials impact building survival.

3.5.3 Heritage Properties

In line with the previous section, there is also a lack of consideration of heritage properties. Heritage properties are designated properties which hold aesthetic, historic, scientific, cultural, social or spiritual value in its character-defining elements, such as materials, forms and location [112]. As such, they are given special protections against alterations in order to preserve its heritage and cultural value. However, while heritage buildings are more vulnerable to fire due to their age and construction prior to existing building codes, these protections also largely prevent the installation of new fire protection systems or replacing structural materials with more resistant ones [113]. In addition to largely being unable to alter features of heritage buildings to allow for new fire protection systems, there is an imperative that in the event of a fire, not only must human life be preserved, but the building itself must also be preserved which presents new considerations for hardening the building against wildfires [113].

In this review, building age was found to have an impact where older houses were more likely to be destroyed, and it was seen across multiple studies. A study done in the San Diego area observed in areas where the structure density was greater than 54 structures per km^2, that buildings over 83 years old were damaged by the wildfire, though, they did not characterize the heritage status of the buildings [93]. A study of the 2013 Linksview Fire observed that the year of construction was a better indicator for building damage than the year of modification [96], which has implications for the effectiveness of structural interventions for heritage buildings. There is limited understanding of heritage materials in fire [114], with one study on heritage timber suggesting it performs less well than contemporary timber [115], and therefore, its performance under wildfire conditions is relatively unknown.

3.5.4 Land Use Planning

While the review initially sought to evaluate structural and landscape features which impacted building survival, the studies also indicated that land planning and urban planning is an important factor in building survival in wildfires. Housing density and distance to the wildland were found to impact the building survival, though, more research is needed on housing density its impact varied in the studies. Additionally, it was observed that houses closest to the wildland were more likely to be impacted [107] and therefore the required protection may vary depending on the location [116]. The National Guide does have sections related to housing density, though it does not provide any prescriptive recommendations, only noting that it should be designed so that structures can follow the construction and vegetation recommendations [29].

3.5.5 Indigenous Communities

Another identified research priority is Indigenous communities and wildfires [117]. The studies did not explicitly identify if the buildings surveyed were part of an Indigenous community. In Canada, Indigenous communities are more likely to be evacuated due to wildfires and wildfire smoke [118]. Wildfires in Indigenous communities are part of complicated jurisdictional arrangements which adds complexity with respect to building codes, fire management, and evacuations [119]. In addition to Indigenous communities being more at risk for wildfires, they are also more at risk of house fires, with fire rates approximately 2.4 times higher than the rest of Canada and death rates in house fires up to 10 times higher [120]. There are no national regulations governing fire safety in Indigenous communities. As Indigenous communities, they are not under the jurisdiction of provincial and territorial building codes and regulations. It is expected for on-reserve Indigenous infrastructure projects to meet the standards of the national model codes to receive federal funding, however, Indigenous communities have the right to create or adopt their own codes [121]. Therefore, fire safety is largely regarded as the responsibility of each individual community, with smaller and more remote communities at a disadvantage due to a lack of resources.

More research is needed to characterize the buildings and fire risks present in Indigenous communities as there is little data as to how their housing performs in fire. However, this data is difficult to obtain as it requires strong relationships between the researcher(s) and the community which takes time to develop [117]. Additionally, it must be noted while some are advocating for the federal government to intervene in fire safety in Indigenous communities [122], there is little information on how legislating or enforcing a code or standard to Indigenous communities would be received [117]. However, it has been reported that it is largely unsupported by Indigenous community members and would be considered a violation of their rights of self-governance and self-determination [123], [124].

3.5.6 Limitations

One limitation of this study was the relatively small sample of publications. The literature review was expanded from the initial exploratory review [89], in order to better capture the available publications. However, publications using both pre- and post- wildfire data are relatively rare, as demonstrated by screening 1,053 publications and only having 25 unique papers meeting the inclusion criteria. Pre- and post-wildfire data collection which can be used to evaluate guidance impacts has been identified as a research need [37], [87] and there are Canadian initiatives in progress for systematic data collection to address the lack of data [125]. Additionally, while the search criteria were broader in order to capture a spectrum of articles, it means that publications focusing on one specific factor such as housing density and defensive actions may have been excluded from the search if it did not include the query terms. The publications were also sourced from one single database, Web of Science. Publications which were not included in the search results of this database, were excluded.

3.6 Summary

In conclusion, there are many structural and landscape factors that contribute to building survival. There was agreement in the studies about structural elements such as the importance of protecting points of entry and areas where firebrands could gather and using non-combustible building materials to reduce the risk of damage. Landscape factors such as defensible space, vegetation directly adjacent to the structure, housing density and arrangement also impacted building survival. These factors and their impact vary depending on the location of the structure and the fire behaviour of the wildfire. These studies have largely been conducted using data from wildfires outside of Canada, resulting in a critical research gap for Canadian wildfire code development. While there were some observations which were supported across the various studies, regional differences were observed as well, highlighting the importance of having Canadian-specific research. Additionally, more research is needed on the performance of different types of buildings, building conditions and housing arrangements in wildfires such as heritage properties and those in Indigenous communities.

Chapter 4: Material Properties and Ignition of Cedar Shingles

4.1 Heritage Properties and Wildfires

Heritage properties are designated properties which hold aesthetic, historic, scientific, cultural, social or spiritual value in its character-defining elements, such as materials, forms and location [112]. As such, they are given special protections against alterations in order to preserve its heritage and cultural value, with the emphasis on conservation and preservation of character-defining elements over replacements [112]. However, these protections also largely prevent the installation of new fire protection systems or replacing structural materials with more resistant ones [113]. In addition to largely being unable to alter features of heritage buildings to allow for new fire protection systems, there is an imperative that in the event of a fire, not only must human life be preserved, but the building itself must also be preserved [113]. A study of building survival after the 2013 Linksview fire in Australia observed that modifications to older buildings had limited impact on their wildfire resistance [96]. Thus, heritage buildings present unique fire safety considerations and risks that must be considered when assessing its fire risk.

While large heritage building fires such as the Notre-Dame Cathedral in 2019 and the National Museum of Brazil in 2018 have brought increased attention to protecting heritage buildings from fires, less attention has been brought to heritage buildings and their wildfire risk. Heritage buildings have been found to be more likely to contain features that increase fire risk, such as wooden structural and non-structural elements [126], [127]. However, if a heritage building contains structural features identified as high risk such as wooden decking, siding and/or roofing or openings, there are limited options for modifying the structural components if the building is protected [113]. There is limited understanding of how heritage materials perform in fire [114], with one study on heritage timber suggesting it performs less well than contemporary timber [115], and therefore, its performance under wildfire conditions is relatively unknown. Older buildings have a higher likelihood of being damaged or destroyed in wildfires, though, their heritage statuses have not been examined [90], [93], [94].

4.1.1 Case Study: Southern Ontario Heritage Property

A house in Toronto, Canada is a heritage property under Ontario's Heritage Act Part IV and is one of the oldest surviving buildings in Toronto as it was built in the early 1800s[3]. Its designated heritage features include its building materials, building elements such as its windows and paneled doors, as well as its architectural features. The house is largely made of timber and wooden features, many of which are documented heritage features. The house is surrounded by vegetation and the area surrounding the house is designated as a cultural heritage landscape, defined as "a property or defined geographical area of cultural heritage significance that has been modified by human activities and is valued by a community" [128]. The area itself is historically not prone to wildfires [129], however in light of its risks as a WUI heritage building and the increased risk of wildfires globally, the house provides a unique opportunity for a case study.

A site visit to the property noted many potential fire hazards. One example would be a tree next to the property has branches physically touching the roof. This could be a path for direct flame impingement. Additionally, it could also be a path for animals to enter the house which could impact the quality of the building materials. The house itself is a wooden construction with wooden frames, shingles and decking which are vulnerable to fire. The house was abandoned in 2009 and is not used by property owners and therefore, the quality of the building and its materials is in decline. At the time of writing, the property has not undergone an official fire risk assessment by qualified individuals, though, a condition assessment and geophysical survey has been completed. The property has limited fire protection systems in the form of smoke detectors and a security system, but no sprinklers. While there is active power in the building, all other systems have been shut off.

[3] The property is being kept confidential to protect it from risk.

Figure 4.1: Tree adjacent to the house touching the roof (author's photo)

Figure 4.2: Wooden decking of the house (author's photo)

This property is representative of the fire risks associated with heritage properties with its timber construction, limited or lack of active fire protection systems and protected status restricting structural changes. Canada has over 17,000 recognized historic places, which are not limited to buildings, but can also include archeological sites, landscapes and districts [130]. Figure 4.3 shows the map of active wildfires in May 2023 in Alberta compared to the heritage listings in the

Canadian Register of Historic Places, which demonstrates that wildfires are threatening heritage properties and there needs to be considerations made for wildfire events[4].

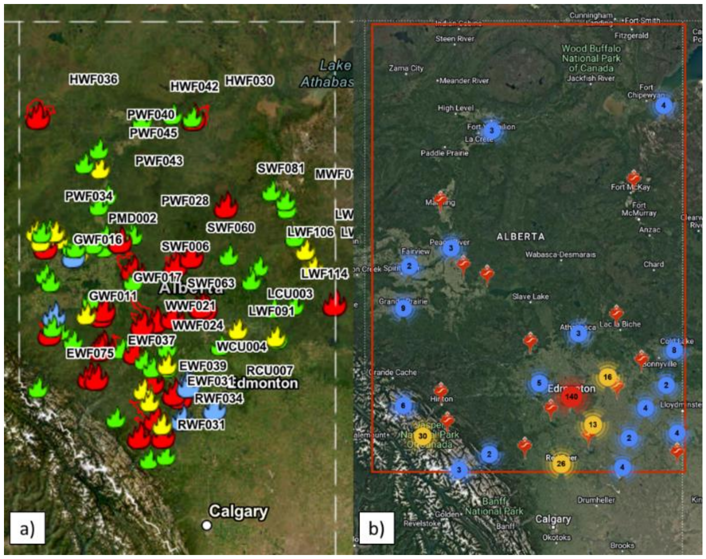


Figure 4.3: Comparison of a) active wildfires in May 2023 (taken from [131][5]*) and b) heritage locations in Alberta (taken from* [132]*)*

Historically, wildfires in southern Ontario have not been a serious concern. However, with climate change, there is increased risk of wildfires where they were previously less of a concern (see Figure 4.4). In June 2023, a brushfire near Highway 401 between Kingston and Gananoque temporarily disrupted Via Rail travel [133]. During Canada's record-breaking 2023 wildfire season, Ontario reported three times as many wildfires as it did in 2022 over the same time span [134]. Average temperatures in Toronto and southern Ontario are only expected to increase. Toronto is predicted to be in the top 10 for number of days of 30°C, maximum recorded temperatures and average length of heatwaves, with other municipalities in southern Ontario such as Windsor, Hamilton and Ottawa also included in the top ten [135]. The 2022 London Wildfires were largely heat-driven where a prolonged heat wave, record high temperatures and drought were enough to ignite wildfires [136].

[4] Alberta was chosen over Ontario as at the time of writing, they were experiencing multiple wildfires, where the area burned nearly 2,000 times higher than last year's.

[5] Contains information licensed under the Open Government Licence – Alberta

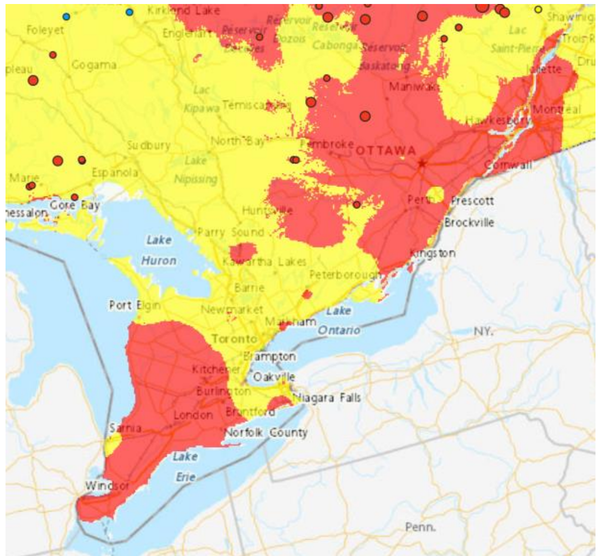


Figure 4.4: Wildfire danger in southern Ontario on June 4, 2023 where yellow is high danger and red is extreme danger (taken from [137][6]*)*

4.2 Cedar Roofing and Heritage

Wood as a combustible building material has been associated with higher rates of building damage and has been identified as a wildfire hazard [35], [39]. Wooden structural and non-structural elements are common in heritage properties [127]. In southern Ontario, wooden shingles were common and made with Eastern white cedar or white pine, and as it became available, Western red cedar [28]. Wood shingles, while used less as a building material than in the past, remain a popular building material due to their versatility, aesthetic appearance and sustainability [138]. Cedar is a popular choice of building material as in addition to being aesthetically appealing, it is durable in various weather conditions, sound-resistant and is naturally insect-repellant [139].

There have been very few studies done on cedar using a cone calorimeter. One study was done examining the impact of heat flux on wood combustion using red cedar, oak, and larch samples (100 x 100 x 10 mm) at 20, 35 and 50 kW/m^2. The samples were dried to have a negligible moisture content. The cedar ignited under all heat fluxes, though the time to ignition decreased as the heat flux increased [55]. Another study examined the impact of weathering on fire performance using cedar samples (100 x 100 x 18 mm) at 50 kW/m^2. They found that weathering of untreated cedar increased the flammability and decreased the ignition time [56].

[6] Contains information licensed under the Open Government Licence – Canada.

While small-scale studies are fewer, there have been larger-scale studies involving cedar assemblies and firebrand ignition. Firebrands are a significant concern for wildfires as they heavily contribute to wildfire spread [35]. There have been studies done on cedar roofing assemblies and firebrands, looking at both ignitability of cedar roofing as well as firebrand generation by the cedar roofing [140], [141]. The cedar roof assembly used dried cedar shakes and found that embers accumulated in gaps between the shakes and resulted in ignition [140]. In addition to the cedar roofing assemblies ignition via firebrands, untreated cedar roofing was also found to produce its own firebrands when ignited, which could contribute to further wildfire spread [141].

4.3 Objectives and Methodology

The objective of this study was to investigate how moisture content and heat flux affected the ignition of Eastern white cedar shingles.

4.3.1 Sample Preparation

Due to heritage materials' protected statuses and relative rarity when compared to contemporary materials [142], heritage cedar shingles could not be procured for testing, though attempts were made through searching through an inventory of heritage materials which the author had permission to use. Modern samples were used instead, which did allow for a more controlled study without the impact of defects and weathering which will be considered in future research. Air-dried, Grade A Eastern white cedar (*Thuja occidentalis*) shingles were ordered that were 18 inches in length and 5/8 inches at the butt. The shingles varied in width from approximately 3 inches to 10 inches. Cone samples were cut from the butt end of the shingle in 100 mm by 100 mm squares. The thickness of the sample varied between 10 mm and 15 mm as the shingles were tapered. The samples were then separated into three categories for conditioning: 1) ambient, 2) dry and 3) wet. Ambient samples had moisture contents between 6%-8%, dry samples were assumed to have a near zero moisture content and wet samples had moisture contents between 30%-40% (see Appendix C for full sample details). The dry and wet moisture conditions were selected in order to represent the end of the moisture content spectrum where the shingles were extremely dry and at their most flammable, and when the shingles were fully saturated, to mimic conditions after rain. Ambient condition was chosen as a control where they were stored in the condition they arrived in. Moisture contents were calculated using the following equation:

$$MC = \frac{m_{sample} - m_{dry}}{m_{sample}} \times 100\% \quad (1)$$

where MC is the moisture content (%), m_{sample} is the mass of the sample and m_{dry} is the dry mass of the sample. For ambient and wet conditioned samples, the dry mass was theoretical and calculated based off of the average moisture content of the dry samples.

Ambient samples were conditioned in an environmentally controlled room for at least 24 hours. The conditioning temperature and humidity varied slightly but was 20℃ and 15% relative humidity. Dried samples were dried in an oven for between 90-115℃ (see Appendix C for full conditioning details). Due to laboratory constraints, the samples could not be left overnight in the oven, and therefore they were dried for as long as possible, then transferred into sealed plastic bags overnight. The day of testing, they were put back in the oven until testing occurred. Dry samples were dried for at least six hours cumulatively. Wet samples were submerged in water for at least 24 hours. As the shingles float, they were held down with weights. Samples were dried until damp with paper towel before testing. It should be noted that while the samples were tested under wet conditions, the samples were not decayed or deteriorated, which can be a serious issue in older properties with uncontrolled moisture [143].

All samples were weighed prior to conditioning and testing. Prior to testing, the samples were wrapped in aluminum foil on the bottom and sides before being placed in the sample holder. As the samples were thinner than the sample holder, there was a ceramic plate and a layer of insulation under the sample so that the exposed side was flush against the top of the sample holder.

4.3.2 Cone Calorimeter

An FTT[7] cone calorimeter was used to measure the time to ignition, heat release rate (HRR) and the mass of the samples. Cone testing procedure was modelled after previous research done by the research team to allow for comparisons using a modified ASTM E1354 test procedure [115], [144]. The samples were tested under three heat fluxes: 1) 20 kW/m^2, 2) 30 kW/m^2 and 3) 40 kW/m^2. The samples were tested for 15 minutes if the sample did not ignite or until two minutes after flameout. A test duration of 15 minutes was chosen in order to align with previous cone tests done by the author's research group for comparison. During the testing, events were marked using the

[7] Fire Testing Technology

built-in cone software and a video of the test was taken using a Canon Vixia HFR800 video camera. Heat release rate (HRR) and mass over the test duration were recorded by the cone software. Once the test had finished, the sample was taken to the fumehood and extinguished using water. Samples were left in the fumehood to dry overnight. Char was measured visually after the test had finished. The samples were cut in half and char depth was measured from the centre of the sample.

Figure 4.5: Cone calorimeter test in progress (author's photo)

4.4 Results and Discussion

4.4.1 Ignition Times

Table 4.1 shows the average ignition times and their standard deviations (all ignition times can be found in Appendix C). Flaming ignition only occurred at 40 kW/m^2 and at 30 kW/m^2 when the samples were dried to approximately zero moisture content in an oven. At 40 kW/m^2, as the moisture content increased, the average time to ignition also increased indicating that an increase in moisture content delays ignition, which was expected [46]. The moisture acts as a heat sink and delays ignition as energy is used to dehydrate the sample as opposed to pyrolysis [46], [145]. However, it was found that the average ignition time for the dried samples at 40 kW/m^2 was slower than the ambient samples with a higher moisture content. One potential reason could be that the char layer formed faster at the lower moisture content which created a protective layer which delayed ignition. The wet samples at 40 kW/m^2 had a large standard deviation as two of the samples (W40-1 and W40-2) ignited at approximately 90 seconds, the third sample (W40-3) did not ignite until 11 minutes into the test.

Table 4.1: Average ignition times in seconds

Heat Flux (kW/m^2)	Conditioning	Average Ignition Time (Std. Deviation) [s]
30	Dry	404 (125)
40	Ambient	26 (6)
40	Dry	46 (16)
40	Wet	284 (327)

At 30 kW/m^2, only two of the dry samples ignited at 315 and 492 seconds respectively, resulting in the large standard deviation. As the critical heat flux for spontaneous ignition of wood is reported to be between 25 to 35 kW/m^2 [46], though the studies did not include Eastern white cedar, it was not unusual that there was no ignition at 20 kW/m^2 heat flux. From the video footage, while some of the samples did create embers, it did not appear that the embers sparked ignition in most of the samples. There is one sample (W40-3) where embers may have contributed to ignition. This sample's ignition time was approximately 11 minutes into the test, which was far longer than the other two wet samples which ignited around 90 seconds.

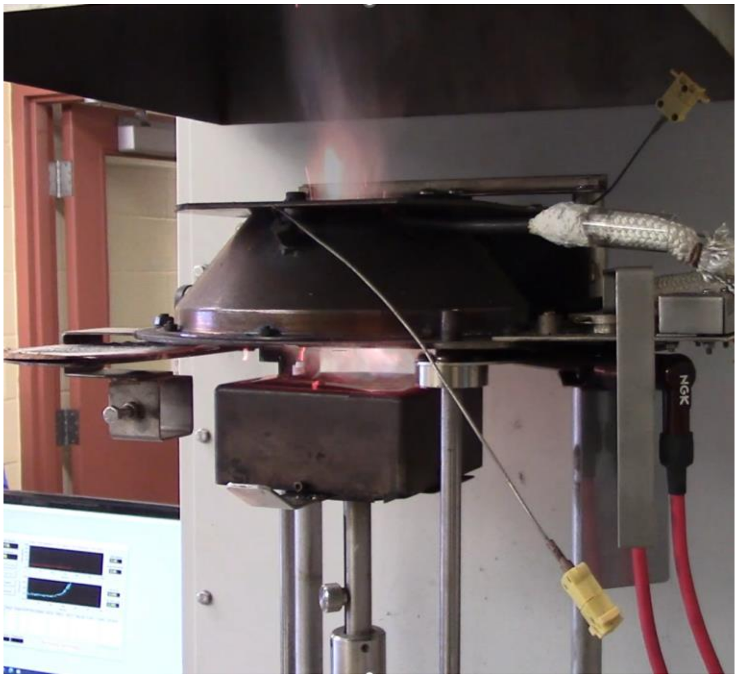


Figure 4.6: Ignition of a sample (W40-3) with embers visible (author's photo)

4.4.2 Heat Release Rate (HRR)

Heat release rate (HRR) is a measure of the heat energy released by the fire [41]. The following Figure 4.7 shows the HRR rate at the different heat fluxes. The HRR of samples which did not ignite remained low. It should be noted, that while those samples did not have flaming combustion, there was pyrolysis and glowing combustion. When the samples ignited, the HRR increased rapidly before decreasing as the shingle is burned and char is formed. There is a double peak present in the HRR graphs for the samples that ignited. It is less present in the samples tested at 30 kW/m^2, but is more clear in the samples tested at 40 kW/m^2. This double peak is a known phenomenon in wood samples tested with a cone calorimeter and is attributed to when the heat impacts the unexposed side of the sample, resulting in the increase of HRR as the material burns [145]. This is considered a secondary ignition and is visible in video footage. In samples that ignited, after the first ignition, the flame slowly became smaller as the shingle burned. When secondary ignition occurs, the flame grew larger again as the material is burned and then again grows smaller as the material is consumed.

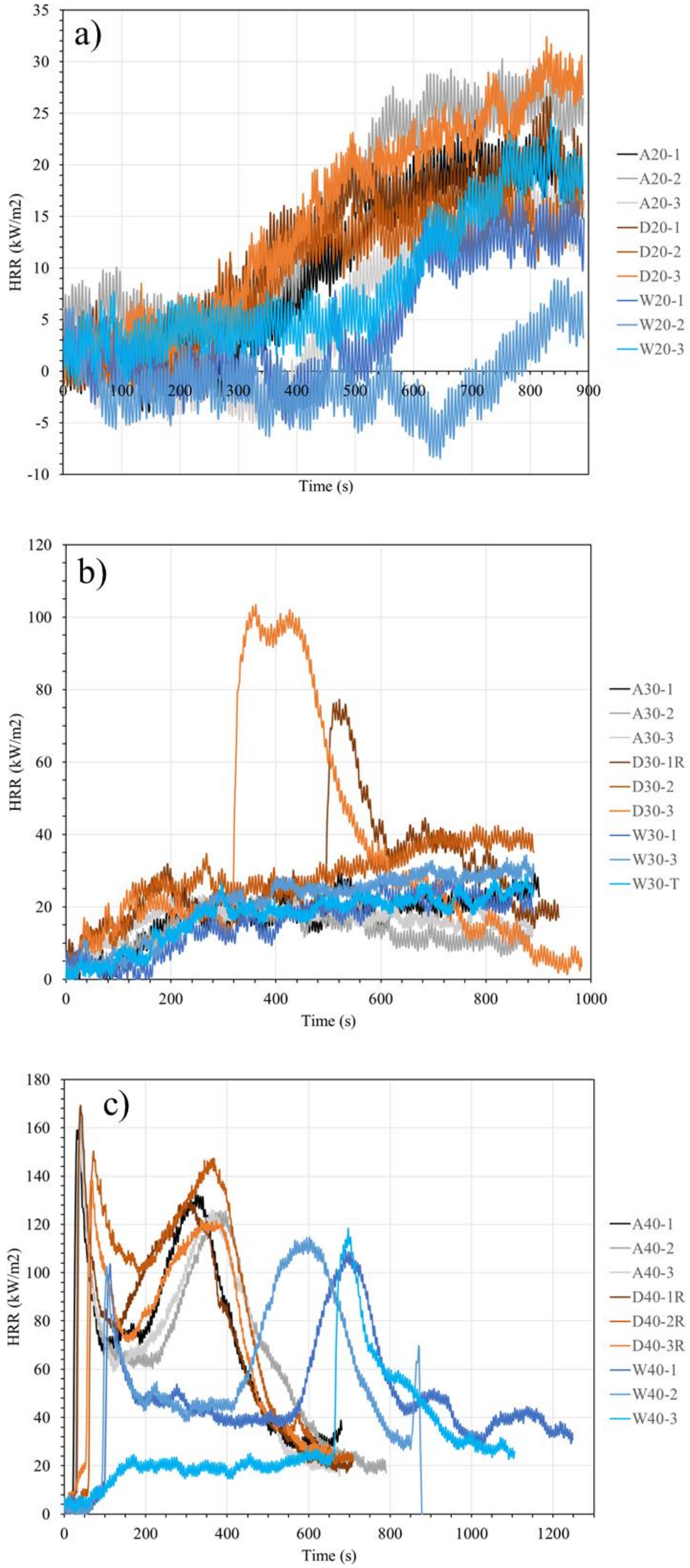


Figure 4.7: HRR over time for a) 20 kW/m² tests b) 30 kW/m² tests and c) 40 kW/m² tests

The size of the second peak can also be impacted by the type of material that is used under the sample as some materials are more conductive of heat than others [145]. In Sample W40-2, near the end of the test, the HRR suddenly rises then falls below zero (Figure 4.7c)). It is unclear why that occurred, video footage of the test did not show an increase in flaming ignition which would be expected with the rise in HRR. This material study focuses on the initial ignition of samples, however, further investigation as to why the third peak may have occurred is recommended.

The peak HRR varied between tests (see Table 4.2, all values are in Appendix C). For samples which ignited, the peak HRR occurred soon after ignition, with the exception of two wet samples tested at 40 kW/m^2 where the peak HRR was recorded in the second peak. In samples that did not ignite, the peak heat flux was recorded closer to the end of the test. In general, the peak HRR also decreased with moisture content, even in samples which did not ignite, such as those tested at 20 kW/m^2. The standard deviations are relatively low, with the exception of the dry samples at 30 kW/m^2 which is due to only two of the three samples igniting. It should be noted that at 20 kW/m^2, the average peak HRR is higher than the amount of heat the sample was exposed to, indicating that even though they did not ignite, they are still adding heat to the environment.

Table 4.2: Average peak HRR of samples

Heat Flux (kW/m^2)	**Conditioning**	**Average Peak HRR (Std. Deviation) [kW/m^2]**
20	Ambient	24.7 (6)
20	Dry	26.3 (6)
20	Wet	16.8 (8)
30	Ambient	26.8 (3)
30	Dry	74.6 (30)
30	Wet	31.0 (3)
40	Ambient	160.7 (7)
40	Dry	152.6 (16)
40	Wet	114.1 (4)

Figure 4.8 (pictured below) shows the HRR of samples tested at 40 kW/m^2 but zoomed in to show the ignition more clearly. One of the wet samples (W40-3) did not ignite until 661 seconds (11 minutes) and is not included in the figure. The dry and wet samples immediately before igniting, also had a slightly higher HRR than the ambient samples. The fluctuations in the values are attributed to fluctuations in the load cell which is very sensitive to movement.

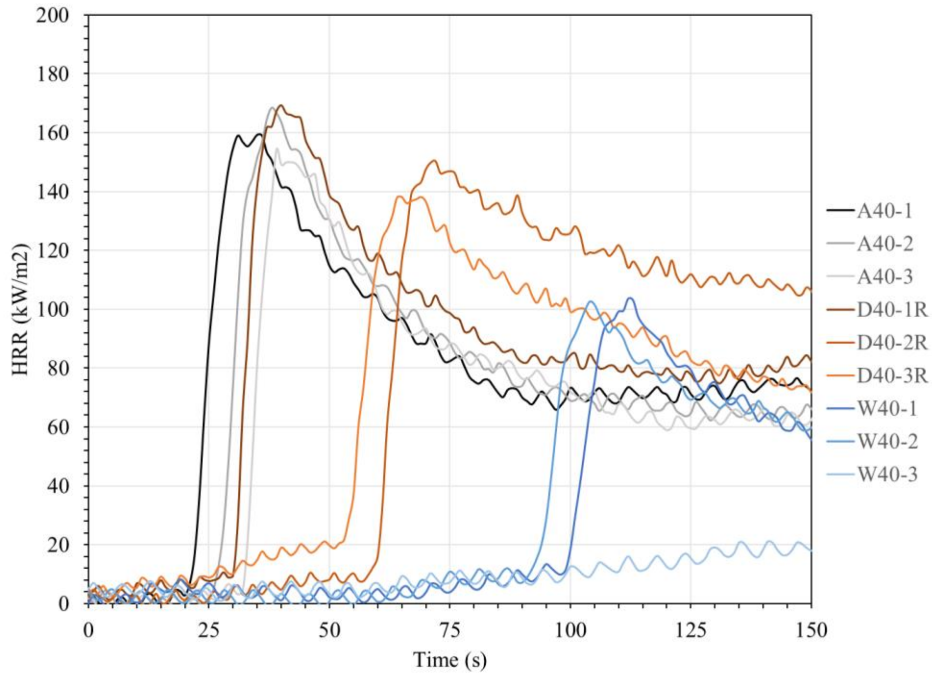


Figure 4.8: HRR of samples tested at 40 kW/m² at ignition

Figure 4.9 below shows the HRR of samples grouped by conditioning type. As the heat flux increased, the samples were more likely to ignite. All the samples tested at 40 kW/m^2 ignited, which was expected based on reported values of critical heat flux of woods [46]. However, it can also be seen in samples that did not ignite, that as the heat flux increased, the HRR of the sample of the sample also increased. The HRR of the samples tested at 30 kW/m^2 increased faster than those at 20 kW/m^2.

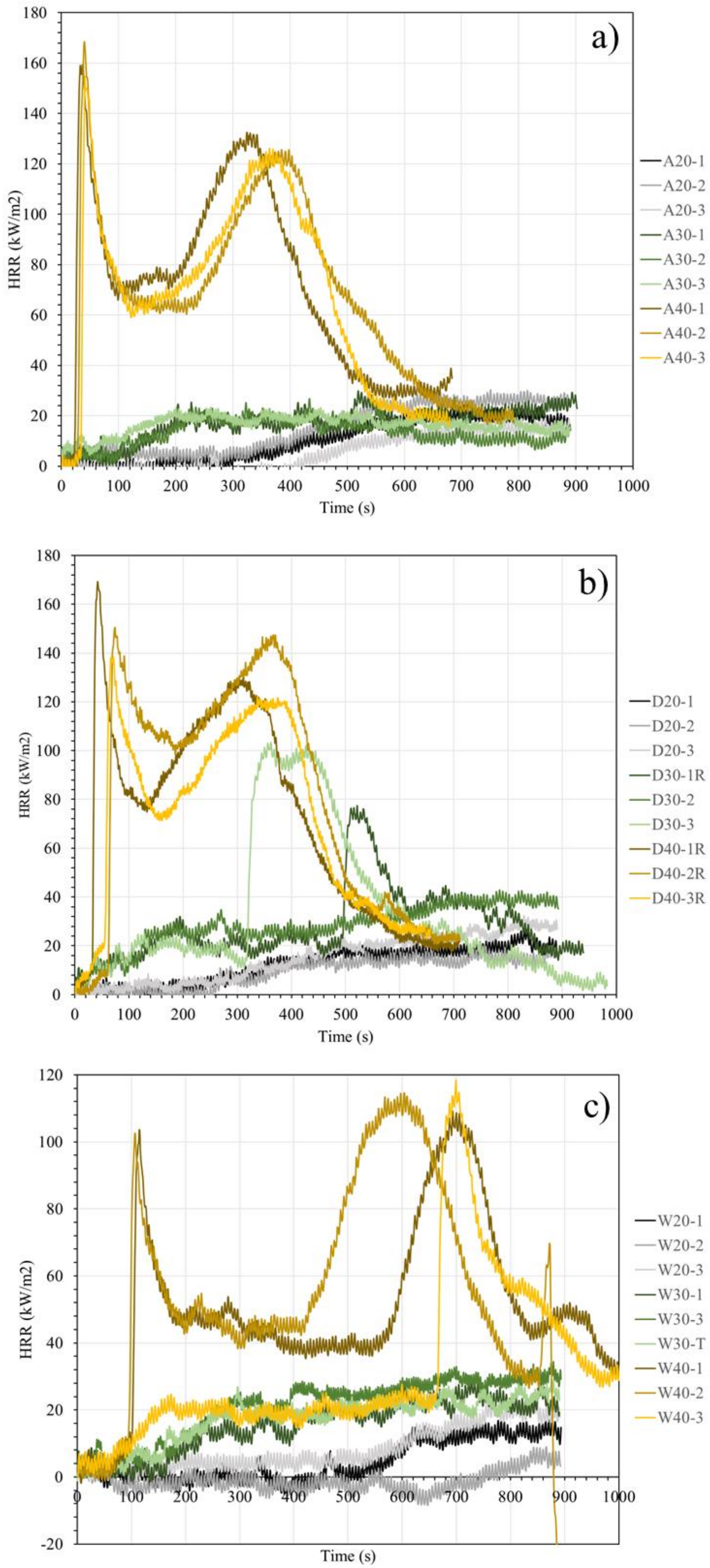


Figure 4.9: HRR of samples conditioned as a) ambient, b) dry and c) wet

4.4.3 Events

When observing the tests, the following events were marked: 1) off-gassing from the shingle, 2) when the top of the exposed sample was completely black, 3) the first appearance of embers or smouldering and 4) ignition and flameout if applicable. The following table shows the average times in seconds of the events based off the video footage. The full list of event times can be found in Appendix C.

Table 4.3: Average event times in seconds (standard deviation in brackets)

	Ambient	**Dry**	**Wet**
		20 kW/m^2	
Off-gassing	10 (1)	6 (2)	47 (21)
Black on top	68 (6)	60 (6)	121 (17)
Glowing/smouldering	480 (83)	284 (19)	652 (122)
Ignition	-	-	-
Flameout	-	-	-
Flaming Duration	-	-	-
		30 kW/m^2	
Off-gassing	3 (1)	5 (1)	27 (3)
Black on top	36 (14)	28 (0)	62 (1)
Glowing/smouldering	140 (13)	92 (17)	184 (11)
Ignition	-	404 (125)	-
Flameout	-	846 (32)	-
Flaming Duration	-	442 (157)	-
		40 kW/m^2	
Off-gassing	3 (1)	1 (0)	19 (4)
Black on top	21 (6)	20 (4)	66 (15)
Glowing/smouldering	-	-	93 (13)
Ignition	26 (6)	46 (16)	284 (327)
Flameout	576 (65)	577 (29)	964 (148)
Flaming Duration	551 (65)	531 (36)	680 (337)

Off-gassing for the dry and ambient samples started within 10 seconds, however, it was closer to 30 seconds for the wet samples. The time at when the top of the sample turned all black varied depending on the heat flux and moisture content. This time was approximated based on the video footage at which point the surface stopped reflecting the red glow from the cone. The time of glowing and smouldering combustion was based off of the time that the first ember could be seen at the surface. As such, the actual time of glowing combustion may have started sooner within the sample.

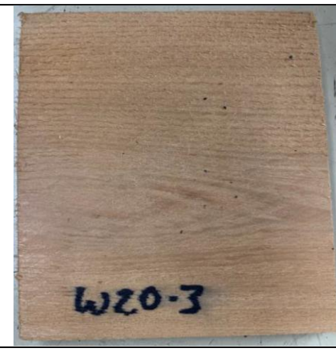
Moisture content had an impact on the pyrolysis of the samples, as shown with the ignition times. While it was less obvious at 20 and 30 kW/m^2 due to a lack of flaming ignition, through the recorded events, it was observed that indicators of pyrolysis such as off-gassing, charring and glowing ignition, were all delayed as the moisture content increased. In the ignited samples at 40 kW/m^2, the duration of flaming ignition also increased with moisture content. This is likely attributed to energy going towards dehydrating the sample as opposed to pyrolysis and therefore, drier samples are burned through more quickly. The heat flux also impacted the pyrolysis, as the time for an event to occur decreased.

4.4.4 Char and Bending

To measure the char, the samples were cut in half and the char was measured at the centre, with the distance from the bottom of the sample until the pitch-black area. That distance was then subtracted from the overall thickness of the sample. This methodology was used, as it was anticipated that some of the thickness had been burned away during the test and therefore, measuring the thickness of the remaining char layer may be an underestimation of the actual char. It should be noted that because the shingles are tapered, the original thickness at the centre of the sample varied. The samples had an average char thickness of 5.8 mm, with a standard deviation of 1.2 mm (see Appendix C for individual char values). The majority of the samples burned straight through (see Table 4.4). Only the wet samples tested at 20 kW/m^2 did not char straight through where char layer measurements could be taken. As the samples were relatively thin, it was expected, especially for samples that ignited, that there would be a significant amount of char.

Figure 4.10: Char layer of a wet sample (W20-1) (author's photo)

Table 4.4: Photos of the unexposed sides of selected samples after testing (author's photos)

Ambient	**Dry**	**Wet**
20 kW/m^2		
		
30 kW/m^2		
		
40 kW/m^2		
		

It was also observed that the cedar shingles bent during the testing. The moisture content affected the direction of the bending, where dry samples bent towards the cone, where the edges bent downwards in a "n" shape, whereas wet samples bent away from the cone, where the edges bent up in a "u" shape (see Figure 4.11). Ambient samples largely bent towards the cone, similar to the dry samples. If the sample ignited, then it bent upwards towards the cone. This bending has been observed in other studies with thin wood samples [55]. The sample bending means that during the test, the heat flux was not consistent, as the heat flux was calibrated to a distance of 25 mm. As the sample bends, the distance between the cone and the sample changes, which also changes the heat flux.

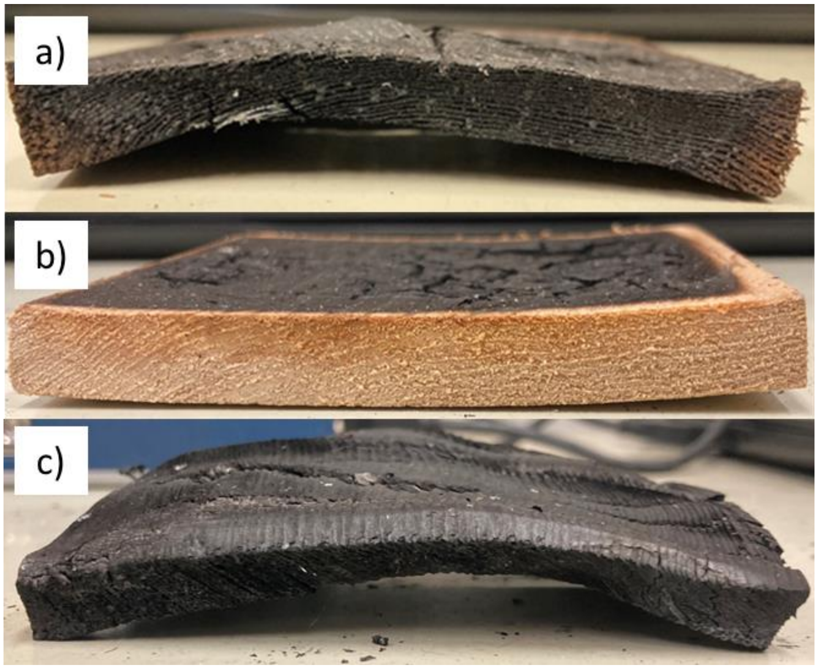


Figure 4.11: Bending of samples a) dry sample at 20 kW/m^2 (D20-2), b) wet sample at 20 kW/m^2 (W20-2) and c) ignited sample at 30 kW/m^2 (D30-3) (author's photo)

4.4.5 Limitations

There are limitations present in the results. One of which was the conditioning of the samples was not the exact same for the samples, which was due to time and laboratory constraints. Therefore, the moisture contents of the samples were not the exact same across the conditioning categories. As the study was done for comparative purposes between conditions, moisture contents were not required to be the exact same in each conditioning category. Another limitation was the small sample size. Each testing category used three samples each, future work may consider increasing the number of samples. Thirdly is that the test duration varied depending on if the sample ignited. It was 15 minutes or two minutes after flameout if the sample ignited. As the primary focus of this study was on ignition of samples, the test duration did not have as much of an impact, however, for future work examining charring rates, using the same test duration and aligning the test durations to previous studies for comparative purposes would be required.

4.5 Summary and Future Work

Cone calorimeter tests of Eastern white cedar shingles were performed at three different moisture conditions and three different heat fluxes. Consistent with previous research on wood burning, moisture content was found to delay the ignition and burning characteristics of the shingles. Increasing the heat flux the shingles were exposed to was observed to increase the burning rate of the shingles. As Eastern white cedar shingles are a relatively common building material in southern Ontario, it is critical to know how they may perform under radiant heat fluxes, as wildfire risks increase.

Cone calorimeter tests of Eastern white cedar shingles were performed to investigate how moisture content and heat flux affected spontaneous ignition, which in wildfire contexts would be associated with radiative ignition due to heat from the fire. However, it is known that firebrands are responsible for a large part of structural ignitions [35]. Therefore, future work should look at piloted ignition of cedar shingles. Additionally, Eastern white cedar was commonly used in heritage buildings in southern Ontario [28]. However, this study used samples of contemporary shingles. There have been limited studies on heritage timber using a cone calorimeter, but studies have indicated that they char at a faster rate than contemporary timber [115], [142], [144]. None of the studies referenced previously used shingles, they used samples cut from larger timber elements. Future research would be to evaluate the ignition of heritage shingles and compare it to modern shingles performance. Both spontaneous and piloted ignition should be investigated.

Chapter 5: Human Behaviour in Wildfire Evacuations

5.1 General

As the number and severity of wildfires increase, due to climate-change associated factors as well as increased interaction between humans and the wildland, so does the amount of people who are impacted [1], [2]. The increase in wildland and WUI fires has also resulted in an increase in number of evacuations and amount of people evacuated, where between 2013-2018 there was an average of almost 50 evacuations per year affecting almost 38,000 people [11]. The largest of those occurred in May 2016 during the Fort McMurray Wildfire which resulted in the evacuation of 88,000 residents and caused approximately $8.9 billion CAD in damages [12]. At the time of writing, there have been wildfires across Canada which have forced evacuations in nine provinces and territories with over 12 million hectares burned [14], [15]. Over 150,000 people have been forced to evacuate, with wildfires in Nova Scotia resulted in the evacuation of over 23,000 people and has destroyed over 350 structures, including 210 homes [14], [20], [21], [146].

Data on human behaviour in wildfires has been identified as a critical research need [22], [23], [25], [58], with a call specifically for more research on wildfire evacuation decision-making and behaviour [33], [59]. The data is used to inform wildfire mitigation and evacuation plans as well as verify and validate wildfire models in order to better prepare for and mitigate the impacts of wildfires on people. The data can also be used to inform behavioural theories, such as the Protective Action Decision Model (PADM) or cognitive biases, or used to develop new theories and frameworks to describe behaviour.

It should be noted that not all data on behaviour during evacuations is transferrable between jurisdictions due to differences in climate, vegetation, and culture. A study investigating wildfire evacuations in Canada between 1980-2019 noted differences in the wildfire characteristics that prompted the evacuation and the evacuation mode, where remote communities are less likely to be able to self-evacuate due to a lack of road access [147]. In Australia has a policy that allows for property owners to stay and defend, though self-evacuation is still encouraged, whereas both Canada and the United States have policies that favour evacuations [148]. There have been limited studies comparing cross-cultural differences, though some studies have observed differences in hypothetical and actual evacuation behaviours between French and Australian participants [60], [149].

A review of research on human behaviour in large outdoor fires, which includes wildland and WUI fires, found that much of the research is on evacuation decision-making, with a focus on the decision to evacuate and evacuation preparation decisions [150]. There have also been studies looking at the behaviours during evacuation such as wayfinding [61], and transportation mode and intermediate actions [62], [63]. Kuligowski (2020) has also identified three main areas of research needs within the field of evacuation research: 1) more information on evacuation decision-making, 2) more evacuation movement data and 3) more behavioural research [59].

5.2 Data Collection Methodologies

There are several different data collection methodologies that have been used for human behaviour. Previous studies have categorized empirical pedestrian data collection into seven general categories: 1) animal experiments, 2) controlled laboratory experiments, 3) virtual reality (VR) and hypothetical choice experiments, 4) evacuation drills, 5) post-event interviews, 6) analysis of natural walking and 7) analysis of natural disasters [151]. These seven methodologies are also categorized largely as laboratory experiments (#1-3) and field experiments (#5-7), where evacuation drills (#4) fall in the middle. These methodologies all come with their own advantages and disadvantages in regards to their realism, credibility and variable control [151].

A review has found that for pedestrian studies, the number laboratory studies, and VR studies are increasing, while animal studies are decreasing. It also found that laboratory studies outnumber field studies, though the reasoning behind the distribution was outside of the scope of the review [152]. Laboratory experiments provide more control over variables and increased replicability, while field experiments provide much more realistic events but limited control over variables [151]. A review found that survey research is most commonly used when collecting data on human behaviour in fire, the majority of which are self-administered questionnaires [153]. Emerging research methods for human behaviour in emergencies also include using GPS data [154], videos [155] and social media [156] to analyze decision-making and actions taken during emergency events.

5.3 Wildland and WUI Contexts

The methodologies listed above have also been adapted for wildland and WUI fire research, however, it must be noted that while there are certainly similarities between crowd behaviour and wildfire evacuation, they are very different contexts and therefore, some of the methodologies are not as applicable. Wildfires' physical impacts generally affect communities as a whole, unlike most modern fires within built infrastructure which are constrained by the building itself. The affected population is also spread out within the community, unlike a building fire or emergency events involving crowds which tend to occur in a relatively small area. Additionally, unlike crowds, in wildfires people mainly evacuate by vehicle [157], therefore, laboratory experiment methodologies based on people evacuating on foot may not be as applicable. Comparisons have been made between wildfires and hurricane research due to similarities in ability to displace large amounts of people, unpredictability of movement and similar timeframes of notifications [68]. However, wildfires are considered more unpredictable from other disasters as they have a wider geographic range of occurrence [158].

A review of human behaviour research for large outdoor building fires, which includes wildfires, found that the majority of studies used empirical data collected from witnesses through methods such as surveys and interviews [59], [150]. While surveys and interviews can collect important behavioural information, it is subjective information and depends on the participant. Additionally, within the field of human behaviour in fires, there is an effort to make survey and interview questions more consistent to allow for better comparisons across studies [150]. While a review of empirical methods for evacuation behaviour as a whole found that the use of virtual reality (VR) has risen in the past few years [152], there is limited use in wildfire contexts [159]. Using GPS data is also an emerging technology and while its use for wildfire evacuations currently limited, there are studies evaluating its potential as a research tool [160]. Evacuation drills are commonly used for training and research purposes and are seen by some as one of the better and more credible tools to evaluate occupant behaviour [161]. However, behaviour during an evacuation drill may not match what happens during an actual emergency event [162]. Additionally, they also have a number of financial, logistical, and ethical issues and difficulties associated with conducting them [163]. As such, very few communities conduct wildfire evacuation drills [164], though in light of recent wildfire disasters, some communities have started in order to better prepare its residents [165], [166].

5.4 2016 Fort McMurray Fire

The 2016 Fort McMurray Fire (also known as the Horse River Fire or Wood Buffalo Fire) is one of the largest WUI fires in Canadian history and the largest evacuation in Alberta's history with 88,000 residents evacuated and almost $8.9 billion in damages [12]. Its evacuation was largely regarded as successful, however, only 24% of residents surveyed considered the evacuation well-organized. The fire began in the afternoon of May 1, 2016 and reached the Athabasca River the next day. Overnight between May 2 and May 3, the fire had "jumped" over the Athabasca River, a distance of almost one kilometre, however, the sky remained relatively clear in the morning, so the approaching fire was not visible to the residents. At 11:00 a.m. local time on May 3, a press conference offered mixed messages to the residents, saying to go along with their day as normal, but also advising to on high alert as fire conditions were extreme. However, by early afternoon, the fire had grown larger and closer to the community due to high winds and mandatory evacuation orders were issued to the communities surrounding Fort McMurray [12]. Evacuation orders in Canada may be encouraged and promoted by the Royal Canadian Mounted Police or local police authorities, however, there is no legislative requirement to leave [167].

At 6:49 p.m. local time, a full evacuation of Fort McMurray was ordered, though many of the surrounding communities had already evacuated. As a rural WUI community, Fort McMurray only has two egress routes, north or south via Highway 63. Approximately 20,000 people evacuated north towards work camps while 60,000 evacuated south towards Edmonton. Because of the remote location, there are very few amenities available along the highway in either direction and many vehicles ran out of fuel before arriving to evacuation camps. The evacuation orders issued in quick succession as well as residents self-evacuating before an official evacuation order caused high congestion on the single vehicular egress route Highway 63 [12]. However, due to the limited resources available at the northern work camps, many evacuees were advised to head south towards Edmonton which forced them to drive back through the wildfire areas. On May 5, the wildfire temporarily closed Highway 63 south of Fort McMurray, preventing evacuation and leaving people in the northern work camps. On May 6, the Royal Canadian Mountain Police

(RCMP) escorted convoys of 50 vehicles south until the work camps were empty. Additionally, some employees and residents were also evacuated from the work camps by air [168].

5.5 Objectives and Methodology

The objective of this research was to analyze videos of Fort McMurray evacuations for notable human behaviour and traffic behaviour and compare the behaviours observed to existing behavioural frameworks. Additionally, the study aimed to collect quantifiable data about the evacuation process. This research contributes to the critical research need for more data on human behaviour in wildland and WUI fires.

The methodology chosen for this study was to analyze video footage of evacuations from Fort McMurray. Video analysis of emergency events such as wildfires, as a method of data collection has been used in the past to collect empirical data on human behaviour from a variety of emergency scenarios, such as earthquakes and evacuations of buildings and stadiums [152], [155]. The advantage of this methodology of analysis is that the videos are taken from real-world events and therefore are considered highly representative and credible. However, as a real-world event and not an experiment, there is very little control over variables and responses. Additionally, it inherently has very low replicability capabilities [151]. The methodology also does not allow for explanations on behaviours observed or the underlying decision-making processes as only the final actions are shown.

A study has been done analyzing YouTube videos of the Fort McMurray Wildfire which included videos of the evacuation, however, the purpose of the study was not to examine the behaviours present, but to investigate the types of experiences and narratives that are present in the videos [169]. At the time of writing, it is believed that this is the first study examining videos of people evacuating from the Fort McMurray Fire for the purpose of collecting data on human behaviour.

5.5.1 Video Analysis

Videos were collected from YouTube, and Facebook, with the majority originating from YouTube. Search terms for videos included “Fort McMurray evacuation”, “Fort McMurray wildfire”, “Fort McMurray” etc. in order to source videos of the evacuation. YouTube’s recommended video function was also used to collect videos. For videos which were included in news media, the original video was found, if possible, for inclusion. The videos inclusion criteria were that the video had to be from the 2016 Fort McMurray evacuation and depict a vehicular journey leaving Fort McMurray. The videos should be one continuous recording with no jump cuts or skipping ahead chronologically. While other public online platforms such as Twitter and Instagram were also searched, only videos from YouTube and Facebook were included based on the above criteria. Three of the videos (Video 2-4) originated from the same user and were videos of the same journey, split into different videos.

Timestamps and descriptions of notable behaviours were recorded from each video. Once the analysis was complete, the observations were analyzed for common themes or observations. Using visual clues such as landmarks and road signs from the videos, the evacuation route taken by each evacuee was retraced in Google Earth using the *Draw Shape* project tool.

5.5.2 Ethical Considerations

All videos were collected from YouTube, and Facebook which are public platforms. As those platforms do allow for different levels of privacy settings for videos, all videos were publicly available to everyone with no restrictions. This research study was approved by York University's Ethics Review Board (Certificate #STU 2022-058). However, it must be noted that the use of social media for research purposes has numerous debates around if the act of posting on a public platform qualifies as informed consent or if a researcher has an obligation to seek explicit consent for use of the data [170], [171]. Anonymity of has also been expressed as a concern of using public information from social media, with arguments on whether to protect the identity of the source or on if proper credit should be given [170]. In order to preserve the anonymity of the evacuees featured in the videos, the names of the videos and their source links have not been provided.

5.6 Results

The evacuation routes from the videos were retraced in Google Earth and presented below (Figure 5.1). While seven videos were analyzed, only five routes are shown. This is because three of the videos (Videos 2 – 4) are of the same evacuation journey by the same individual and their route has been combined into one. All five evacuations were of residents who went south towards Edmonton. The majority of videos ended once they were on Highway 63 and leaving Fort

McMurray. All of the routes used main roads to get to the highway. Three of the evacuation routes started when they were leaving residential areas, while two of them started while they were nearing or on the highway. This is due to when the individuals chose to begin their filming and not necessarily indicative of where they started their evacuation. A conversation captured in Video 5 indicated that they had stopped at a Walmart prior to evacuating.

In the majority of videos, evacuees were observed to drive towards the highway with no detours. However, in Video 7, they briefly took a short detour. They entered a plaza ahead of an intersection and remained there for a few minutes. As there is no audio, it is unclear why they entered the plaza. Once they left the plaza, they took a side residential street and then cut through the parking lot of a different plaza to return to the main road and by-pass the congested intersection.

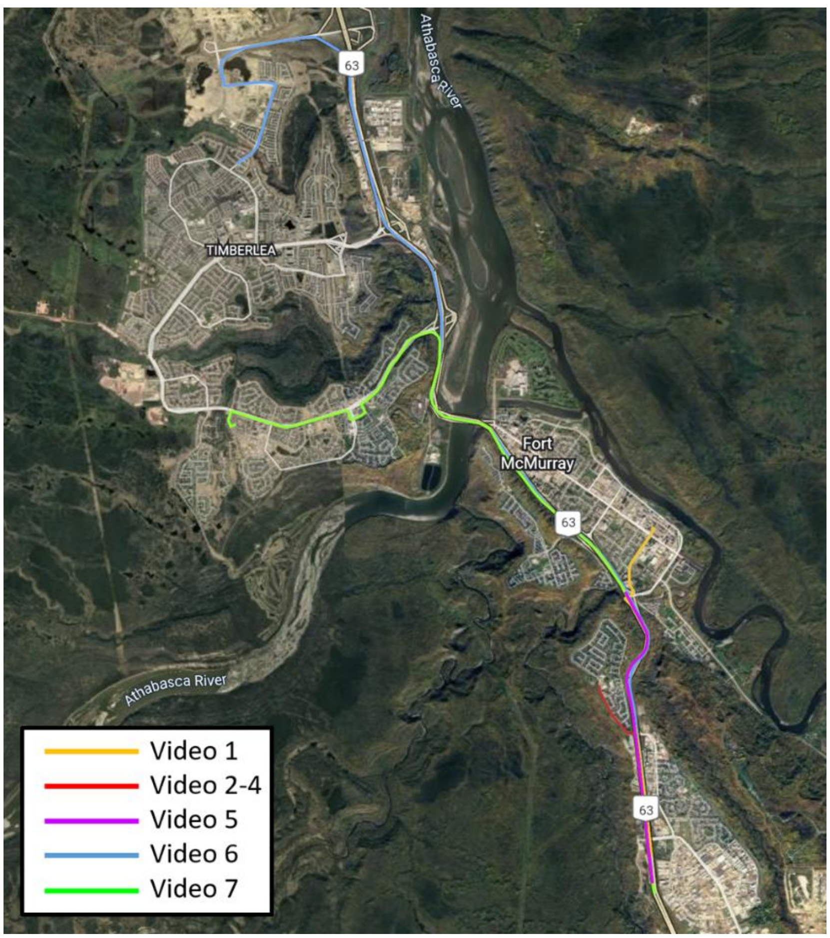


Figure 5.1: Evacuation routes from videos mapped in Google Earth[8]

[8] Maps Data: Google, CNES/Airbus, Maxar Technologies

5.6.1 Video Behavioural Observations

The full tables presenting notable behaviours and observations from the individual videos are included in Appendix D. Common observations and themes are presented below.

5.6.2 Lane Reversals

Notable traffic behaviours were observed across all the evacuation videos. One notable theme through all the videos was the different lane uses. It was observed that lane changes were primarily driven by the direction of authorities or by the wildfire conditions. In Video 1, authorities, assumed to be police, directed vehicles to use the northbound lanes to evacuate south, assumedly to increase the traffic capacity going southbound. In Video 6, there was also a lane reversal directed by authorities, however, this one appeared to be motivated by fire behaviour and not for traffic flow reasons. In fact, earlier in Video 6, officials had directed some vehicles who were using the northbound lane back into the southbound lane. However, when approaching a stretch of highway where there were flames close to the roadside, officials had closed the southbound lane and directed people in the northbound lane to be farther from the flames. Later in the video, once past the area where flames were close to the roadside, some cars returned to the southbound lane, while others continued south in the northbound lane. While the lane reversals observed were directed by authorities, they were not part of official government evacuation plans [168].

In Video 2 and 3, there was also use of the opposite lane, however, these were not authority-driven. In a residential two-way street, the right lane was heavily congested, while the left lane was largely empty with only emergency vehicles using it. However, in Video 2, vehicles began changing into the opposing lane, presumedly to get ahead of the congestion. There appeared to be a bandwagon effect, as once the first car began to change lanes, another four cars did the same. However, it also caused an issue where an emergency vehicle was attempting to use the left lane in the designated direction and was forced to wait for the other evacuating cars to pass and merge back into the right lane before moving past.

In Video 3, cars also began using the left lane, however, this was motivated by fire behaviour as large flames approached the side of the road. As flames approached cars changed into the left lane to avoid the curb. The evacuee was heard stating they could “feel the heat through the car” while on a phone call in Video 4. They continued to use the left lane once past the large flames as the right lane was still heavily congested until they reached an intersection and were directed by authorities into the proper lanes. Again, there appeared to be a bandwagon effect as some cars also began changing into the left lane seeing other cars doing the same. However, in Video 4, more cars began changing into the left lane as the right lane was heavily congested when approaching a intersection.

5.6.3 Lane Use

In Video 1, on the highway, there were three lanes going south. It appeared as though the majority of vehicles were using the left and middle lanes as there were flames close to the right lane. However, as the left and middle lanes were also the slowest due to the high traffic load, some cars can be seen using the right lane, closest to the flames in order to presumedly move faster and avoid the congestion of the middle and left lanes. This behaviour was notable as it occurred within three lanes that did not involve any lane reversals.

5.6.4 Other Traffic Behaviours

The smoke visibility also was observed to affect the traffic behaviour. In Video 4, cars noticeably slowed down when the visibility decreased due to the smoke. In Video 7, it was also observed, however, it is more unclear due to the video time lapse. While there have been limited studies on the effects of smoke on driving behaviour in wildfires, it is consistent with results observed in virtual reality experiments on the topic as well as walking speeds in smoke and driving speeds in fog [159]. Additionally, cars turned on their blinkers in response to the decreased visibility in Video 4. There also appeared to be a bandwagon effect as once one car turned their blinkers on in response to smoke, other cars began to do the same.

There were also a number of unusual traffic behaviours observed during the videos. These behaviours further demonstrate how traffic, fire and human behaviour are all linked as such behaviours are typically not accounted for in traffic models. In Video 3, traffic was forced to stop as there was an animal running across the road, presumedly to escape the flames. In the same video, cars were observed driving outside the marked road and down a hill in order to avoid congestion and enter an intersection. It was also observed during Video 7, where a car was seen driving in the grass divider, separating the northbound and southbound lanes of Highway 63. Also in Video 7, cars had to maneuver around a policeman and their car who were parked a few metres past the intersection near the grass divider.

5.6.5 Audio Observations

A disadvantage to video-only analysis is that underlying motivations and decision-making processes are solely speculative based on observed actions. While not all the videos included audio, there were audio conversations that provided more insight into the thoughts of the evacuees as well as some background on their evacuation journey. In Video 4 and Video 5, both evacuees had phone calls with someone else. The content of the phone calls was similar with the evacuees recounting their journey and the fire damage they saw. Both phone calls also included reassurances that they were leaving the area.

Video 5 was the only video where it was confirmed that there was more than one evacuee in the vehicle through the video's title. As such, the couple had conversations with each other. Their conversations were mainly related to the wildfire damage they see while evacuating, such as exclaiming that a Denny's and a hotel by the highway that was a common landmark was on fire or passing a burning forest area next to the highway. They also expressed worry during the evacuation, with the woman specifically concerned about smoke inhalation and wishing she had a mask. They also provided some insight to their evacuation journey that was not featured in video itself, saying they had stopped at a store prior to evacuating and the man contemplating whether to a gas station near the highway was open and the woman saying not to bother and to just keep going.

5.7 Discussion

5.7.1 Human Behaviour Observations

Some behaviours observed were consistent with different existing behavioural theories such as cognitive biases where there did appear to be a bandwagon effect. However, not all behaviours observed have been categorized under contemporary behavioural frameworks, due to a lack of validation of those theories during wildland fire evacuations and are simply stated such as driving outside of marked lanes. Additionally, some frameworks lack applicability to the context of the videos analyzed. Many of the theories which have been applied to wildfire contexts, such as

PADM, have largely been applied to pre-decision phases and not actions during the evacuation itself [172]. As the footage analyzed is of the residents' evacuation itself and not the pre-evacuation stages, there is not enough evidence to categorize behaviours under PADM which relies on pre-decision information and behaviours. Additionally, behavioural frameworks describing group behaviour were also not used as each video showed an individual evacuation journey and as a video, the underlying motivations are not available, the impact of a collective identity is not evident.

5.7.2 Video Behavioural Observations

As mentioned previously, the use of lane reversals was evident across many of the videos, driven by the direction of authority, or by the driver's own risk perception based on traffic congestion or fire behaviour. While the use of lane reversals is not an uncommon traffic control method used during large-scale evacuations, Fort McMurray's lane reversals were all "unofficial" on the part of the local authorities and the residents [168]. There is limited empirical data on individual driving behaviour during evacuations and as such, it is difficult to compare the lane reversal behaviour observed in the videos to other evacuation events. As the videos were all of individual evacuations and not the evacuation as a whole, it is difficult to determine the impact of these lane reversals on the evacuation, though a previous study did find that it reduced the congestion [168].

There were also driving behaviours observed where evacuees appeared to engage in their own risk assessment before making a driving choice. For example, in Video 1 some residents chose to use the right-most lane which was close to the wildfire instead of using the more congested middle lanes. In other videos, when faced with high levels of traffic congestion, drivers chose to use the opposite lane or drive outside of marked roads. These unique driving behaviours have not been researched in detail. The majority of studies done on traffic during evacuations focus on the traffic flow itself and not on individual driving behaviours enroute. While a study has found that some evacuees may choose to use backroads to avoid congestion [173], more local measures such as lane changes and driving outside unmarked lanes has not been studied.

Not all the driving behaviours were motivated by traffic behaviour and congestion, as fire behaviour also played a role in actions. In Video 6, authorities closed one of the highway lanes due to the fire's proximity to the side of the highway. In Video 3, cars swerved into the opposite lane to avoid flames approaching the right curb. These actions further support the need for coupled modelling as these are actions which may not be represented in current modelling due to a lack of coupling and data. Smoke from the fire was also observed to slow cars down and motivate others to turn on their blinkers. While there have been limited studies on the effects of smoke on driving behaviour in wildfires, it is consistent with results observed in virtual reality experiments on the topic as well as walking speeds in smoke and driving speeds in fog [159].

5.7.3 Cognitive Biases and Other Behaviours Observed

Cognitive biases, defined as "systematic deviations from normal or rational judgment using inferences" can effect how the information is perceived [69]. During the video analysis, the bandwagon cognitive bias, defined as doing an action because others are doing the same [69], was observed. This bandwagon effect has also been observed in studies of indoor building evacuations and exit choice [174]. In Video 2 and Video 3, when one car changed into the opposite lane to avoid congestion or flames, other cars did the same. Additionally, in Video 4, when the visibility got worse due to smoke, cars began to turn on their blinkers. While some may have chosen to do so independently, there appeared to be a bandwagon effect as it was staggered across the cars.

The presence of authority may have indicated that there was the "authority bias" where actions are done because an authority figure does or requests it [69] as there were authority figures directing traffic. The presence of authority was mainly seen at intersections and lane merges where they directed traffic. Additionally, as noted above in Section 5.62, during the evacuation, authorities had changed the lane directions of the highway to one-way, in order to allow for more evacuees to head south. These lane reversals were unofficial decisions on the part of the local authorities and not part of the government's official plans [168]. In addition to directing lane reversals, at intersections they were observed to manage the traffic flow as well as direct traffic towards the egress routes. While some intersection traffic lights still functioned, traffic was largely directed by police which played a role in the evacuation route.

Additionally, authorities were also present at highway entrances, directing vehicles. Due to Fort McMurray's remote location, there were only two vehicular egress routes, either north or south on Highway 63. Thus, evaluating authorities' impact on egress route choice is difficult as evacuees did not have many options. Some hurricane studies have found that when evacuating from a community, residents preferred familiar routes [59] which is consistent with indoor evacuation studies [175], however, it has been found that some evacuees will use other non-highway roads if available [157], [173]. It is difficult to make conclusions on evacuation route strategies due to the already limited egress routes that were available to residents, as all routes observed in the videos used major roads which led to the highway.

There may have been other cognitive biases that could have been identified, however, the purpose of the video analysis was not to identify cognitive biases present and thus they may have been missed. It must be noted that the cognitive bias framework has not been validated using wildland and WUI fire contexts. Identifying cognitive biases specific to wildfire evacuations using video analysis is recommended as future work.

5.7.4 Use of Audio Observations

The audio observations may provide useful information which supplement the observations in the video analysis as evidenced by Video 5. The video begins when the couple is already on Highway 63, however, they state in the video that they had stopped at a Walmart before evacuating which provides useful insight on pre-evacuation activities as evacuation planning may have to take into account not only evacuee preparation at their residence, but also potential stops. Additionally, the woman expresses concern about smoke and wishes she had brought a mask. The Government of Alberta does advise bringing non-medical masks as part of an emergency evacuation kit [176], however, it is unclear how many residents made use of this resource during the Fort McMurray Fire or had an emergency kit, especially in light of the short evacuation warning time.

5.7.5 Video Analysis Methodology and Observed Behaviours

The results of this study also suggest that this methodology is useful to observe and collect traffic and human behaviour during wildfire evacuations. There is also supplementary information available about the evacuees and their evacuation experience if the video contains audio. This is supported by using this methodology to analyze other videos of wildfire evacuations such as the 2018 Camp Fire in California and the 2023 Tantallon Fire in Nova Scotia (see Appendix D). These analyses are not part of the main analysis but were completed to determine whether behaviours observed in the Fort McMurray Fire were also observed in other fires.

In the videos, using the opposite lanes for evacuation were also observed in both the Camp and Tantallon fires. However, in those videos, it was much less clear as to whether or not it was authority-driven or self-directed. In one video from the 2018 Camp Fire, the use of the opposite lanes created an issue where emergency vehicles headed in the opposite direction using the opposite lanes, were unable to pass smoothly which created a delay, which was also visible in Video 2 from Fort McMurray. In another video from the 2018 Camp Fire showed evacuees using all the lanes of a large road to evacuate. Another video from the 2023 Tantallon Fire in Nova Scotia showed the car driving in the centre of the road, with flames on either side. However, the visibility was very poor, so it was unclear whether it was on purpose to avoid the flames, or because the road markings themselves were not visible. Videos from Camp and Tantallon also contained audio which provide insight to the evacuation journey, and support evidence from Fort McMurray. In one of the videos from the Camp Fire, a man advises the other passengers in the car (presumed to children) to put their shirts over their mouths and take shallow breaths to protect from smoke. In the same video, the evacuees also remarked on the heat from the fire that they could feel in the car.

5.7.6 Limitations

There are a number of limitations associated with the results. The first is the limited sample size of videos. The observations seen in these videos should be limited to these videos until further research has been done. These videos may not be representative of all evacuations out of Fort McMurray, nor can the behaviours observed claim to be representative. Additionally, there were no videos of an evacuation route north up Highway 63. As these are videos, the benefits are that unlike post-disaster surveys, videos are not influenced by the evacuee’s perception and memory, though there may be some bias by the evacuee as to which videos are posted publicly. However, because only their actions are portrayed in the video, the underlying motivations behind the decision-making process are solely speculative and are without input from the individuals. Another limitation is that the video analyses were all conducted by one person, the author, with no specific methodology for categorizing behaviours under existing frameworks.

5.8 Summary

In conclusion, this study presents different behaviours observed from videos of residents’ evacuations from the Fort McMurray Fire in 2016. These behaviours included using opposite lanes, both directed by authorities as well as a self-directed and unusual traffic behaviours such as driving outside of marked roads to avoid congestion. An analysis of videos from other wildfire evacuation also supported those observations, demonstrating that some behaviours may not be unique to each wildfire. Additionally, it demonstrates that using video analysis can produce useful information and data to inform wildfire preparation and evacuation strategies. Behavioural models such as PADM and cognitive biases can be applied to describe the decision-making process of some of the behaviours observed, however, many of the models have not been validated in wildland fire contexts. The behaviours observed appeared to be influenced by traffic and fire behaviour, further supporting the need for more data to support coupled modelling.

Future work would be to expand the video analysis to a larger sample size of videos as well as to wildland and WUI fires other than Fort McMurray. Additionally, work should be done to incorporate timelines of fire behaviour and notable behaviour into the evacuation route maps for a more dynamic representation of the evacuation. The series of three dash camera videos also contained speed data as part of the recording which could be analyzed further and potentially correlated to the approximate visibility for to contribute to research of the effect of smoke on evacuations. Some of the videos used were also featured in news reports with interviews of the evacuee. An analysis of those interviews could be used to supplement the video analysis and potentially provide further insight into the evacuee's behaviours.

Chapter 6: Conclusions and Recommendations

6.1 Summary

This research aimed to investigate structural and human factors of wildland-urban interface (WUI) fires and contribute to the research need for Canadian-specific wildfire data. This information can be used to help design and create wildfire resilient communities in Canada as it provides insight as to what factors contribute to building survival after wildfires, material performance under radiant heat and the behaviour of residents during a wildfire evacuation. Wildfires are increasing in number and severity and in Canada, severe are expected to increase by 1.5 to 6 times [4]. The 2023 Canadian wildfire season is the worst on record, with over 12 million hectares burned and over 150,000 people evacuated at the time of writing [14], [15], [146]. Chapters 3 to 5, which studied different topics related to WUI fire research on structural and human factors are summarized below, as well as Chapter 2 which provides important background context. These studies identified research gaps in wildfire research, examined the ignition of a common building material, cedar shingles and investigated evacuee behaviour during a real wildfire event. Together, they can be used to inform community wildfire resilience and emergency management through their insights on structural vulnerabilities to wildfires and how people behave during wildfire evacuations. The conclusions and recommendations generated by the studies are included in subsequent sections.

A review of wildfire science, basic fire dynamics and human behaviour in emergencies was provided in Chapter 2 to give background and contextualize the research in the subsequent chapters. Wildfire and the factors that impact wildfire behaviour are provided for greater understanding of what measures people can do to impact wildfire behaviour. A brief overview of fire dynamics and structural ignition was provided in order to better understand what structural factors increase risk of wildfire damage in subsequent chapters. The fire dynamics behind the burning of wood was given due to structural wood's combustibility which increases the risk of wildfire damage. Human behaviour in emergencies and existing behavioural frameworks are provided to understand current research gaps and how human behaviour and decision-making is examined.

The protection and resilience of communities to wildfire is a critical research need in light of the increased wildfire risk globally. Canada does not have a wildfire-specific building code, though it does have wildfire guidance in the form of FireSmart Canada and the *National Guide for Wildland-*

Urban Interface Fires, but they are voluntary and non-enforceable. To inform the development of a Canadian wildfire building code and guide building constructure and land use development in WUI areas, Chapter 3 investigated structural and landscape factors which contribute to building survival through a literature review of post-wildfire studies. The review concluded that there was a lack of post-wildfire data in general, as well as in Canada. There was agreement in the studies about structural elements such as the importance of protecting points of entry and areas where firebrands could gather and using non-combustible building materials to reduce the risk of damage. Landscape factors such as defensible space, vegetation directly adjacent to the structure, housing density and arrangement also impacted building survival. The review also noted a number of research gaps, such as a lack of Canadian studies and that the studies reviewed did not consider unique buildings such as heritage properties and Indigenous communities.

Structural ignition is a large concern when considering the protection and mitigation of wildfire impacts in communities. It is known that wood as a building material increases the risk of damage due to wildfires due to its combustibility and therefore, knowing how it performs in wildfire conditions is critical. Chapter 4 presented a material study of Eastern white cedar shingles under a radiant heat flux. The heat flux exposed, and moisture content of the samples were varied to see the impact on spontaneous ignition. Increasing moisture content delayed ignition and pyrolysis of the shingles. The peak heat release rates were also impacted by the heat flux and moisture content, increasing as the moisture content decreased or as the heat flux increased. However, there was an exception where the dry samples at 40 kW/m^2 had a longer average ignition time and lower average peak heat release rate.

The data collected can be used to inform ignition models of Eastern white cedar shingles. At the time of writing, this is believed to be the first cone calorimeter study that used Eastern white cedar which is relatively common building material in older houses, including heritage properties in Ontario. It is known that species can impact the type of burning due to differences in chemical composition, the species can also impact moisture content and density which influence pyrolysis.

The number of evacuees due to wildfires in Canada is growing. To address the need to understand how people behave during evacuations, Chapter 5 was a case study investigating the traffic and human behaviour of evacuees from the 2016 Fort McMurray Fire. Using videos of evacuees sourced from public platforms, the route evacuees took, notable traffic behaviours and human behaviours were recorded. Behaviours recorded included using opposite lanes, both directed by authorities as well as a self-directed and unusual traffic behaviours such as driving outside of marked roads to avoid congestion. The behaviours observed appeared to be influenced by traffic and fire behaviour, further supporting the need for more data to support coupled modelling.

This study represented, at the time of writing, the first study examining wildfire evacuation footage for the purpose of data collection on human behaviour in fire. This study observed behaviours that are currently not accounted for in uncoupled evacuation models such as driving outside of marked lanes and swerving to avoid flames on the side of the road. It also provides insights that can assist in community evacuation planning.

6.2 Conclusions

Based on the results of the studies completed in this thesis, the following conclusions can be drawn.

- **Lack of post-wildfire data on building survival**: There is a lack of post-wildfire building data that can be used to inform construction and land use practices. The studies obtained data from multiple sources and there is a lack of a systematic methodology and classification system for characterizing buildings across different jurisdictions. As wildfires are very complex events, data from actual wildfires is critical in order to inform our management and mitigation strategies as well as how to design wildfire-resilient communities.
- **Fire behaviour influences factors of building survival:** Structural ignition resistance is dependent on many factors, not just the building construction and landscape. What factors impact building survival can vary depending on the fire behaviour of the wildfire, such as the number of firebrands. As fire behaviour also depends on many factors such as climate, fuel type and topography, the location of the wildfire is also important. This emphasizes the need for regional data as there will be regional differences between communities.
- **Moisture content and heat flux impacts ignition:** Moisture content and heat flux impact the ignition of Eastern white cedar shingles in a manner that is consistent with other studies of wood fuel. Increasing moisture content delays ignition and decreases the peak heat release rate. However, an exception occurred at 40 kW/m^2 where the dry samples

performed better than the ambient samples. It is posited that a faster forming char layer is responsible, but more research is needed.

- **Unusual traffic behaviour occurs in evacuations:** During evacuations, there is unusual traffic behaviour by the evacuees, some which is prompted by the direction of authorities, others by the fire behaviour in the surroundings. Behaviours include using opposite lanes, driving outside of marked areas and slowing down as visibility decreased. These behaviours can be attributed to existing behavioural theories such as PADM and cognitive biases, however, most frameworks have not been validated in wildfire contexts.

The conclusions were based on the studies done as part of the thesis, with the overarching conclusion that wildfire is a complex event and there are many different factors that contribute to community wildfire resistance and resilience. These conclusions come with their own limitations as outlined in the previous chapters. Many of the limitations are associated with small sample sizes due to the lack of data availability or resources.

6.3 Recommendations

Based on the results and conclusions of the studies, the following recommendations are made.

- **Post-wildfire data collection:** There is a need for data from real wildfires and wildfire evacuations. Wildfires are complex events and are difficult to capture through experiments and modelling due to the many factors which contribute to its behaviour and actions that are taken. There is a lack of post-wildfire data collection as well as a systematic approach to collecting data across jurisdictions which would allow for easier comparison as wildfires occur globally.
- **Material performance in wildfires:** More research is needed on material performance and ignition potential in wildfires. Diverse materials and building types need to be evaluated and the condition of the structure and its components should be considered. Heritage buildings present a unique case due to their protected statuses restricting structural changes. Indigenous communities face a higher risk of being impacted by wildfires and how the infrastructure performs in wildfires is still unknown.
- **Land Use Considerations:** In addition to investigating structural and landscape factors related to building survival, there is evidence that the housing arrangement and location

plays a role in building survival. More research is required to investigate these factors as it would play a role in future land development and urban planning in wildland-urban interface areas.

- **Video Analysis:** Video analysis has emerged as a methodology to collect human behaviour in emergencies. The study demonstrates that useful data can be collected from this method of analysis and be used to inform wildfire evacuation models and evacuation management strategies. With social media, it has become increasingly common for people to film themselves during notable events which may create a large sample size, however, there should be careful consideration of research ethics when using such data. Caution should be taken when observing behaviours, and it is suggested that multiple people examine the footage to avoid potential biases.

6.4 Closing Remarks

Wildfires are increasing in number and severity, bringing both new and existing threats to Canadian communities in the wildland-urban interface. Wildfire research needs to be multidisciplinary in order to protect against and mitigate the impacts of severe wildfire events. The overarching goal of this research was to contribute to creating and designing wildfire resilient communities in Canada and help make communities and people safer in wildfires. The research herein presented a study of different structural and human factors in wildland and WUI fires. This research can be used to create and design more wildfire resilient communities through informing research needs and priorities, identifying structural and landscape vulnerabilities to properties in the WUI and informing evacuation management using real-life data on human behaviour.

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Appendices

Appendix A: Identifying Research Needs for Canadian Wildfire Building Code Development

Attached Paper:

Carton, H., Gales, J., and Kennedy, E.B. (2023). Identifying Research Needs for Canadian Wildfire Building Code Development. CSCE 2023: Canadian Society for Civil Engineering (CSCE) 2023 Annual Conference, Moncton, New Brunswick.

A1. Abstract

In Canada and around the world, the number and severity of wildfires are in-creasing, due to the combined effects of global warming, historical fire suppression strategies and increased interactions between humans and the wildland. Since 2011, Canada has averaged approximately 5,700 wildland fires resulting in 2.6 million hectares burned annually. Canada's wildland-urban interface (WUI) accounts for approximately 3.8% of its land area and a population of over 4.1 million people, and is expected to expand due to growing populations, increased urbanization, and seasonal increases due to recreational activities. In response to the growing wildfire risk to Canadian communities, the National Research Council of Canada (NRC) developed Canada's first National Guide for Wildland-Urban-Interface Fires. This guide was developed based on existing international wildfire reference documents, such as codes, standards, and guidelines. However, as Canada does not have its own wildfire code, much of the guidance followed other countries familiar with wildfires, such as the Unit-ed States. However, wildfire data is not always regionally transferrable due to differences in climate, vegetation, infrastructure, and materials.

This study conducted an exploratory literature review of the effectiveness of wildfire codes, regulation and/or guidance that should be considered in a future Canadian wildfire building code. The objective of the literature review was to 1) identify existing research and knowledge gaps in wildfire code development studies and 2) prioritize potential research needs to inform the development of a Canadian wildfire code. Studies found that combustible materials were more likely to lead to building damage, however, building features such as windows and eaves which provide openings for firebrands also posed a large wildfire hazard. Additionally, vegetation and landscape management play a large role in building survival. However, these studies were largely conducted outside of Canada revealing a need for Canadian data. There is also a gap in existing

re-search regarding Indigenous communities and their unique needs, nor did they consider the quality of existing buildings or those which may be difficult to modify such as heritage properties.

Keywords: Wildfires, Wildfire codes, Wildfire-urban interface, Building survival, Fuel treatments

A2. Introduction

Wildland fires (Figure 1) have been increasing in both number and severity due to climate-change associated factors such as rising temperatures and drier summers as well as increased interactions between humans and the wildland through population growth, urbanization and seasonal increases due to recreation [1], [2]. Additionally, decades of fire suppression as the primary form of fire management has led to in-creased fuel loads and changes in forest composition that also contribute to the growing wildfire issue [3]. As wildfires are suppressed and extinguished, the forest stands are older and more flammable and more fuels build up, which can increase the risk of severe wildfires [4]. This phenomenon is known as the "wildfire paradox" [5]. Canada's wildland-urban interface (WUI) currently accounts for approximately 3.8% of its total land area, or 32.2 million hectares [1], with an estimated population of 4.1 mil-lion people [6]. Since 2011, Canada has averaged approximately 5,700 wildland fires resulting in 2.6 million hectares burned annually [7].

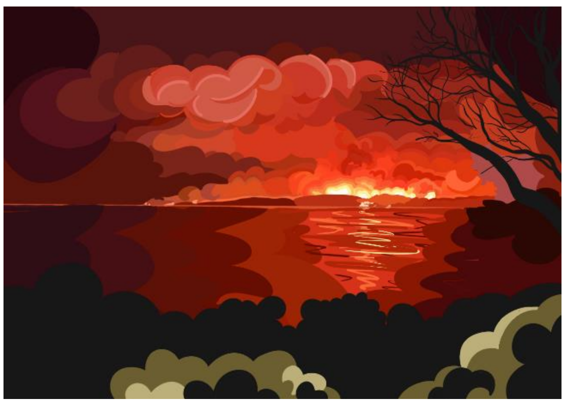

Figure A1. Wildland fire

Increasing the resilience of communities to wildfires has been identified as a re-search priority by multiple organizations [8]–[11]. Within the Blueprint for Wildland Fire Science in Canada, Theme 3 ("Building Resilient Communities and Infrastructure") specifies the creation and development of codes, standards and regulations to better protect communities in the WUI [11]. In light of the increased wildfire risks, Canada published its first National Guide for Wildland-Urban-Interface

Fires, hence-forth referred to as the National Guide or Guide, with the goal of improving the resilience of Canada's buildings through guidance on interrupting wildland fire spread through structural and vegetative methods [12]. While this is only a guide and is currently voluntary and non-enforceable, unlike existing wildfire guidance such as FireSmart Canada, the guide was designed with the potential to become a future code [12]. The guide was developed based on existing international wildfire reference documents, such as codes, standards, and guidelines. As Canada does not have its own wildfire code, much of the guidance followed other countries familiar with wildfires, such as the United States. However, wildfire data is not always regionally transferrable due to differences in climate, vegetation, infrastructure, and materials.

This study aimed to conduct an exploratory literature review of studies examining the effectiveness of wildfire codes, regulation and/or guidance that should be considered in a future Canadian wildfire building code. The objective of the literature re-view is to 1) identify existing research and knowledge gaps in wildfire code development studies and 2) prioritize the identified research needs to inform the development of a Canadian wildfire building code.

A3. Canadian Code Development

In Canada, fire and building codes are regulated provincially, where provinces and territories can develop their own codes or choose to adopt or adapt national model codes [13]. National model codes are developed by the federal government in order to provide the different building code jurisdictions with a model to follow and encourage consistency and compatibility across the jurisdictions [13]. At the time of writing, Canada has five model codes addressing different aspects of building safety, but the National Building Code (NBCC) and the National Fire Code (NFCC) are the two that primarily concern the fire safety of newly constructed and existing buildings. They are designed to complement each other, with the NBCC covering fire safety requirements at the time of construction, versus the NFCC covering the operation and maintenance of fire safety systems of buildings [13]. However, neither of the model codes explicitly address wildfires and wildfire protection [12].

The model codes are formally developed by the Canadian Commission on Building and Fire Codes (CCBFC) and updated every five years through a broad-based consensus process [14]. Proposed code changes are submitted to the CCBFC where they are examined by an expert standing committee within CCBFC for technical and scientific merit. Committee members are nominated to the committees and represent regulatory or industry bodies, with some members joining under general interest categories. If the proposed change is found to have merit, it undergoes a series of private and public reviews by relevant standing committees within CCBFC, as well as provincial and territorial authorities and the public. Comments received from the reviews are taken into consideration and then the proposed change (and its revisions if applicable) is submitted to CCBFC for final approval. If approved, the change is included in the next edition of the national code [14].

In November 2022, it was announced that the federal government was changing the national code development process to better integrate the provinces and territories, respond to priorities from different jurisdictions and harmonize the construction codes [15]. The CCBFC was replaced with the Canadian Board for Harmonized Construction Codes (CBHCC) comprising of federal and provincial/territorial representatives. The current code development process with CCBFC will remain in place until the next code development cycle in 2025 [15].

A4. Wildfire and WUI Codes

A4.1. Canada

Canada does not have a specific wildfire or WUI code or wildfire-related standards, and wildfire is not explicitly addressed in the NBCC or NFCC, though some provisions inherently contribute to wildfire resistance such as those relating to spatial separation and reducing fire exposure from adjacent buildings (NBCC 3.2.3, 9.10.14 and 9.10.15) [12], [13]. However, it does have the national program, FireSmart Canada, which was established over 20 years ago to provide homeowners with resources and guidance on how to protect their home from wildfires [16]. The guidance includes identifying priority zones, vegetation management strategies and structural materials guidance [17]. FireSmart is not limited to homeowners and provides guidance and recommendations at the community-level through infrastructure and utility planning guidance and emergency management strategies [17]. A review of wildfire standards and guidelines from around the world found that Canada’s FireSmart guidance was strong in identifying wildfire risk and providing clear land management strategies and accessibility of utilities. However, they also determined it lacked detail in describing building protection measures, fire protection systems and environmental factors [18].

Recently, Canada published its first National Guide for Wildland-Urban-Interface Fires with the potential for it to serve as the basis for code in the future [12]. The guide was developed using existing wildfire codes, standards and guidelines, with many from the National Fire Protection Association (NFPA) which issues codes and standards in the United States [12]. The risk mitigation guidance provided largely falls under three categories: 1) vegetation management, 2) structural materials and 3) community planning. Vegetation management guidance includes identifying priority zones surrounding a structure and strategies to reduce fuel loading in those zones including but not limited to vegetation thinning, pruning and removed dead litter. Structural materials guidance outlines construction guidance and materials selection to minimize the risk of building ignition through recommending less-combustible or non-combustible building materials and design recommendation such as reducing openings or penetrations [12]. However, this guide is currently voluntary and non-enforceable. It has not undergone the intensive review associated with code development, nor has it been reviewed for potential conflicts with other regulatory requirements [12]. While the guide drew on FireSmart, the objectives of FireSmart and the guide are not identical, as FireSmart is more focused on increasing the wildfire resilience of existing communities whereas the Guide is broader "with the potential for eventually being considered for code provisions" [12].

A4.2. International

Internationally, there are other countries with their own wildfire codes, regulations, or guidelines. Notably, both the United States and Australia have wildfire-specific codes at the national level as well as the state level. NFPA 1144: Standard for Reducing Structure Ignition Hazards from Wildland Fire in the United States specifically ad-dresses building design and construction as well as vegetation management, as does the Australian standard AS 3959: Construction of Buildings in Bushfire-Prone Areas [18]–[20]. Other wildfire-prone countries such as France and Italy do not have specific wildfire codes, but parts of their fire code are applicable to wildfires in addition to regional guidance [18]. In addition to individual countries' codes, there is also the International Wildland-Urban Interface Code (IWUIC) developed by the International Code Council (ICC) [21]. The IWUIC is a model code and designed to be adapted for use in other jurisdictions' building and fire codes.

A5. Methodology

The aim of the literature review was to find studies evaluating the effectiveness of wildfire codes and guidance. The literature review was a semi-structured review conducted using Web of Science and York University's library catalogue. Some of the studies were sourced from previous literature reviews done by the author as well as through other studies. The literature review was conducted in January and February 2023. As an exploratory review, this review was not exhaustive and was meant to analyze potential research gaps and priority research areas. The search terms included, but were not limited to: "building survival wildfire", "fuel treatment effective-ness", "structural ignition wildfire" etc.

The review chose to focus on examining building survival and wildfire code im-pacts using studies post-wildfires as opposed to wildfire modeling and laboratory experiments. While both are critical to furthering our understanding of wildfires and material performance, due to the complexity of wildfires and their interactions with infrastructure, it is difficult to replicate actual wildfire conditions at smaller scales [22]. Pre- and post-wildfire data collection has been identified as a key research need and can be used to validate and improve laboratory and modelling methodologies [23].

A6. Preliminary Results

A6.1. Structural Materials and Design

The National Guide provides recommendations on building design and materials, largely directed at using non-combustible materials or combustible materials of certain dimensions to reduce ignition likelihood and reducing gaps or openings [12]. There have been studies reviewing structural wildfire resistance of different materials. Wooden building materials are considered to have the highest fire risk due to their combustibility [24]. This is supported by other studies reviewing building survival after wildfires, such as after the California wildfires, with wooden roofing and decking increasing the risk of impact [25]. A study after the 2016 Fort McMurray fire also found that combustible decking, porches and fences increased the likelihood of building damage, where surviving homes had on average less than two combustible attachments [26]. Another study found that in extreme fire weather, eaves and windows which could provide points of entry for firebrands were a larger factor than building materials [27]. Firebrands are estimated to cause over 50% of structural ignition in wildfires and ignition via firebrand is relatively understudied in comparison to fire generation and transport [24]. The importance of window systems to wildfire damage was supported in another study of the San Diego area which also found the type of window system to have higher correlations to damage than roofing and exterior materials. This study also highlighted the importance of WUI community planning as housing density and defensible spaces were also found to be correlated in building survival [28].

A study using statistical methods to evaluate building features and their impact on building survival after wildfires in California and Portugal found that deck material had a high impact. Additionally, in California, vent screens also had a high correlation to damage whereas in Portugal, the exterior materials had a high correlation. The study highlights the importance of region-specific data as the construction type of the houses and severity of damage in both regions differed [29]. A study in Australia examined the impact of wildfire building codes on building survival in the 2013 Linksview fire. They found that housing built after the state introduced “Planning for Bushfire Protection” code in 2002, survived more often than older houses, where 27.3% of houses built in the 2000s were impacted compared to 69.6% of pre-1990s houses impacted. However, they also found that the construction standards for modifying older houses did not have as much of an impact on building survival, which has implications for older and heritage properties [30]. A study examining building survival after the 2018 Camp Fire in California also found that the year of construction played a role as buildings that were constructed after California implemented wild-fire-specific building provisions and codes survived more often [31], which was also supported by another study in the San Diego region [28]. The year of construction acted as a proxy for the likelihood of structure hardening measures against wildfires. Another study of California wildfires also found that the average age of destroyed houses was older than surviving houses (approximately 40 years versus 50 years), though the study did not investigate why [27].

A6.2. Vegetation Management

The National Guide also provides recommendations on vegetation management sur-rounding the property. The guide defines priority zones around the house, accounting for slopes, and recommendations on managing the vegetation to reduce the fuel loads surrounding the house [12].

Vegetation has been found to impact the probability of house survival in addition to building materials. Many of the studies examining building survival also included the surrounding vegetation as an impact factor and found that defensible space and vegetation management were equally as important as building materials. The vegetation immediately adjacent to the house was found to impact building survival, where removing vegetation from directly touching the structure, decreased the likelihood of building damage [28]. A study of defensible space using housing data post-wildfires in San Diego County, California between 2001-2010 found that the most effective treatment distance was between 5 – 20 m depending on the surrounding topography, where the increase of defensible space between 0-7 m and 8-15 m had the greatest impact on house survivability. The study also found that the level of vegetation treatment was also key, with an effective clearance of 40% [32]. A study in Sweden examined building survival after two separate fires. They found that vegetation and the surrounding landscape had a larger impact on building survival over building characteristics. However, it must be noted that the majority of the buildings surveyed were of similar characteristics with combustible exteriors. The presence of a lawn, creating a low combustible defensible space around the property correlated to building survival. The authors also noted that while the vegetation largely consisted of coniferous trees, deciduous trees surrounding gardens may have also contributed to reducing the fire intensity [33].

A study examining building survival after the 2016 Fort McMurray Fire assessed buildings hazard and compared them to their post-wildfire condition. Buildings were assessed for wildfire vulnerability using FireSmart Canada's hazard ratings, where the presence of hazard factors such as combustible building materials, surrounding fuels earned points. Based on the number of points, buildings could be categorized under Low, Moderate, High, and Extreme FireSmart Hazard levels. A "FireSmart" building were those whose hazard was considered Low or Moderate. The study found that surviving buildings were more likely to have been "FireSmart" and vegetation accounted for the majority of their hazard ratings. Of buildings that were considered "FireSmart" but were still damaged, there were easily flammable ornamental shrubs within 3 m of the home or there were substantial fuel sources such as wooden sheds, firewood or petroleum products within 5 m [26]. This supports Syphard et al.'s conclusion of the importance of vegetation management within 5 m of the building [28], [32].

However, one study examining California wildfires between 2013-18 and building survival found that structural characteristics had more of an impact on building survival than vegetation characteristics. The authors propose that it was due to firebrand ignition as firebrands can be transported over large distances [27]. It should be noted that the study on Fort McMurray also concluded that ignition was largely driven by firebrands that could travel well ahead of the fire front [26].

A7. Discussion

A7.1. Location

Many of the studies reviewed and those that were referenced within those studies took place outside of Canada, many of them examining fires in California and Australia, with the exception of the report on Fort McMurray. This highlights the need for Canadian- and region-specific data as wildfire data is not easily transferred between countries or regions due to differences in climate, vegetation, infrastructure, and materials. This was evident in some of the studies. One study compared California and Portugal building survival after wildfires and observed differences in severity of dam-age and building construction [29]. While decking materials were found to be a factor in building survival in both datasets, venting systems played a larger role in California wildfires, versus exterior walls in Portugal. However, even within California, there were regional differences observed in building survival factors [27]. By contrast, a study conducted in Sweden found that buildings were of similar characteristics and ignition was through direct flame contact [33]. However, structural ignition during the 2016 Fort McMurray Fire was found to be largely ember-driven [26]. Pre- and post-wildfire data collection which can be used to evaluate guidance impacts has been identified as a research need [23] and there are Canadian initiatives in progress for systematic data collection to address the lack of data [34].

A7.2. Building and Building Material Quality

The studies reviewed focused on the impact building materials and vegetation characteristics on survival post-wildfires as per the objective. However, this does exclude characterizing the building condition/quality prior to the wildfire event and how the building condition itself may impact building performance in wildfires. While the Australian study on the 2013 Linksview Fire did identify whether buildings had been modified, they found that the year of construction had a larger impact [30]. Further research should be done to compare the performance of newly constructed buildings and modified buildings with similar materials.

A7.3. Indigenous Communities

Another identified research priority is Indigenous communities and wildfires [35]. The studies did not explicitly identify if the buildings surveyed were part of an Indigenous community. In Canada, Indigenous communities are more likely to be evacuated due to wildfires and wildfire smoke [36].

Wildfires in Indigenous communities are part of complicated jurisdictional arrangements which adds complexity with respect to building codes, fire management, and evacuations [37]. In addition to Indigenous communities being more at risk for wildfires, they are also more at risk of house fires, with fire rates approximately 2.4 times higher than the rest of Canada and death rates up to 10 times higher [38]. There are no national regulations governing fire safety in Indigenous communities. As Indigenous communities, they are not under the jurisdiction of provincial and territorial building codes and regulations. It is expected for on-reserve Indigenous infrastructure projects to meet the standards of the national model codes to receive federal funding, however, First Nations communities have the right to create or adopt their own codes [39]. Therefore, fire safety is largely regarded as the responsibility of each individual community, with smaller and more remote communities at a disadvantage due to a lack of resources.

More research is needed to characterize the buildings and fire risks present in Indigenous communities as there is little data as to how their housing performs in fire. Additionally, it must be noted while some are advocating for the federal government to intervene in fire safety in Indigenous communities [40], there is little information on how legislating or enforcing a code or standard to Indigenous communities would be received [35]. However, it has been reported that it is largely unsupported by Indigenous community members and would be considered a violation of their rights of self-governance and self-determination [41], [42].

A7.4. Heritage Properties

Heritage buildings are also largely unaddressed by wildfire and WUI codes. The National Guide is aimed at newly constructed communities or existing communities that are to be expanded or modified [12]. Heritage properties are designated proper-ties which hold aesthetic, historic, scientific, cultural, social or spiritual value in its character-defining elements, such as materials, forms and location [43]. As such, they are given special protections against alterations in order to preserve its heritage and cultural value. However, while heritage buildings are more vulnerable to fire due to their age and construction prior to existing building codes, these protections also largely prevent the installation of new fire protection systems or replacing structural materials with more resistant ones [44]. In addition to largely being unable to alter features of heritage buildings to allow for new fire protection systems, there is an imperative that in the event of a fire, not only must human life be preserved, but the building itself must also be preserved which presents new considerations for hardening the building against wildfires [44]. A study of building survival after the 2013 Linksview fire in Australia observed that modifications to older buildings had limited impact on their wildfire resistance [30]. Another study done in the San Diego area observed in areas where the structure density was greater than 54 structures per km2, that buildings over 83 years old were damaged by the wildfire, though, they did not characterize the heritage status of the buildings [27].

The studies reviewed were examining the effectiveness of different building characteristics and vegetation management strategies against wildfires. Vegetation management and reducing the fuel load surrounding the building, especially immediately adjacent, has been identified as an effective measure to harden the building against ignition and would be likely be allowed under heritage protections [32]. However, if a heritage building contains structural features identified as high risk such as wooden decking, siding and/or roofing or openings, there are limited options for modifying the structural components if the building is protected [44]. It must also be noted that there is limited understanding of heritage materials in fire [45], with one study on heritage timber suggesting it performs less well than contemporary timber [46], and therefore, its performance under wildfire conditions is relatively unknown.

A7.5. Limitations

As an explorative, non-exhaustive literature review, there are limitations. As this was not a systematic review, only an exploratory, semi-structured one, there are studies that have not yet been incorporated into the literature review. Additionally, this re-view was focused on empirical data following actual wildfires and did not consider laboratory or modelling experiments examining building features or vegetation management effectiveness. This was a conscious decision to focus on data from actual wildfire events, however, laboratory and modelling experiments can provide important information on material and wildfire behaviours that contribute to building survival.

A8. Conclusions

In conclusion, some critical research gaps have been identified in structural wildfire hardening and vegetation management. The studies on building survival and its fac-tors after wildfire have largely been conducted outside of Canada. While there were some observations which were supported across the various studies, regional differences were observed as well, highlighting the importance of having Canadian-specific research. Additionally, the studies have not considered Indigenous communities and their unique needs, nor has it considered existing buildings which may be difficult to modify such as heritage properties. As such, much of the future work identified is centered around increasing knowledge of building performance in wildfires, in WUI communities in Canada and Indigenous communities who are at a higher risk for wildfire. Heritage properties or other properties which may not be modifiable should also be considered when evaluating structural hardening measures.

A9. Acknowledgements

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A10. References

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Appendix B: List of Articles Reviewed for Chapter 3

The following is a list of the 25 articles that were found in the literature review search and included for analysis. They are listed in alphabetical order.

1. Bhandary, U., & Muller, B. (2009). Land use planning and wildfire risk mitigation: An analysis of wildfire-burned subdivisions using high-resolution remote sensing imagery and GIS data. Journal of Environmental Planning and Management, 52(7), 939–955. https://doi.org/10.1080/09640560903181147

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11. Meldrum, J. R., Barth, C. M., Goolsby, J. B., Olson, S. K., Gosey, A. C., White, J., Brenkert-Smith, H., Champ, P. A., & Gomez, J. (2022). Parcel-Level Risk Affects Wildfire Outcomes: Insights from Pre-Fire Rapid Assessment Data for Homes Destroyed in 2020 East Troublesome Fire. Fire, 5(1). https://doi.org/10.3390/fire5010024

12. Penman, S. H., Price, O. F., Penman, T. D., & Bradstock, R. A. (2019). The role of defensible space on the likelihood of house impact from wildfires in forested landscapes of south eastern Australia. International Journal of Wildland Fire, 28(1), 4–14. https://doi.org/10.1071/WF18046

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Appendix C: Supplementary Information for Chapter 4

The following information was collected during the cone calorimeter testing and is intended to supplement and support the information presented in Chapter 4. Averages were calculated using Excel's AVERAGE function and standard deviations were calculated using Excel's STDEV.S function. The density of the sample was calculated using the measured mass at testing, divided by the volume of the sample, which averaged 125 cm^3 for all samples.

Table C1: List of samples and their condition

Sample	Date Tested (2023)	Conditioning	Estimated Moisture Content at Testing [%]	Estimated Density at Testing [g/cm^3]
30 kW/m²				
A30-1	21-Feb	20°C, 15%	7.2	0.34
A30-2	23-Feb	20°C, 12%	8.0	0.35
A30-3	23-Feb	20C, 12%	8.0	0.34
D30-1R	23-Feb	7.75h in oven at 115°C over 2 days	Negligible	0.28
D30-2	23-Feb	8.4h in oven at 115°C over 2 days	Negligible	0.31
D30-3	23-Feb	10.25h in oven at 115°C over 2 days	Negligible	0.33
W30-1	23-Feb	25h submerged in water	36.4	0.47
W30-3	23-Feb	28h submerged in water	34.8	0.46
W30-T	23-Feb	28.5h submerged in water	29.9	0.44
40 kW/m²				
A40-1	22-Mar	20°C, 15%	6.3	0.29
A40-2	22-Mar	20°C, 15%	6.3	0.31
A40-3	22-Mar	20°C, 15%	6.3	0.30
D40-1R	29-Mar	9.5h in oven at 90°C over 2 days	Negligible	0.31
D40-2R	29-Mar	10.25h in oven at 90°C over 2 days	Negligible	0.36
D40-3R	29-Mar	10.75h in oven at 90°C over 2 days	Negligible	0.30
W40-1	22-Mar	44.5h submerged in water	34.2	0.49
W40-2	22-Mar	46h submerged in water	32.4	0.46
W40-3	22-Mar	47h submerged in water	31.1	0.48
20 kW/m²				
A20-1	24-Mar	20°C, 15%	6.5	0.33
A20-2	24-Mar	20°C, 15%	6.5	0.34
A20-3	29-Mar	20°C, 15%	6.5	0.29
D20-1	29-Mar	7h in oven at 90°C over 2 days	Negligible	0.32

Sample	Date Tested (2023)	Conditioning	Estimated Moisture Content at Testing [%]	Estimated Density at Testing [g/cm^3]
D20-2	29-Mar	7.75h in oven at 90°C over 2 days	Negligible	0.29
D20-3	29-Mar	9h in oven at 90°C over 2 days	Negligible	0.33
W20-1	22-Mar	48h submerged in water	33.1	0.46
W20-2	24-Mar	44.5h submerged	29.9	0.47
W20-3	24-Mar	45.5h submerged	38.8	0.42

Table C2: Event times in seconds

Sample	Off-gasing	Top is Black	Glowing/ Smouldering	Ignition	Flameout
30 kW/m^2					
A30-1	2	53	126	-	-
A30-2	4	28	143	-	-
A30-3	4	28	151	-	-
D30-1R	6	28	102	492	823
D30-2	5	28	101	-	-
D30-3	5	28	72	315	868
W30-1	28	62	177	-	-
W30-3	29	61	197	-	-
W30-T	23	63	178	-	-
40 kW/m^2					
A40-1	3	15	-	20	538
A40-2	4	21	-	26	651
A40-3	3	26	-	31	540
D40-1R	1	24	-	28	590
D40-2R	1	20	39	57	597
D40-3R	1	17	-	53	544
W40-1	19	82	84	98	1097
W40-2	23	61	-	92	805
W40-3	15	54	102	661	989
20 kW/m^2					
A20-1	10	73	430	-	-
A20-2	10	62	576	-	-
A20-3	11	70	434	-	-
D20-1	6	60	273	-	-
D20-2	8	66	273	-	-
D20-3	5	54	306	-	-

Sample	Off-gasing	Top is Black	Glowing/ Smouldering	Ignition	Flameout
W20-1	35	115	596	-	-
W20-2	35	140	792	-	-
W20-3	72	108	568	-	-

Table C3: Peak heat release rates of samples

Sample	Peak HRR [kW/m^2]	Time of Peak HRR [s]
30 kW/m^2		
A30-1	29.8	519
A30-2	26.8	434
A30-3	23.7	517
D30-1R	77.4	521
D30-2	42.9	782
D30-3	103.5	362
W30-1	29.4	722
W30-3	34.4	877
W30-T	29.2	875
40 kW/m^2		
A40-1	159.3	35
A40-2	168.5	38
A40-3	154.3	39
D40-1R	169.3	40
D40-2R	150.3	72
D40-3R	138.2	69
W40-1	109.2	693
W40-2	114.6	602
W40-3	118.4	697
20 kW/m^2		
A20-1	24.5	710
A20-2	30.3	751
A20-3	19.2	847
D20-1	26.6	833
D20-2	20.0	880
D20-3	32.4	827
W20-1	17.1	868
W20-2	9.0	864
W20-3	24.4	835

Table C4: Char measurements of samples

	W20-1	**W20-2**	**W20-3**
Thickness at centreline before testing [mm]	12	12	12
Distance from bottom to char layer [mm]	5.5	7.5	5.5
Thickness of Char Layer [mm]	6.5	4.5	6.5

Appendix D: Supplementary Information for Chapter 5

The following tables were used to record notable events and behaviours during the video analysis.

Table D1: Behaviours observed during Video 1

Time (M:S)	Description of Behaviour
0:00	• Beginning of video
0:09	• Car passes a public transit bus which is stopped at a bus stop with lights flashing • Smoke is visible billowing ahead
0:22	• Joins other cars on the highway • Fires are burning on the right side of the highway
0:24	• Large flames visible on side of the road
0:27	• Car moves to the left lane to get from behind a truck
0:30	• Flames are visible across the highway on the left, the evacuee changes the camera angle to film it
0:33	• Right-most lane is emptiest, but it is next to flames on the curb • Cars in the right-most lane are going fastest
0:35	• Middle lane looks like it's mainly trucks • The visibility darkens when passing large flames
0:45	• Left lane is slowest while the right lane is fastest
1:03	• Passes vehicles on the sides of the road, unmoving (presumedly abandoned)
1:10	• At a highway intersection, they are directed to split off to the left into the opposite lane • Police have reversed the direction of that lane so all lanes are heading south
1:16	• All signs are backwards so passengers cannot read them
1:26	• At another highway intersection and directed to the right lane of the same opposite road
1:31	• End of video

Table D2: Behaviours observed during Video 2

Time (M:S)	Description of Behaviour
0:00	• Starts video behind a truck behind a long line of cars though the next lane is clear • Flames and large plumes of smoke are visible ahead
0:07	• Police car passes using the opposite lane in the same direction, appears to be used for emergency vehicles
1:00	• Cars moving very slowly in stops and starts • Flames are visible ahead
1:08	• The car shifts to the left, though it is unclear if they wanted to see ahead or intended to change lanes and changed their mind
1:30	• The car passes by large flames, an ember is burning on the curbside

	• Police lights and more cars are visible ahead
1:42	• The car changes into the empty left lane but stops to let a motorcyclist passed • The truck originally in front of the car starts to change lanes as well
1:55	• Truck moves ahead but the car stops as a fire truck is moving in the opposite direction ahead in the same lane
2:07	• Another 3 cars switch lanes and moves past them and changes back into the right lane • During that time, the fire truck can't move forward until the other cars let them
2:17	• Once the emergency vehicles move past, the car moves back into right lane and goes forward
2:46	• Visibility worsens as smoke plume moves past • Flames are visible ahead and embers are falling
3:00	• End of video

Table D3: Behaviours observed during Video 3

Time (M:S)	Description of Behaviour
0:00	• Cars moving slowly and stopping intermittently. The visibility is very poor, and flames can be seen next to the cars, on the curb of the road. • Spot fires are visible in the vegetation next to the road, likely caused by embers.
0:11	• States they "can't get a hold of anybody now"
0:55	• Large flames approach the side of the road and cars change into the left lane • In a separate video (Video 4), they can be heard saying they could feel the heat through the car
1:10	• Minor congestion cars approach an intersection. High number of embers begin falling on the cars and visibility decreases. • Cars now using both lanes
1:32	• Cars are forced to stop as an animal (possibly a deer) runs across the road.
1:38	• Right lane is congested, and more cars begin to change into the left lane where traffic is moving.
2:10	• All lanes are slow as traffic approaches an intersection
2:25	• Cars can be seen driving down a hill, outside of the marked road in order to enter the intersection (Highway 63) and avoid the congestion from the roadway.
2:55	• The car is directed to turn right onto Highway 63 by police.
3:00	• End of video

Table D4: Behaviours observed during Video 4

Time (M:S)	Description of Behaviour
0:10	• Passes an abandoned car, states it's like the "apocalypse"
0:19	• As visibility worsens, they turn on the car blinkers, other cars also do the same
0:30	• Visibility is incredibly poor due to the smoke, only car lights are visible
0:52	• Some small spot fires can be seen on the right side and the visibility slightly improves • The highway is not congested but traffic is still going slowly, likely due to the limited visibility
1:18	• Visibility improves as out of a plume, can hear a sigh of relief
1:40	• The driver calls someone and talks about how he could feel the heat from the car when passing the flames
1:55	• They say on the call that "people were starting to panic" because the flames were right next to them. They also mention how traffic was going in one-way both lanes
2:05	• More cars start to appear as well as some congestion as they approach an intersection
2:25	• They say on the call that he doesn't know where to go
3:00	• Video ends

Table D5: Behaviours observed during Video 5

Time (M:S)	Description of Behaviour
0:10	• The woman is talking on the phone about how they just left Walmart, and "everything is on fire"
0:50	• Large flames are visible on both sides of the highway, and they are driving towards a smoke plume • The man says "Thank God we're getting out of here"
1:05	• The woman wants to get through smoke as quickly as possible and wishes she had a mask, while the man is reassuring her
1:28	• The woman is concerned about their cat who is in the car with them • The man states that he doesn't know how long the highway will be open • The right-most lane is mostly empty
1:35	• They pass a low burning fire on the roadside and the woman repeatedly says "Oh my god"
2:05	• They pass by cars in a ditch, and both question why there are abandoned vehicles
2:45	• They pass through an intersection and the man briefly considers if the gas station is open but the woman dismisses it immediately
2:55	• Both expresses awe and dismay at a Denny's and hotel that are burning near the highway

4:20	• They pass through another intersection and spend a long time looking at the fire and its damage around the highway
4:30	• The man sees water being sprayed over an area in the distance, says its Centennial (maybe Sentinel) storage
4:43	• The man says he should have his "belt on"
5:06	• End of video

Table D6: Behaviours observed during Video 6

Time (M:S)	Description of Behaviour
0:15	• A large smoke plume is visible in the distance
0:25	• There is a long line of cars in left lane as approaching highway entrance
0:40	• Less congestion for cars going straight than those entering the highway entrance on the right
0:53	• The camera turned as if to move straight, but shifts back to turn right onto Highway 63 • Police are managing the traffic flow
1:10	• They encounter congestion on the Highway, assumedly due to other cars entering the highway ahead
1:30	• They changed into the left lane as other cars did to avoid congestion
1:52	• More congestion as a highway entrance merges ahead
2:20	• There is a long line of cars on the highway
3:45	• Police directed cars going south in the northbound lane into the southbound lane
4:22	• Moved into left northbound lane (one-way) by the police • Likely due to flames visible ahead near the side of the road
4:45	• Passes by an area burning on the right side of the highway (cars had been directed to the other lanes)
5:05	• Some cars move back into the southbound lanes instead of staying on the northbound lane once past the burning area
5:07	• The video skips about two minutes according to time in dash cam
5:20	• The car approaches an intersection managed by police
6:30	• More congestion approaching an intersection
6:38	• End of video

Table D7: Behaviours observed during Video 7

Time (M:S)	Description of Behaviour
0:15	• Turned right at onto the main road by the police
0:30	• Can see pedestrians walking on the sidewalk • The cars are moving slowly as approaching an intersection

0:50	• Can hear an automated evacuation order over the radio (this video is time-lapsed so it's uncertain if the audio was correctly synced)
1:00	• The automated announcement states Highway 63 is closed south of MacKenzie Boulevard due to the fire
1:18	• There is congestion leading up to the intersection where police are managing traffic • Police are stopping and talking to people in vehicles/on sidewalks
1:25	• Can see a car on the right with its hood up, indicating possible mechanical issues before it's fixed and they continue
1:35	• The car turns into a plaza before the intersection, past the gas station and waits for a bit
1:40	• They go down a side street and cut through a different plaza to avoid the intersection and get back onto the main road
1:51	• They have to maneuver around a policeman and their car in the middle of the road • All lanes are going one direction and some cars are driving in the grass divider between the lanes
2:00	• The centre lanes next to the divider are moving the slowest
2:15	• Police blocked off going straight from one of the lanes, so the car had to turn onto the highway
2:35	• Visibility has gotten worse
3:00	• Cars appear to be slowing as they near a fire on the side of the road, though it's hard to tell due to the time lapse
3:30	• All lanes are moving around the same speed
4:35	• They pass by several cars abandoned on the sides of the roads
5:45	• They pass through an intersection managed by police
5:52	• They encounter more cars and some slight congestion • A car is pulled over on the curb with another car helping them
5:55	• End of evacuation portion

Table D8: Behaviours observed during Camp Fire Video 1

Time (M:S)	**Behaviour**
0:00	• Video starts • The car is driving past burning houses
0:05	• Someone whimpers and a man says "that sucks" as they drive past
0:23	• Someone is crying as they film their burning surroundings
0:27	• A woman (the person filming) starts praying
0:30	• The car drives into the middle of the road to avoid low flames, but moves back into the right lane afterwards
0:45	• The car drives through a heavy cloud of smoke and there is a car pulled over which they pass

1:02	• They pass another car driving slowly using opposite lane which was empty, moves back into the right lane after
1:10	• End of video

Table D9: Behaviours observed during Camp Fire Video 2

Time (M:S)	Behaviour
0:00	• Video starts
0:01	• A woman is speaking saying it is very hot in the car, a man is also with her (presumably a family based on the title of the video)
0:08	• Man and woman appear to be anxious at the congestion
0:12	• Car is moving slowly and man and woman speaking nervously
0:22	• Man says to calm down and woman says to breathe (to other occupants in car, believed to be children) • Man advises to put their shirts over their mouths
0:30	• Could hear someone wheeze, man expresses frustration at being stopped
0:50	• Woman is breathing heavily • Can see lots of congestion with cars all heading in one direction across multiple lanes (unsure if there is lane reversals or just a large one-way road)
0:53	• Woman says there explosions everywhere and car wheels popping
1:38	• There are lots of smoke and embers, • Woman is breathing heavily, says “wind is blowing so hard”
1:48	• Woman tries to calm other passengers (children) ands says to driver to "keep going"
2:06	• There is less congestion and the car is moving faster • Woman says "that was so scary"
2:14	• Video ends

Table D10: Behaviours observed during Camp Fire Video 3

Time (M:S)	Behaviour
0:00	• Video starts
0:05	• There is a child in the car speaking, • Lots of congestion and cars across all lanes • A car appeared to be heading the opposite direction, but stopped and turned around
0:15	• One car makes a U-turn and goes the other way
0:27	• Man (assumedly their parents) reassures the child that they won't catch on fire
0:49	• Visibility dims, harder to see cars
1:14	• Visibility is very poor • Traffic is slow and can hear honking from other cars

1:18	• Child exclaims that they "can't see my mom" (may be travelling separately)
1:30	• Car begins moving faster, visibility is still poor
1:55	• Can hear sirens and emergency vehicles are going the opposite way, cars changed lanes to let them past
2:20	• Visibility is still poor
2:25	• Cars go past using the opposite lane (potentially blocking emergency vehicles)
2:40	• Emergency vehicles are parked on the opposite shoulder of the road
2:53	• Once past emergency vehicles, car moves back into the opposite lane
2:58	• End of video

Table D11: Behaviours observed during Tantallon Video 1

Time (M:S)	**Behaviour**
0:00	• Video starts • The road is relatively empty, smoky, fire on both sides
0:05	• Evacuee exclaims "that's fire" while driving
0:15	• Driver remarks that they can't see anything
0:20	• Car drives close to flames • Car appears to move closer to middle of the road
0:27	• Sudden stop as another car appears in front of them • Very low visibility
0:30	• Slowed down because of car in front • Still very low visibility
0:45	• Evacuee makes calming remarks "okay, don't worry"
1:10	• Visibility is very low, can barely see the car rear lights
1:37	• Visibility lightens, can see the road markings again • The car was driving outside of the right lane
1:42	• End of video

Appendix E: Ethics Approval and Renewal for Video Analysis

YORK
UNIVERSITÉ
UNIVERSITY

OFFICE OF RESEARCH ETHICS (ORE)
3rd Floor, Kaneff Tower

4700 Keele St.
Toronto ON
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Tel 416 736 5914
www.research.yorku.ca

Certificate #:	**STU 2022-058**
Approval Period:	**06/20/22-06/20/23**

ETHICS APPROVAL

To: **Hannah Carton**
Graduate Student of Civil Engineering
hcarton@yorku.ca

From: Alison M. Collins-Mrakas, Director, Research Ethics
(on behalf of You-ta Chuang, Chair, Human Participants Review Committee)

Date: Monday, June 20, 2022

Title: **Fire Spread in the Wildland-Urban Interface**

Risk Level: ☒ Minimal Risk ☐ More than Minimal Risk

Level of Review: ☒ Delegated Review ☐ Full Committee Review

I am writing to inform you that this research project, **"Fire Spread in the Wildland-Urban Interface"** has received ethics review and approval by the Human Participants Review Sub-Committee, York University's Ethics Review Board and conforms to the standards of the Canadian Tri-Council Research Ethics guidelines.

Note that approval is granted for one year. Ongoing research – research that extends beyond one year – must be renewed prior to the expiry date.

Any changes to the approved protocol must be reviewed and approved through the amendment process by submission of an amendment application to the HPRC prior to its implementation.

Any adverse or unanticipated events in the research should be reported to the Office of Research ethics (ore@yorku.ca) as soon as possible.

For further information on researcher responsibilities as it pertains to this approved research ethics protocol, please refer to the attached document, **"RESEARCH ETHICS: PROCEDURES to ENSURE ONGOING COMPLIANCE".**

Should you have any questions, please feel free to contact me at: 416-736-5914 or via email at: acollins@yorku.ca.

Yours sincerely,

Alison M. Collins-Mrakas M.Sc., LLM
Director, Office of Research Ethics

RESEARCH ETHICS: PROCEDURES to ENSURE ONGOING COMPLIANCE

Upon receipt of an ethics approval certificate, researchers are reminded that they are required to ensure that the following measures are undertaken so as to ensure on-going compliance with Senate and TCPS ethics guidelines:

1. **RENEWALS:** Research Ethics Approval certificates are subject to annual renewal. **Failure to renew an ethics approval certificate or (to notify ORE that no further research involving human participants will be undertaken) will result in the closure of the protocol.** No further research activities may be undertaken until such time as a new protocol has been reviewed and approved. **Further, it may result in suspension of research cost fund and access to research funds may be suspended/withheld**;

2. **AMENDMENTS:** Amendments must be reviewed and approved **PRIOR** to undertaking/making the proposed amendments to an approved ethics protocol;

3. **END OF PROJECT**: ORE must be notified when a project is complete;

4. **ADVERSE EVENTS**: Adverse events must be reported to ORE as soon as possible;

5. **POST APPROVAL MONITORING:**
   a. More than minimal risk research may be subject to post approval monitoring as per TCPS guidelines;
   b. A spot sample of minimal risk research may similarly be subject to Post Approval Monitoring as per TCPS guidelines.

FORMS: As per the above, the following forms relating to on-going research ethics compliance are available on the Research website:

a. Renewal
b. Amendment
c. End of Project
d. Adverse Event

YORK UNIVERSITÉ UNIVERSITY

Certificate #:	**STU 2022-058**
Initial Approval:	**06/20/22-06/20/23**
Amendments:	
Renewals:	**06/02/23-06/02/24**
Current Approval Period:	**06/02/23-06/02/24**

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ETHICS RENEWAL

To: **Hannah Carton - Graduate Student**
Department of Civil Engineering
Faculty of Lassonde School of Engineering
hcarton@yorku.ca

From: Alison M. Collins-Mrakas, Director, Research Ethics
(on behalf of Janessa Drake, Chair, Human Participants Review Committee)

Date: Friday, June 2, 2023

Title: **Fire Spread in the Wildland-Urban Interface**

Risk Level: ☒ Minimal Risk ☐ More than Minimal Risk

Level of Review: ☒ Delegated Review ☐ Full Committee Review

I am writing to inform you that this research project, **"Fire Spread in the Wildland-Urban Interface"** has received ethics review and renewal by the Human Participants Review Sub-Committee, York University's Ethics Review Board and conforms to the standards of the Canadian Tri-Council Research Ethics guidelines.

Note that renewal is granted for one year. Ongoing research – research that extends beyond one year – must be renewed prior to the expiry date.

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Any adverse or unanticipated events in the research should be reported to the Office of Research ethics (ore@yorku.ca) as soon as possible.

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Should you have any questions, please feel free to contact me at: 416-736-5914 or via email at: acollins@yorku.ca.

Yours sincerely,

Alison M. Collins-Mrakas M.Sc., LLM
Director, Office of Research Ethics

RESEARCH ETHICS: PROCEDURES to ENSURE ONGOING COMPLIANCE

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2. **AMENDMENTS:** Amendments must be reviewed and approved **PRIOR** to undertaking/making the proposed amendments to an approved ethics protocol;

3. **END OF PROJECT**: ORE must be notified when a project is complete;

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5. **POST APPROVAL MONITORING:**
    a. More than minimal risk research may be subject to post approval monitoring as per TCPS guidelines;
    b. A spot sample of minimal risk research may similarly be subject to Post Approval Monitoring as per TCPS guidelines.

FORMS: As per the above, the following forms relating to on-going research ethics compliance are available on the Research website:

a. Renewal
b. Amendment
c. End of Project
d. Adverse Event

Appendix F: Fire Building Codes in Developed and Developing Countries: A Case Study Comparison Between Canada and Costa Rica

Attached Paper:

Guevara Arce, S., Carton, H., and Gales, J. (2022). *Fire Building Codes in Developed and Developing Countries: A Case Study Comparison Between Canada and Costa Rica*. CSCE 2022: Canadian Society for Civil Engineering (CSCE) 2022 Annual Conference, Whistler, British Columbia.

F1. Abstract

In Canada, the development of fire codes and standards are based upon governmental resources aiming to advance requirements deemed insufficient or potentially non-reflective of current design trends. This has led to recent advancements of fire-safe engineered timber and urban interface protection from wildfires. It has at this time minimalized attention to the marginalized populations exposed to fire hazards, such as the numerous informal settlement fires observed across Canada in the last few years.

Developing countries, generally, do not have the financial or administrative resources to advance their own fire codes and standards in such a manner. In general, developing countries adopt codes and standards from more established sources to fit their necessities. However, these codes and standards may not be wholly representative of their current design trends or fire problems. For example, in Costa Rica, adopting the National Fire Protection Association (NFPA) Standard 101 has caused confusion around the required fire protection needed for acceptable design as it was not created with Costa Rica in mind. The adopted NFPA code, more importantly, does not consider how to protect marginalized populations living in informal settlements.

Informal settlements are a growing issue in both developing and developed countries. Informal settlements are at a greater risk of fire and other hazards due to the physical characteristics of the structures and lack of regulation thereof, socio-economic vulnerability of the residents, and the political and institutional marginalization of the settlements.

Considering Costa Rica and Canada, the present study serves three purposes: to compare Developed (Canada) and Developing (Costa Rica) code advancement approaches; to determine

code applicability to informal settlements and to compare each country's approach to informal settlements.

F2. Introduction

Building design codes and regulations are meant to protect human lives and structural integrity of the building in the event of a hazard through providing standards that buildings must adhere to (Calder and Weckman 2020). Codes have historically been prescriptive but have recently began transitioning to performance-based codes (Meacham 2010). In Canada, codes are developed based upon national governmental resources aiming to advance requirements deemed insufficient or potentially non-reflective of current infrastructure design trends. However, developing countries, generally, do not have the financial or administrative resources to advance their own fire codes and standards in such a manner and instead adopt codes and standards from more established sources to fit their necessities. However, building and fire codes are typically developed with specific scopes and are only applicable to conventional infrastructure and do not address unconventional buildings and non-traditional housing such as informal settlements.

Informal settlements – commonly defined as residential areas where residents have no guaranteed permanency, a lack of basic services and amenities, and housing does not comply with building codes and regulations – are a growing issue in both developed and developing countries due to a lack of affordable housing, increased urban population growth and economic vulnerability (UN-Habitat 2015). Informal settlements are at a greater risk of fire and other hazards due to the socio-economic vulnerability of the residents, the physical characteristics of the structures, and the political and institutional marginalization of the settlements (UN-Habitat 2018). The UN has targeted informal settlements through the Sustainable Development Goals (SDGs), notably SDG #11: make cities, inclusive, safe, resilient, and sustainable, but also through SDG #1: to end poverty in all forms and SDG #10: to reduce inequality within and among countries (UN-Habitat 2017).

The objective of this paper addresses important interrelated themes to the above: 1) compare Developed (Canada) and Developing (Costa Rica) code advancement approaches, 2) determine code applicability to informal settlements and 3) compare each country's approach to informal settlements.

F3. Code Advancement Processes

These countries were chosen for this study due to the differences between how they are addressing the housing and informal settlement issues they have been experiencing. Canada is a developed country with a known affordable housing crisis and informal settlements which can be compared with a country who is also dealing with similar issues, though in different forms. Canada has accessibility to greater economic resources to address these issues, while for Costa Rica to obtain solutions must take different approaches, due to the relative lack of monetary resources to work in housing issues.

Costa Rica was chosen for comparison due to the housing solution efforts the government has been done through the years, aiming to provide decent housing to all Costa Ricans. There are records since 1904 about government actions focused on solving housing problems affecting the country (Guevara Arce 2020). In 1949, it was established in the Costa Rican Political Constitution that the State has the obligation of providing acceptable housing to the population with limited economic resources (Guevara Arce 2020). These efforts have placed Costa Rica on top of the region, as Costa Rica is the country with the lowest percentage of urban population living in informal settlements in Latin America (The World Bank 2018).

F3.1. Canada

In Canada, building and fire safety regulation is under the jurisdiction of the provinces and territories who can choose to adopt or enforce the national model codes or develop their own codes (Canadian Commission on Building and Fire Codes 2015a). Canada has five national building model codes: National Building Code of Canada (NBC), National Fire Code of Canada (NFC), National Plumbing Code of Canada (NPC), National Energy Code of Canada for Buildings (NECB) and the National Farm Building Code of Canada (NFBC). The NBC and NFC are the two main model codes that concern the fire safety of newly constructed and existing buildings. The NBC and NFC are designed to complement each other, where the NBC covers fire safety requirements at the time of building construction and reconstruction while the NFC generally covers the ongoing operation and maintenance of fire safety systems of buildings in-use (Canadian Commission on Building and Fire Codes 2015b).

As model codes, they were created to provide the different building code jurisdictions with a model to follow, to encourage consistency and compatibility across the jurisdictions (Canadian Commission on Building and Fire Codes 2015a). The codes are developed by the Canadian Commission on Building and Fire Codes (CCBFC) and updated every five years through a broad-based consensus process (National Research Council of Canada 2020). Proposed code changes are submitted to the CCBFC where they are examined by the appropriate expert standing committee within CCBFC for merit. Committee members are appointed to the committees through nominations under regulatory, industry or general interest categories. If the proposed change is accepted, it undergoes a series of reviews by relevant standing committees within CCBFC, provincial and territorial authorities and the public. Comments received from the reviews are taken into consideration before the proposed change is submitted to CCBFC for final approval. If approved, the change is included in the next edition of the national code (National Research Council of Canada 2020).

F3.2. Costa Rica

Law 8228 and its Decree No. 37615-MP (Araya 2022). It allows the Costa Rican Fire Corps to issue technical standardization, which will be mandatory for individuals or legal entities, either public or private, in matters of security, fire protection, and human security (Asamblea Legislativa 2002). After the creation of the law and decree, the Fire Corps was obliged to create a guide that helps professionals apply the regulations, mainly concerning the processing of plans, which resulted in the creation of the "Manual of technical provisions for human safety and fire protection" in 2005, where the entire regulatory package of the National Fire Protection Association (NFPA) was adopted (Asamblea Legislativa 2005). In the next years, four more editions were published, mainly updating the information and making it more comprehensible for the users (Unidad de Ingeniería 2013), as the adoption of NFPA standards has caused confusion in the required fire protection needed for acceptable design. The last version was published in 2020, in this edition the document converts from a manual into a regulation (Araya 2022), but it must be highlighted that none of these documents addressed how to protect marginalized populations living in informal settlements.

F4. Informal Settlements

Nearly 1 billion people or 32 percent of the world's urban population live in informal dwellings and around 88% (881,080,000) informal settlement dwellers are estimated to be living in developing countries (UNHabitat 2017). This means that issues with informal settlements are not equally distributed between developed and developing countries, and it is magnified in the latter. Lack of affordable housing is a growing problem, related to population growth which is estimated to increase by 2 billion in the next 30 years (United Nations n.d.). The growth is expected to lead to increased use and density of existing informal settlements and/or the creation of new ones.

Informal settlements have a higher fire risk due to poor electrical connections and the use of open flames for cooking, warmth and lighting which create ignition sources that generate a latent risk. Additionally, the high density of dwellings and short distances between them, the use of combustible construction materials, the topography of the land, among other factors, are features that can worsen a fire emergency, turning a fire rapidly into a conflagration. Koker et al. found that a dwelling inside an informal settlement can reach flashover within a minute or less after ignition and that downwind neighbour structures can be ignited in less than a minute (Koker et al. 2020).

F4.1. Canada

Homelessness in Canada has been a growing concern since the 1980s due to less spending and support for social services and affordable housing, and rapid declines in job availability and permanency, resulting in approximately 235,000 individuals experiencing homelessness per year and 35,000 on any given night (Gaetz et al. 2016). It's estimated that 0.010% of the urban population in Canada live in informal dwellings (The World Bank n.d.), which corresponds to approximately 3,000 people. This is without considering the effects of the COVID-19 pandemic where the number of encampments soared across Canada as people decided to abandon overcrowded shelters or felt they were unwelcome to rest in friend's homes (Crawford 2021). The City of Toronto estimates that in 2021, there were 421 tents and other temporary structures located within the city at 100 different locations, mainly parks and right-of-way passages (City Manager 2021). The 2021 Streets Need Assessment estimated approximately 7,347 individuals were experiencing homelessness in Toronto, with 163 individuals residing in encampments, however both figures are likely below the actual figure as only public spaces were included and hidden homelessness was excluded (City of Toronto 2021a).

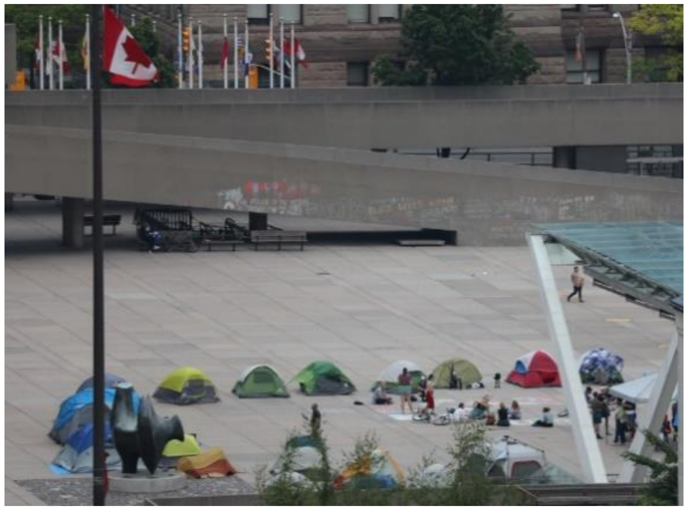

Figure F1. Temporary informal settlement during Summer 2020 located in Central Toronto (Authors' photo)

In 2020, Toronto Fire Services responded to 253 fire incidents in encampments. This represented a 247% increase over incidents in the same period in 2019 (City Manager 2021), however that number includes incidents of suspected fires, not only actual fires which occurred (FactCheckToronto 2021). Fire risks in homeless encampments include open flames, unsafe wiring and power generators as well as unsafe fuel and other flammable material storage (City Manager 2021). Many of these risks are associated with Canada’s colder climate and the need to stay warm along with a lack of fire prevention training or suppression equipment such as fire extinguishers (Gibson 2021). There is little to no active or passive fire protections within homeless encampments.

F4.2. Costa Rica

In 2018, around 3.9 percent of the urban population in Costa Rica were living in informal settlements (The World Bank 2018), which meant approximately 195,000 dwellers. In the same year, the Engineering Unit of the Costa Rican Fire Corps reported a total of 50 fires in informal settlements (Engineering Unit of the Costa Rican Fire Corps 2019), but this data might not reflect the real number of fires as several times inhabitants try to extinguish the fire by themselves without calling the emergency services (Guevara Arce 2019). The houses inside informal settlements are in constant risk of fire, as they are surrounded by potential causes of fires, including short circuits due to electrical connections in disrepair, cooking and lighting with open flame, poor maintenance and manipulation of gas cylinders, attempted controlled burns of wires or dry grass, candles or wood burning without surveillance, as well as children playing with matches, candles, or left alone in their houses (Guevara et al. 2021). In addition to the constant risk of fire, there is a lack of active and passive fire protection, which may worsen the severity of the fire and increases the likelihood of having greater losses.

In 2019, two large fires affected two different informal settlements in Costa Rica. The first one occurred on April 13th in La Carpio, located in La Uruca district of San Jose. Seven people died in a house where 15 people were living. Some of the survivors escaped through the ceiling as the fire started in the only available entrance. The cause of the fire was arson (Guevara Arce 2020).

The second fire occurred on September 16th 2019 in El Pochote, located in Hospital district of San Jose. In this event, 40 houses located in 2,400 m^2 were burned, leaving approximately 216 people homeless. The cause of the fire was a short-circuit (Guevara Arce 2020), Figure G2 shows the fire footprint.

Figure G2. El Pochote fire footprint (by permission from Fernández 2019).

F4.3. Differences Between Informal Settlements

There is a marked difference between the informal settlements of Costa Rica and the homeless encampments in Canada. Comparing the level of informality, Canada can be considered more informal than Costa Rican informal dwellings, as in the latter, there are physical houses instead of mainly tents. These houses can be multi-storied (see Figure 3). Tents are the primary form of shelter in Canadian informal settlements as they are the most convenient and available option to residents as municipalities prevent larger shelters, such as tiny houses, from being constructed using legislative restrictions. Additionally, the size of informal settlements differs between the two countries as an informal settlement in Costa Rica can reach up to 25,000 people (around 5,000 families), (Ministerio de Vivienda y Asentamientos Humanos (MIVAH) n.d.) almost three and a half times the estimated amount people experiencing homelessness throughout Toronto. As Canada's municipalities leverage zoning by-laws and building code provisions to prevent large temporary shelters, homeless encampments tend to be scattered in different areas of cities. In Toronto, tent encampments were found at 59 unique park locations and 41 right-of-way passages (City Manager 2021).

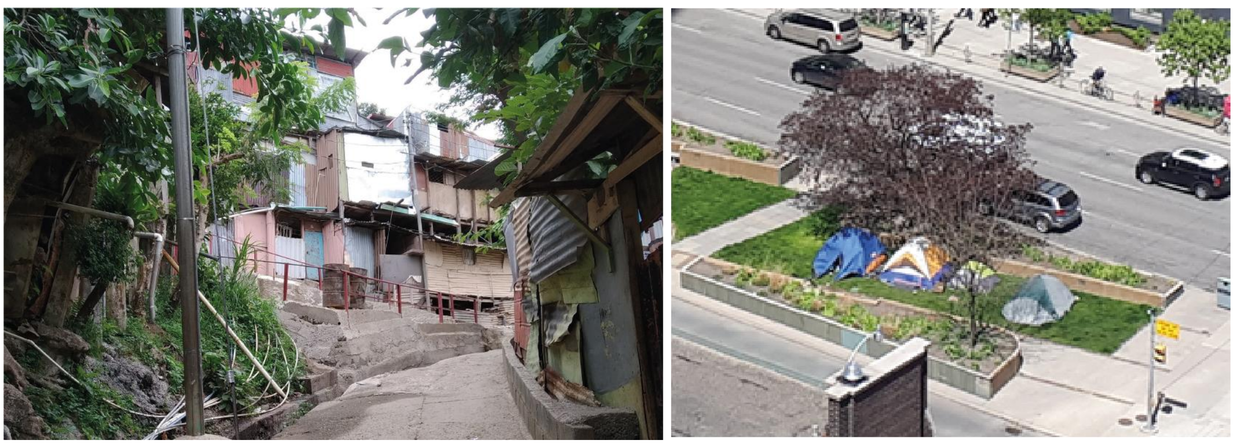

Figure G3. Costa Rican multi-storey informal dwellings vs smaller Canadian tent encampments (Author's photos).

Although living in illegal tenure, the people in Costa Rican informal dwellings have a fixed space in which can remain for years or even decades. For example, La Carpio, the biggest informal settlement in Costa Rica was established in 1993 (Ministerio de Vivienda y Asentamientos Humanos (MIVAH) n.d.). Whereas in Canada, the primary method of dealing with encampments is to forcefully evict them from the area using building and fire code provisions and municipal zoning by-laws, preventing permanent and/or longer-term encampments (Farha and Schwan 2020). Additionally in Costa Rica, the residents manage to get basic services as water and electricity, though mostly in an illegal manner. In some cases, national companies develop projects to minimize the informality condition and enhance their living situation. For instance, the National Company of Force and Light (CNFL) started a project of grouped metering and network shielding, providing informal dwellers with a minimum of passive fire protection and legal electricity at an affordable price. In Figure G4, the left picture shows the cabinets installed for electricity distribution, and the right picture depicts the connections the community did in order to legalize their services.

Figure G4. Grouped metering (Author's photos).

Another difference is the ability to trace and census them, although in both cases it is difficult due to their nomad behaviour. It is more probable for people to stay longer in informal buildings than in tents, as the latter posses more ease for location changes. In Canada, the issue of homelessness, affordable housing and social services falls across multiple jurisdictions which means there is no centralized system for surveying the number of people experiencing homelessness. Employment and Social Development Canada (ESDC) conducts voluntary community Point-in-Time counts every few years to count a community's sheltered and unsheltered homeless (Employment and Social Development Canada 2022). However, these counts are voluntary and may not specify whether "unsheltered" means they live in an encampment depending on the municipality (Employment and Social Development Canada 2019). There are also no surveys about the different forms of shelter within homeless encampments.

F5. Building Codes and Informal Settlements

Informal settlements exist in an unclear legal area as they are often situated on land the residents do not own. Additionally, due to the nature of informal settlements, the buildings and structures used are often whatever is available and constructed to provide shelter, without any regards to building or fire regulations. While there are existing frameworks on informal settlements that propose to create policies in order to update land use and ensure informal settlements meet minimum safety requirements (Arup 2018; Farha and Schwan 2020), there have not been any proposals to incorporate informal settlements in building and fire safety regulations themselves.

In Canada, homeless encampments are not considered permanent buildings and do not directly fall under the authority of building codes. Tents are the most common form of shelter in homeless encampments as one of the few available forms of shelter. Larger shelters, such as tiny homes, are considered permanent shelters and as such fall under building and fire code regulations which municipalities have utilised in order to have them dismantled as they lack active and passive fire protections. Additionally, as a vulnerable population, many of whom lack financial means, any building or structural regulations are unlikely to be followed due to a lack of ability. There are currently no official processes in place to regulate the safety of tent encampments. Municipalities have commonly employed zoning by-laws to criminalize temporary shelters in city spaces and allow police to forcefully evict residents of encampments using those powers. However, these by-laws have come under legal scrutiny and been found to violate Section 7 of the Canadian Charter of Rights and Freedoms that stipulates all Canadians have a right to “life, liberty and security of the person” which the Supreme Court of Canada has interpreted it to include the right to housing (Farha and Schwan 2020). While there are programs in place for municipalities to provide access to sleeping bags, propane stoves as well as burn bins, in order to reduce the use of open flames for warmth (Gibson 2021; Samson 2022), there are few initiatives in place to provide housing or supply residents with safe(r) building materials in encampments, outside of directing them to existing services such as city shelters and social housing programs.

Some cities have started initiatives using tiny homes as an alternative to homelessness and a form of affordable housing (Koutalianous et al. 2021; Wong et al. 2020). However, this move has not been without resistance. Tiny homes have largely been promoted as a sustainable alternative to traditional forms of housing, however, they occupy a gray area within building codes and pose a number of safety risks, including fire (Ford and Gomez-Lanier 2017). While some types of tiny homes can fit under existing building codes and regulations, there are prescriptive requirements that tiny houses are non-compliant with by nature of the smaller space (Chown 2016). Tiny homes lack of fire protection outside of fire alarms and the smaller space impacts egress as well as fire spread within the home (Koutalianous et al. 2021). There is also very little research the material behaviour in fire of tiny homes and on fire spread within and between tiny homes. It has been observed that fires spread quickly within the homes with very little time for effective fire suppression. In March 2022, there was a fire within a tiny home village for the homeless in Lake Merritt, California where it was reported that three tiny homes were destroyed within ten minutes as fire spread between the tiny homes. One resident stated “the walls were just melting” around her during the fire (Kendall and Lin 2022).

The City of Toronto settled a lawsuit against an individual who was constructing tiny wooden shelters for homeless individuals. These shelters consisted of a single insulated room with one window and a door, designed to protect against freezing temperatures (Jones 2020). The City’s position at the time were that the tiny shelters were not legal dwellings and violated municipal by-laws against structures on City-owned land (City of Toronto 2021b). While not included as part of the legal proceedings, the City also had concerns regarding the fire safety of the tiny shelters as they were made of a combustible materials, and had not been inspected by Toronto Fire Services to confirm fire safety features (City of Toronto 2021b; Jones 2020).

In Costa Rica, there are no legal and administrative provisions to facilitate the regulation of informal settlements, this generates problems regarding access to basic services, health, accessibility, and security. Additionally, it makes it impossible for the Costa Rican government to apply the corresponding controls and to collect payments for the services provided (Chacon Monge n.d.). However, it was found that dwellers of Costa Rican informal settlements self-regulate their communities, reinforced with jurisdictional support, attaining a certain degree of fire safety. For instance, in Bajo Zamora, an informal settlement visited by the author, minimum distances in alleys must be respected to be able to construct there. Furthermore, community members organized an emergency brigade which is also in charge of fire prevention and mitigation. While tent encampments in Canada have been observed to have some degree of self governance, if and how they manage fire risks and fire safety has not been explored (Young et al. 2017).

In Costa Rica, there have been several efforts done by different institutions to study, improve and try to formalize informal settlements. In 2007, there was an intent to tailor the national norms and regulations to make them more flexible for people living in informal settlements. This project gathered around 12 public and private stakeholders. Three workshops were carried out through the Commission of Experimental Norms to reform the Urban Development Plan (PDU) of the San

Jose Municipality. The main objective was to analyze the experiences these different stakeholders had when applying proposals in informal settlements to create special norms or guidelines that can help to intervene with the urban planning of these settlements. These workshops allowed for several conclusions in different topics to be obtained, such as formalities, general and specific rules for design criteria, minimum access dimensions, design criteria in health, citizen security, and emergencies (Guevara Arce 2020). This project was abandoned as people with legal tenure began to complain, as they stated that it was unfair for people with no legal tenure of the land to receive special treatments and permissions for their constructions.

Later, in 2017, the National Company of Force and Light (CNFL) - one of the stakeholders involved in the 2007 formalization project -, began grouped metering and network shielding projects in informal settlements. The main objective was to formalize the users to avoid electrical and money losses for the company, but it drove several institutions to look for solutions to improve the settlements they were intervening in. For instance, in Tejarcillos (another settlement visited by the author), after CNFL installed the electrical posts and made the connections, the San Jose Municipality intervened and increased the width of the main road. Also, Ebi, a company in charge of solid waste treatment, donated a hook lift dumpster for the community to throw their waste in one place and make it easier to collect at the site. All these improvements not only enhanced the physical features of the informal settlement but also the feeling of belonging of the dwellers, which in turn, resulted in communities committed to taking responsibilities to keep the informal settlement safe.

In 2021, a law was proposed to the Legislative Assembly aiming to transform, rehabilitate, regenerate, regularize and enhance the condition of the informal settlements in order to provide a better quality of life for the inhabitants. The law would be carried out through the creation of intervention zones, in which urban renewal programs are carried out, to allow for the relaxation of urban regulations and the provision of public services and infrastructure, as well as the granting of property titles (Chacon Monge n.d.). This law is under revision and waiting for the approval of the plenary.

F6. Lessons Learned for Canada from Costa Rica

Code development processes between Canada and Costa Rica differ where Canada uses a broad-based consensus process to update codes, Costa Rica adopted the NFPA Standard 101 and has been slowly updating the information to tailor it to Costa Rican buildings and infrastructure before adopting it as an official regulation. However, while informal settlements are an issue in both countries and expected to grow, neither country has indicated any move towards incorporating or recognizing the risk of informal settlement fires into building and fire codes. However, as noted previously, in Costa Rica, several actors are trying to formalize the informal settlements, although so far it has not been possible. Canada has not made any indication they will attempt to formalize informal settlements, however, decriminalizing homeless encampments and ensuring homeless encampments meet minimum safety requirements and have access to basic services are identified as key principles in *A National Protocol for Homeless Encampments in Canada* (Farha and Schwan 2020). Canada aims to reduce homelessness by 50% in 10 years through its National Housing Strategy (Employment and Social Development Canada 2017), however, it has not included regulation or improvement of informal settlements as part of its directives, instead focusing funding on creating new affordable housing options and improving its shelter system (Employment and Social Development Canada 2020).

With Canadian municipalities' history of criminalizing homeless encampments, following Costa Rica's lead to conduct workshops and studies tailored specifically to informal settlements as a preliminary step is a critical one, not only to fill existing knowledge gaps from a lack of information, but also to generate trust within a marginalized community that has been found to distrust government social services and supports (Herring and Lutz 2015). Additionally, creating a specific strategy on informal settlements would help address the National Housing Strategy goal of reducing homelessness by 50% as informal settlements, homelessness and affordable housing are all interconnected. It would also help Canada fulfil its human rights obligations under both international and national law.

F7. Limitations

Statistics on homelessness and homeless encampments in Canada are largely unavailable or patchworked together from different jurisdictions. Homeless encampments are often not reported as their own category and grouped with "unsheltered" and as such, any demographic data may not be entirely applicable. There is also a lack of fire incident data in homeless encampments available which makes it difficult to gauge the true risk and dangers present. In addition to lacking fire incident data, there is a research gap in investigating fire risks and fire spread within North American informal settlements as there are not many studies available.

There is also a lack of studies related to the community within informal settlements and if and how they navigate safety risks, such as fire, within encampments. There is also a lack of information regarding Costa Rican informal settlements' physical characteristics, fire record data, features of the communities such as demographic, social, economic data, and so forth. In addition, the available information is outdated or incomplete, thus, making an accurate characterization of the diverse informal settlements of the country is extremely difficult. Similar to Canada, there is also lack of studies on the community and community organization within informal settlements which was observed during a previous site visit by the authors.

F8. Conclusions

Neither Canada's nor Costa Rica's code development processes lend themselves easily to incorporating informal settlement regulations into their codes. As informal settlements are a globally, growing issue, both countries need to develop approaches in order to address informal settlements and informal settlement safety. Costa Rica is currently in an early stage of preliminary investigations. The stakeholders are trying to understand the issue of informal settlements and how to begin addressing it, aiming to find out what are the future steps to propose solutions for different problems related to the informal settlements. While there have been some Canadian initiatives to begin addressing homeless encampments, from a government standpoint, priority has been given to homelessness prevention, improved shelter access and quality and increased availability of affordable housing.

It is crucial to conduct surveys and research studies to create and update information on informal settlements and their conditions to fill knowledge gaps. This would give better and more accurate recommendations for each settlement, as all of them have different characteristics that made them unique. Additionally, more research to identify and address fire risks within informal settlements is required in order to better provide recommendations to improve the fire safety of its residents. Fire spread within informal settlements and tent encampments is understudied and would contribute to understanding fire risks in informal settlements. However, while both countries are working to address the issue of informal settlements, with the anticipated increase in informal settlements due to population growth and worsening of poverty and the affordable housing crises, these measures may not be sufficient.

F9. Acknowledgements

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Appendix G: Wildfire Evacuation Modelling Coupling Traffic and Fire Behaviour

Attached Paper:

Carton, H., Khan A., and Gales, J. (2020). *Wildfire Evacuation Modelling Coupling Traffic and Fire Behaviour*. NCUR 2020: National Conference on Undergraduate Research. Montana State University, Bozeman, Montana.

G1. Abstract

In Canada and around the world, wildfires are increasing in number and severity. Annually, Canada experiences 6,200 wildfires resulting in over 2.7 million hectares burned. Canada often borrows data from other countries with a history of wildfires, however, evacuation data cannot be easily transferred due to differences in climate, vegetation, culture, and community needs. Canadian-specific data is needed to inform the development of evacuation policies and guidelines, as existing and emerging challenges from wildfires increase. The goal of the research discussed in this paper was to couple traffic modelling and fire behaviour using a Canadian case study community. Current evacuation models do not couple traffic, pedestrian, and/or fire behaviour, which results in the loss of data concerning key interactions and influences that inform decision-making during evacuations. Historical data on fire spread in remote communities was reviewed to determine if fire propagation values could be obtained, however, severe limitations were found in the methodology which decreased its utility for traffic modelling. Various traffic modelling scenarios were developed and will be used to model fire behaviour through closing roads to mimic fire spread. This project will contribute to the international movement to improve wildfire evacuation modelling through coupling traffic, fire and pedestrian behaviour.

Keywords: wildfires, traffic modelling, fire behaviour

G2. Introduction

In May 2016, Alberta experienced the Fort McMurray Wildfire that forced the evacuation of its 88,000 residents within a few hours, the largest evacuation in its history, and caused over $8.9 billion in damages[1]. Severe wildfire events in Canada, like the Fort McMurray Fire, are increasing due to climate change-associated factors such as higher temperatures, and increased interaction between people and the wildland[2]. The increase in wildfire events is not limited to Canada. In late 2019 and early 2020, bushfires in Australia killed 33 people and burned over 11 million hectares following record high temperatures and drought associated with rising temperatures due to climate change[3]. However, whereas Canada's wildfires tend to occur in relatively rural areas, wildfires have been occurring in populated areas of Australia[4]. It is also difficult to compare fire regimes in Canada and Australia due to vastly different vegetation, climate and culture surrounding evacuation.

Canada experiences an average of 6,200 wildfires annually which result in over 2.7 million hectares of wildland burned[5]. While the United States, Southern Europe, Australia, and Canada all have a history of severe wildfires, Canada alone has an absence of modelling tools that integrate fire-associated factors into decision-making and must often borrow data from other countries[6]. However, evacuation data cannot simply be transferred between countries due to differences in climate, vegetation, and culture. In addition, community needs vary between countries, as demonstrated by the difference between Australia's and the United States' evacuation policies; Australia has a policy that lets residents stay behind and defend their property whereas the United States issues mandatory evacuations[7]. Canada favours evacuation[8], however, with the exception of Manitoba, there is no legislative requirement to evacuate, thus evacuation orders cannot be legally enforced[9]. Furthermore, wildfires in Canada can occur on Indigenous lands, where evacuation orders are a part of complex jurisdictional arrangements between different levels of government, which adds confusion during wildfire events[10]. As part of the research objective, this project aims to address research needs identified in the *Blueprint for Wildland Fire Science in Canada (2019-2029)*[11] through collecting Canadian-specific data to help Canada keep pace with current and emerging wildfire challenges.

G3. Background

G3.1. Importance of Coupled Modelling

Current modelling tools used for wildfire evacuations can be split into three main modelling categories: 1) traffic, 2) pedestrian (or human) and 3) fire behaviour[12]. From the Fort McMurray evacuation, devastating dash cam videos emerged of residents evacuating their homes[14] which demonstrates how traffic, human and fire behaviour are linked (Table G1). However, these tools are used independently with limited coupling between them. The lack of coupling results in the loss of information about key interactions and influences that inform decision-making in response to wildfires[12]. While there is an international effort to develop models that will combine all three types of modelling used for wildfires[13], the coupling of models has not been performed.

Table G1: Events during the evacuation of Fort McMurray depicting traffic, fire, and/or human behaviour

Time*	Description of Event
0:00	• Beginning of video • Cars move slowly and stop intermittently. The visibility is very poor, and flames can be seen next to the cars, on the curb of the road. • Spot fires are visible in the vegetation next to the road, likely caused by embers.
0:55	• Large flames approach the side of the road and cars begin to change into the further lane to avoid the flames. • In a separate video taken by the same individual, voices can be heard stating that they can feel the heat through the car (1:53*)[15]
1:10	• Minor congestion as cars approach an intersection. High number of embers begin falling on the cars and visibility decreases.
1:32	• Cars are forced to stop as an animal (possibly a deer) runs across the road.
1:38	• Right lane is congested, and cars begin to change into the left lane where traffic is moving.
2:10	• All lanes are slow as traffic approaches a large intersection.
2:25	• Cars can be seen driving down a hill, outside of the marked road in an effort to enter the intersection and avoid the congestion from the roadway.
3:00	• End of video

**Times listed (minutes:seconds) are the times of the video player, not the time shown in the dash cam video itself.*

Fire behaviour is evident on a local scale when, for example, cars swerve into another lane to avoid flames or slow down as visibility decreases, and on a regional scale should wildfires block an egress route and evacuation is forced to change directions. In addition, the video demonstrates that during evacuations abnormal traffic behaviour can emerge, which is unlikely to be accounted for in most traffic model simulations. Therefore, models that integrate traffic, fire, and pedestrian behaviour are required to increase the accuracy of wildfire evacuation models to help decision-making.

G3.2. State of the Art for Coupled Modelling

Coupled evacuation modelling has not been performed at the time of writing, though, there is an international effort to develop integrated models[13]. However, the work has been focused on the development of framework specifications for a novel modelling software and not the integration of existing models[13]. Traffic evacuation models require sub-models relating to travel choice, behaviour of vehicles in the network, as well as the traffic patterns that emerge[16]. A number of gaps in existing traffic models are present, one of which is the calibration and validation of evacuation traffic models[16]. Models can be calibrated using surveys where preferences are asked before an event, after the event surveys, through empirical traffic counts, and by simulation experiments[16] though these may not accurately reflect the actual behaviour during a wildfire evacuation.

Existing fire models also have many limitations in terms of not only coupling potential, but also accuracy of predictions. Wildfire behaviour is very difficult to predict due to numerous factors which interact with each other to effect wildfire behaviour[13]. Many models have programmed assumptions into their underlying calculations that may impact their applicability[17]. The inherent accuracy or inaccuracy of fire models is difficult to quantify as there are many parameters that effect fire behaviour and some models may be more sensitive to certain parameters and less sensitive to others[17]. The non-linear nature of fire behaviour makes it even more difficult to correlate input accuracy with output accuracy of fire models[17]. The limitations of existing fire models make it difficult for them to be integrated with traffic and/or pedestrian models as inaccuracies accumulate.

Currently, there are international efforts towards developing frameworks for coupled capabilities and directing future research[13]. For example, the National Fire Protection Association (NFPA)'s WUI-NITY research program aims to develop a framework for coupled models. While the final report is not publicly available at the time of writing, the research has been reported on during public presentations given to the fire research community[18]. The WUI-NITY research program advocated for the collection of badly needed raw evacuation data from controlled field experiments and real evacuations. Subsequently, the researchers illustrated their framework considering the evaluation of a simulated traffic community evacuation performed in Roxborough Park, Colorado in 2019[18]. NFPA's WUI-NITY program used the Lighthill-Whitham-Richards traffic model[19] for illustrative purposes, however, their framework is not meant to be specific to one traffic theory but capable of being integrated to validate different traffic theories that may rely on different congestion and driver behaviour assumptions. The WUI-NITY report will have useful insights to extend beyond featured modelling theories, particularly when considering modelling algorithms used frequently by practitioners such as PTV VISSIM which uses the Wiedemann car-following model[19]. PTV VISSIM uses a reactionary traffic flow calculation based on driver interaction with nearby traffic which will be examined in the context of WUI evacuation.

G4. Methodology

G4.1. Historical Data Collection

Data collection of fire behaviour was done to determine the rate of fire propagation towards communities. The propagation of the fire front is dependent on many variables[20], however, in order to simplify the rate of spread, it was assumed that the rate is linear and independent of topography, environmental conditions such as wind direction, and vegetation. Using the assumptions above, the rate was determined through a review of information about two historical fires which approached remote Canadian communities triggering large evacuations. The communities chosen were Fort McMurray, Alberta (2016) and Slave Lake, Alberta (2011).

Geospatial satellite data from two sources was used to estimate fire propagation. The first source was the Canadian Wildland Fire Information System (CWFIS) which is run by Natural Resources Canada (NRCan). An interactive map available on the official CWFIS website shows historical fires as well as current conditions[21]. Final estimated fire perimeters are publicly available for download from their website, however, estimated fire perimeters on specific days were obtained as shapefiles (.shp) files through email request. The fire perimeter estimates are made by combining and processing season-to-date hotspot data[18]. Hotspot detection using satellites is done by equipping satellites with detectors that measure electromagnetic wavelengths[22]. However, some limitations in using satellites to detect fires include missed detections due to thick cloud or smoke cover and the inability to detect the active burning area through satellite imagery due to varying size and spatial overlap of the pixels[22]. Therefore, the perimeter estimates should be considered rough estimates, best used with large fires[22].

The second source was NASA’s Fire Information for Resource Management System (FIRMS)[23]. There were two types of data sets collected: 1) Moderate Resolution Imaging Spectroradiometer (MODIS) Collection 6 and 2) Visible Infrared Imaging Radiometer Suite (VIIRS) 375 m, which represent data taken from different satellites and are referred to as MODIS and VIIRS respectively for the remainder of this paper. Each hotspot/active fire detection represents the centre of a pixel which was found to contain one or more thermal anomalies, such as fires or volcanoes[24]. MODIS has a pixel size of approximately 1 km, while VIIRS has a pixel size of approximately 375 m[24]. However, while it may approximate areas where an active fire is burning, it does not represent a fire front, though multiple active fires in a line are generally interpreted as a fire front[24]. Fire detection is done using a contextual algorithm focussing on the mid-range infrared radiation emitted from fires[24]. However, like CWFIS data, there are limitations on the data obtained. Fires may be missed due to the fires starting and ending between satellite observations, cloud cover, smoke cover or tree canopy obscuring the fire, or if the fire is too small or cool to be detected[24]. These limitations were considered when using FIRMS data to estimate fire front propagation.

Using publicly available satellite data that depicted the fire front approaching Canadian communities over a specified time, the relationship between time and distance from a community was plotted, which helped estimate the linear propagation of the fire front. The distance of the fire front was measured from the geographic centre of the city, which is a consistent way of measuring the fire front when using different case studies. The distance from the geographic centre to the fire front was chosen to be the closest fire front from the centre using radial distance. The geographic centres were calculated using ArcGIS Pro version 2.3, referred to as ArcGIS henceforth. Municipal boundaries were downloaded as shapefiles from Altalis, a webstore which is a source of spatial data and imagery of Alberta[25]. The geographic centroid was calculated using a built-in function in ArcGIS; the distance was measured using the built-in “Measure Distance” tool.

G4.2. Traffic Scenario Development and Traffic Modelling

Scenario development for the traffic modelling included baseline evacuation scenarios, where there was no fire propagation integrated into the model, and scenarios with fire behaviour coupled into the model. Human behaviour was not considered in the development of the scenarios, however, it is acknowledged that human behaviour would impact traffic behaviour, as observed in Fort McMurray (see Table G1). Human behaviour was not considered due to both ongoing research in human behaviour under emergency conditions[26], and to a knowledge gap in how to incorporate unusual pedestrian behaviour into the traffic model. The traffic modelling will be used as an exploratory step in the coupling of evacuation models, which at the time of writing, has not yet been performed.

The traffic modelling will be done using the software PTV VISSIM, a microscopic simulation program for multi-modal traffic flow modelling[27]. The program can simulate urban and highway traffic, including pedestrians, cyclists, and motorized vehicles. It is based on several mathematical models, which allows it to simulate multiple car behaviours, such as car following, lateral movement, tactical driving and pedestrian behaviour[28]. PTV VISSIM is capable of dynamic routing and assignment, based on iterative simulation[28]. The software is commonly used for studies on motorway traffic, performance of signalized and non-signalized intersections, and traffic calming schemes[28,29].

A simplified model of a case study community was created due to time constraints and to reduce complexities in the road network. The area of interest is composed of 530 permanent cabins in less than a 0.15 km^2 area, with 285 cabins in the back-cabin area and 245 cabins in the front cabin area[29]. The cabin area was reported to be fully occupied in the summer months; therefore, 100% occupancy was assumed for the model[29]. In order to maintain consistency with previously modelled scenarios, despite the simplification of the network, the road width of the inner roads was assumed to be 2.5 m, and the outer roads were assumed to be 3.0 m[29]. For this model, the road width was not expected to impact the simulation[29]. To simplify the cabin area, it was decided to model the community as a square, with 16 individual blocks within. Based on a cabin area of 0.15 km^2, the equivalent square dimension would be approximately 390 m by 390 m. The dimensions were rounded up to 400 m by 400 m to account for area taken up by roads. The road away from the cabin area was traced using the Open Street Map background, included in PTV VISSIM. The original cabin area modelled in PTV VISSIM in a previous study, versus the simplified cabin area, is shown in Figure G1 below. For more detail, a previous study has outlined all considerations and assumptions of the case study community[29].

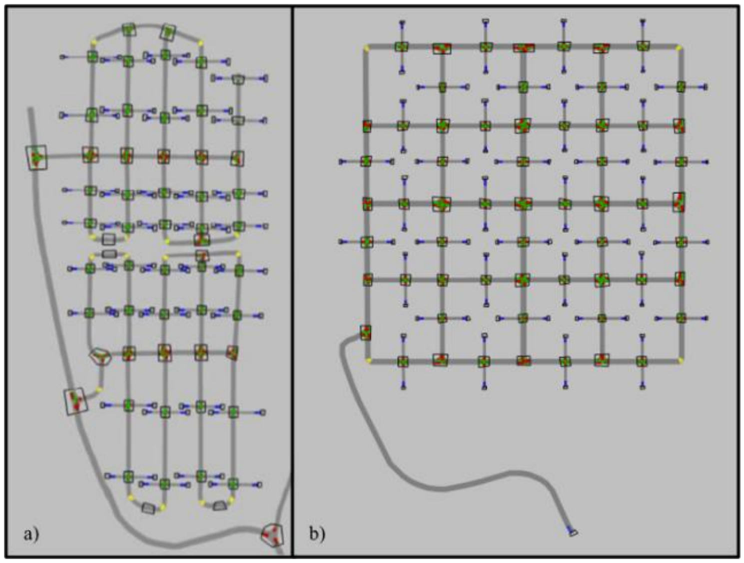

Figure G1: Simplification of the case study community in PTV VISSIM a) Original modelled cabin area[29] b) simplified modelled cabin area

The speed limit in the cabin area is 30 km/h, as observed using Google Maps Street View. Speed distribution was modelled using the *Desired Speed Decisions* function. As all intersections were un-signalized, the *Conflict Areas* function was used to determine right-of-way. There is no public transit in the community[29] only personal vehicles which were modelled using PTV VISSIM's default *Car* type.

For traffic analysis, the different blocks in the cabin area as well as the exit location were designated as *Zones*. *Parking Lots* were created within the cabin area to serve as vehicle origins and assigned to *Zones*, while a *Parking Lot* at the end of the egress road represented the single exit destination. The origin-destination (OD) matrix was used to represent traffic generation, and dynamic assignment was used to model spatial and temporal movements of vehicles. *Reduced Speed Areas* were used at sharp corners of the road network to temporarily slow traffic. *Queue Lengths* and *Vehicle Travel Time* functions were used to measure the queue length at the intersection of the exit road to the cabin area. A preliminary road network has been created, but traffic modelling has not yet been carried out at the time of writing and will be part of future work.

G5. Results

G5.1. Historical Data Collection

G5.1.1. Fort McMurray

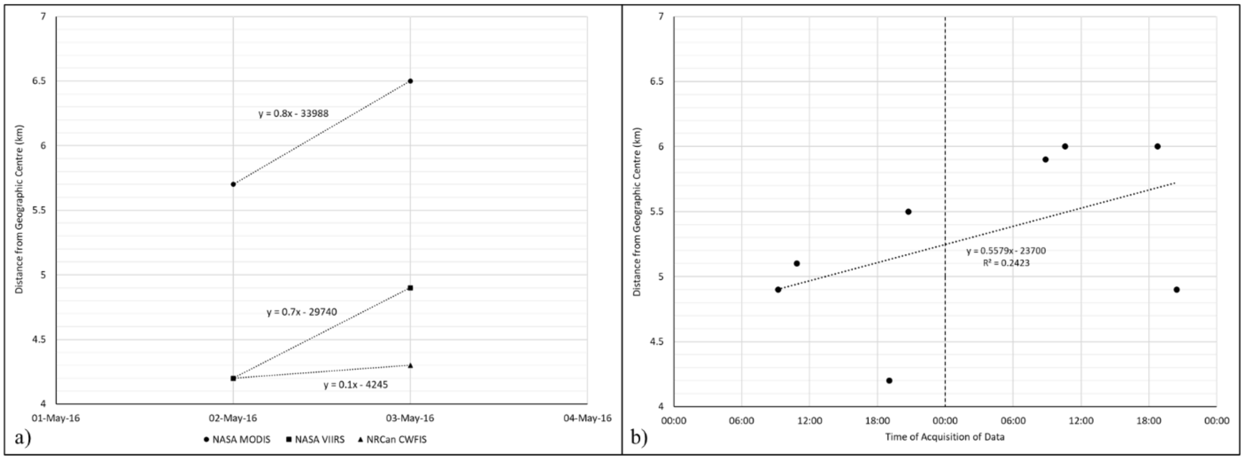

Figure G2: Fort McMurray Results a) over days b) VIIRS data only using time of acquisition data

The distance from the geographical centre of Fort McMurray versus time is plotted above. While the fire was detected on May 1, 2016[30], no satellite data from NASA or CWFIS was available for that date. From the data, the fire is assumed to have started on May 2, 2016; by May 4, 2016, it had already reached the city and gone past the point of reference. The data obtained from NASA also includes the time of acquisition. Using NASA VIIRS data, a new plot was developed to show the distance to the nearest hotspot from the centre of Fort McMurray.

G5.1.2. Slave Lake

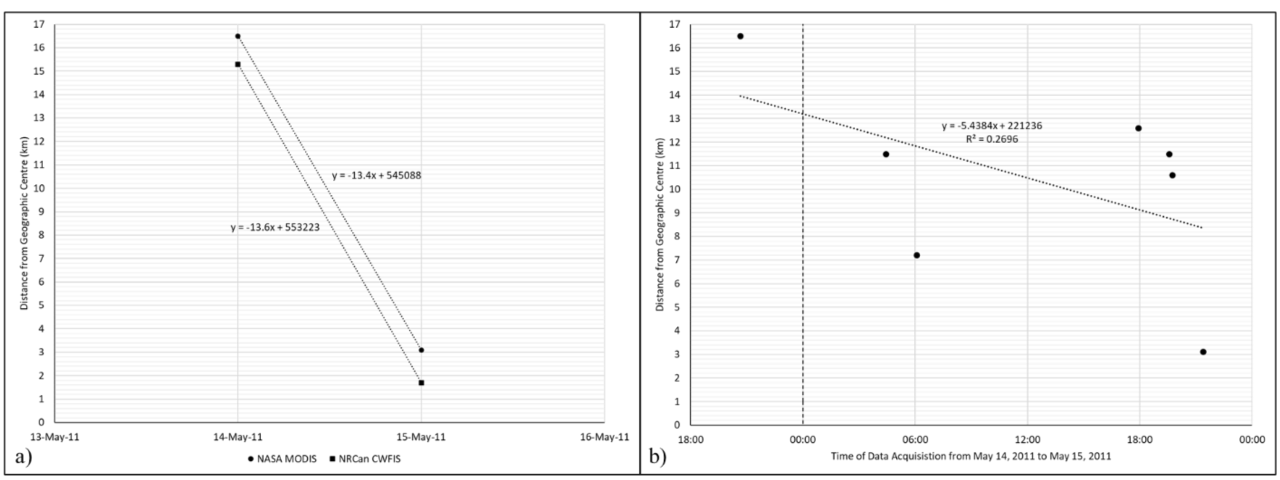

Figure G3: Slave Lake Results a) over days b) MODIS data only using time of acquisition data

The distance of the fire front from the geographic centre of Slave Lake was also plotted using CWFIS and NASA data, as well as a more detailed plot using MODIS data. There was no VIIRS data available for this fire, as VIIRS data is only available from January 20, 2012 onwards[23]. It should be noted that for Slave Lake, there were two wildfires of concern, one to the west of the town and another southeast. The measurements were taken from the closest fire, which aside from the May 14, 2011 data point, was the wildfire in the southeast.

G5.2. Traffic Modelling Scenario Development

Baseline scenarios are the scenarios that will be run to model evacuation of the cabin area without incorporating fire behaviour. The assumption used in these scenarios is that the fire will not impede any of the roads in the cabin area or its single exit road. The model does not include areas of the case study community outside of the cabin area, or the highway out of the community.

There are three main types of evacuations in Canada: 1) immediate evacuation, 2) pre-warned evacuation and 3) self-evacuation[31]. Immediate evacuations occur when there is very little warning and evacuations occur very quickly, as opposed to pre-warned evacuations, where there is usually enough information and time to plan evacuations ahead of the hazard[31]. In self-evacuation, groups or individuals decide to evacuate spontaneously, without direction from authorities[31]. For baseline scenarios, immediate and pre-warned evacuations will be modelled, and are described below. For the purpose of this study, it will be assumed that there is no self-evacuation.

Table G2: Description of baseline evacuation scenarios

#	Scenario	Description
1	Immediate Evacuation	• A fixed number of cars (530) will leave the cabin area in a very short time interval to model immediate evacuations.
2	Pre-warned Evacuation (1)	• Cars will leave the cabin area in stages, with the areas furthest from the exit road (top-right corner) leaving first.
3	Pre-warned Evacuation (2)	• Cars will leave the cabin area in stages, with the areas closest to the exit road (bottom-left corner) leaving first.

The next scenarios developed were scenarios that incorporated fire behaviour into the traffic model, under the assumption that the fire directly effects the roads in the cabin area, but not the exit road. They were also based on the baseline scenarios to aid comparisons between the scenarios.

Table G3: Description of coupled fire behaviour scenarios

#	Scenario	Description
4	Immediate Evacuation – Linear Fire Spread	• A fixed number of cars (530) will leave the cabin area in a very short time interval to model immediate evacuations. • Roads will be closed after specific time intervals to simulate linear fire progression, beginning in the zone farthest from the exit
5	Immediate Evacuation – Firebrands	• A fixed number of cars (530) will leave the cabin area in a very short time interval to model immediate evacuations. • Roads will be closed at random after specific time intervals to simulate ember-driven fire generation

Pre-warned evacuations will not be considered when coupling fire and traffic behaviour under the assumption that if the fire reaches the cabin area with residents still at the cabins, then not enough information and warning was provided to allow for a pre-warned evacuation. Linear fire propagation will be modelled as a cascade originating from the area farthest from the exit road. Intervals at which roads will be closed are to be determined. Ember-driven fire propagation, or fire propagated by firebrands, is included as a scenario since firebrand ignition of fuels has been identified as a current research gap in addition to being an important method of fuel ignition[32]. Firebrands have been known to create new spot fires after being transported large distances[32], such as when the Fort McMurray Fire jumped the Athabasca River[30]. As such, ember-driven fire propagation is expected to be modelled by closing roads at specific intervals, however, the roads closed will be chosen at random.

G6. Discussion

G6.1. Historical Data Collection

G6.1.1. Fort McMurray

From both plots, it appears as though the fire perimeter is moving away from the geographic centre with time. However, in reality, the fire was not moving away from the city. The progression of the fire was measured from the geographic centre of the city to the nearest point which was developed for consistency across different events. This ignored any fire progression that was not in the direction of the geographic centre, which is one of the reasons for a low rate of fire spread, and created the misleading impression that the fire was travelling away from the community. It is also important to note the limitations of the satellite data collected, noted in the previous sections. CWFIS mapped data is not meant to be used for precise tracking of the active fire perimeter, though it does provide more accurate data on the final burned perimeter[22]. NASA FIRMS' data does not provide fire front data, only data concerning fire hotspots which were used to approximate fire front distance[24].

G6.1.2. Slave Lake

There were issues with measuring distances for Slave Lake's data. In ArcGIS, to measure the distance, the "Measure Distance" function was used. It allowed the user to specify a point and drag the mouse to a second point and record the distance between the two points. There was an error in the tool in that if the distance between points was greater than approximately 8 km, the distance reset to approximately 6 km despite it clearly being greater than that. To avoid the error, the distance was measured in two steps then added before the counter could reset. This resulted in less accurate measurements of distance between the fire front and the geographic centre, though it was not expected to greatly impact the results due to existing limitations of the methodology, detailed below. This issue did not appear with Fort McMurray, as the fire front appeared within 7 km of the geographic centre and did not prompt the distance counter to reset.

G6.1.3. Limitations of the methodology

When put into practice, there are severe limitations in the utility of this method for determining historical fire spread. One of the main limitations is in the data itself. CWFIS data is made from processing and combining season-to-date hotspot data[22]. Due to data limitations, NRCan advises that the perimeter estimates be seen as very rough estimates[22]. In addition, unlike NASA FIRMS' satellite hotspot data, CWIFS data within the .shp files in ArcGIS appear as separate polygons with no time of acquisition, and therefore, the greatest temporal resolution is assumed to be one day. NASA FIRMS hotspot data also has limitations, described in above sections. In relation to this methodology, the issue with the hotspot data is that it is not a fire front[24]. Multiple hotspots can be assumed to be a hotspot, but this is not certain. In addition, while the hotspots data in ArcGIS do have a time of acquisition, it was assumed that the hotspots at the time were the only areas actively burning. This, however, was hard to confirm, especially if the other actively burning areas were too small to be picked up by the satellite or were obscured.

Another issue is with the method of measuring the fire propagation. Radial distance from the geographic centre was chosen, as it is a method that can be applied to different case studies in a consistent manner. However, fire propagation is not always linear towards the centre, as demonstrated by the results from Fort McMurray. Viewed on its own, it appeared as if the fire front was moving away from the city, when in reality, it was moving closer to other outlying areas[30]. The methodology does not account for fire propagation or fire growth in directions away from the geographic centre, nor does it consider the inhabited areas of the city away from the centre which would be forced to evacuate if the fire front moved near it.

Additionally, the methodology did not properly account for multiple fires approaching the region, as shown with the results from Slave Lake. In Slave Lake, there were two wildfires, one to the west and another to the southeast. The southeast wildfire was the one to move into the town, and the distances measured were done using the southeast fire, except for the first day as the southeast fire was not yet detected. The western fire spread away from the town. However, if this methodology were applied to additional case studies where two or more fires were approaching a specified area, the appropriateness of using the closer fire would have to be reconsidered especially when the designation of "closest fire" is in flux. It also has implications in situations where the fire has curved around the region of concern as it may be difficult to determine which fire front should be used as the reference.

The results from this methodology also do not consider the many different factors that affect fire propagation. The rate of fire spread is dependent on many different factors including meteorological conditions, such as wind, topography of the area, and fuel characteristics[20]. While, those factors were not considered initially for simplification purposes, use of this methodology provided a misleading picture of how the fire propagated in the past case studies and its impact on the community.

G6.1.4. Implications for coupled model validation

The validation of models is key to determining their applicability and accuracy. While there is a movement to couple traffic, human and fire behaviour into a single evacuation modelling tool[13], validation of such a model has not yet been discussed in detail. Research gaps were noted in validation of fire models and human behaviour models regarding traffic behaviour in evacuations[13].

The results from the historical data collection have important implications for the use of previous wildfire data for validation use of coupled models. The methodology used had several limitations which make incorporating the results into traffic modelling questionable. It opens a wider discussion on how to use previous wildfire data to inform and validate models, if the fire behaviour depends on so many factors that were not incorporated into the methodology used in this project. Also, the question of how to validate coupled models if the fire sub-model cannot be properly validated with historical data must be considered. Wildfires continue to grow in number and severity; therefore, work should be done to try and develop methods to use the data collected from these events to inform and validate new and more accurate evacuation models.

G6.2. Traffic Modelling Scenario Expected Results

Comparing Scenarios 1 and Scenarios 2 and 3, it is expected that the evacuation times and queue lengths will decrease when staged evacuation is modelled. Scenarios 2 and 3 are expected to have faster evacuation times and queue lengths, since, unlike immediate evacuations, not all the cars will enter the road network at once. As across all scenarios, there is only a single egress route. Staging the evacuation is expected to lead to less congestion and faster evacuations. Between Scenario 2 and 3, it is expected that Scenario 3 will have shorter evacuation times, as the areas closest to the egress route will evacuate first. By the time the areas farthest from the exit begin to evacuate, the roads should be mostly clear of cars that left before them. However, in Scenario 2 where the cars farthest from the exit evacuate first, they might still be in the network when the other areas begin to evacuate, which may result in more congestion and a longer travel time than Scenario 3.

When comparing Scenario 1 to Scenarios 4 and 5, it is expected that the evacuation times increase when roads close. In addition, not all cars may be able to evacuate the cabin area successfully, due to road closures. Notably in Scenario 4, cars originating from the area at the top right-hand corner where the road closures will begin, may be unable to leave the network. It is anticipated that during Scenario 4, the queue length to the egress road may extend into the areas where the roads are being closed, which would represent the queue length at which fatalities due to the fire spread would occur. When comparing expected results from Scenario 5, it is expected that there will be more queue lines and longer evacuation times as roads will be closed randomly, potentially including the path to the egress route. Due to the randomness of the route closures, it is expected that unlike Scenario 4, where the route closures will begin away from the exit, route closures may occur closer to the egress route, which may result in more congestion.

G7. Conclusions and Future Work

In conclusion, while there has been work done on improving evacuation models and fire spread research, there remain knowledge gaps identified in Canada, as well as internationally. Those knowledge gaps include a lack of knowledge on integration of human, fire, and traffic behaviour into existing evacuation models, as well as a lack of knowledge of traffic behaviour during wildfire evacuations.

The fire progressions of the 2011 Slave Lake Fire and the 2016 Fort McMurray fire were determined using radial distance from the geographic centre of the communities. The methodology was found to have severe limitations that made it an unreliable method to calculate fire progression of past fires. The limitations included determining the accuracy of the fire perimeter from the satellite data itself, as well as limitations of the methodology, which did not consider parameters such as wind, topography, vegetation, or direction of fire spread due to complexity and time constraints. Therefore, the propagation data should not be used in traffic modelling until the methodology is improved.

Future work for this project includes completing the traffic modelling and testing different road network configurations. More research will be done to improve the methodology to determine fire propagation that more accurately reflects the rate of spread. Further work should be done to investigate how environmental conditions would affect the rate of fire propagation, which was not considered in the scope of this project, due to its complexity and time constraints.

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Appendix H: Experiential Assessment as an Alternative to Traditional Examinations in Engineering

Attached Paper:

Carton, H., and Gales, J. (2023). *Experiential Assessment as an Alternative to Traditional Examinations in Engineering*. CEEA 2023: Canadian Engineering Education Association Conference, Kelowna, British Columbia.

H1. Abstract

Following the return of in-class teaching, in-person experiential education activities can be once again considered. Herein, an experiential test (midterm) was constructed for a second year Civil Engineering Materials course in Canada. The midterm was held during the semester's reading week and students had one week to complete the assessment. The students visited an outdoor large central park in Toronto with written instructions to what they were to study on site. Questions were based on the student's examination of materials at the site and related to the six learning outcomes of the course with associated graduate learning attributes. These students were then to film their answers at the site and compile these videos for a group presentation-based submission. The graded results saw increased student perception and significance of learning outcomes in the course compared to written in-class midterms in the same course which demonstrated continual development of the course. Student feedback was considered for the development of future versions of this midterm.

Keywords: Experiential learning, Land acknowledgement, Civil Engineering, Student presentations, Student mental health, Academic integrity.

H2. Introduction

Assessments of student learning is a key component of education and are used to determine students' level of learning. Assessments are used to guide the course content, to assess individuals' competency in the content and to evaluate programs effectiveness [1]. Generally, examinations such as midterms and final exams fall under the second category to assess students' comprehension and competence with the material. Traditional written examinations are typically closed-book, set in a fixed time period and are the dominant method of assessment in higher education [2]. A review of traditional closed-book exams found that they are considered an efficient method of examination in how much content it can cover in one examination as well as being cost effective in its administration and marking [2]. However, traditional assessments have long been criticized for lacking authenticity and an emphasis on memorization over comprehension of material [2], [3].

Different methods of assessment have been explored as an alternative to traditional assessments. This shift has been occurring for a number of years, however, the Covid-19 pandemic exacerbated it as the traditional assessment format was not entirely feasible while public health measures such as social distancing and limiting public gatherings were in place [4]. Many educators used online examinations as a way to replicate the traditional examination format, however, some used it as an opportunity to use alternative forms of assessment to add flexibility and increase authenticity [4]. This was done with the intention to supplement traditional assessments, not replace them as it's argued that using a range of different assessment methods, as opposed to only one would be more beneficial for student learning [4, 5]. A study examining students' perceptions on different types of assessments found that students who were assessed with "learner-centered assessments" such as portfolios and team projects believed they were more effective and fairer than students who were assessed with more traditional methods [6].

An example of this process may incorporate experiential engagement with the curriculum. The Experiential Learning Cycle can be described as the cycle of a concrete experience (having an experience), reflective observation (reviewing the experience), abstract conceptualization (learning from the experience) and active experimentation (trying what you have learned) [7]. A study surveying assessment methods for courses that used experiential learning, found that there was some agreement between the teaching methodology and the assessment method where experiential components were assessed with experiential assessments [8]. Common forms of experiential assessment were project reports, presentations, and case-based exams, which can be used to relate theory to real-life situations. The Covid-19 pandemic, however, necessitated many Canadian engineering institutions move to deliver their courses entirely remotely. The virtual course delivery created a challenge in incorporating traditional hands-on and experiential learning opportunities for engineering students [4]. Following the return of in-class teaching, experiential education activities can be once again considered for teaching learning outcomes within engineering courses. The purpose of this study is to consider the renewed creation of novel experiential activities. In this case, specifically for Civil Engineering Material courses.

Civil Engineering Materials is a course which introduces students to various types of engineered materials which can be used for the design of the built environment such as landfills, buildings, roadways, transportation infrastructure etc. Its learning objectives are core to sustainability aspects of all materials with emphasis in their production and use.

The higher goal of this study is to integrate a modified, experiential- and project-based learning assessment as a replacement to traditional written examinations. Herein, an experiential midterm was constructed based upon the five learning outcomes as specified for a second year Civil Engineering Materials course. The midterm was held during the semester's reading week and students had one week to complete. The students were to visit an engineering site in Toronto (High Park -43° 38' 43.7460" N and 79° 27' 53.1072" W) and tasked with the creation of a video submission to demonstrate their comprehension of the questions that were asked. Questions were based on the student's examination of materials at the site and related to the five learning outcomes of the course and were largely qualitative in nature as is the course. The students were encouraged to construct a proper land acknowledgement as part of their submission based on the Indigenous history of the land they were visiting. Following the midterm, the students were given the option to informally provide feedback on how the midterm could be improved if they completed the assessment. This paper will explore this activity in an effort to promote renewed efforts by academics in creating experiential learning opportunities for their students. The study will also aid discussion for academics attempting to break away from the traditional exam model in lieu of project based learning successes in engineering.

H3. Experiential Assessment Development

H3.1. Graduate Attributes

All undergraduate engineering programs in Canada undergo accreditation by the Canadian Engineering Accreditation Board (CEAB) under Engineers Canada, where programs are evaluated for their academic quality [9]. Graduates of accredited engineering programs are eligible to begin the process of earning their professional engineering license while graduates of non-accredited programs must undergo additional assessment to prove their academic qualifications meet licensure requirements [10]. Engineering programs are required to demonstrate that graduates have specific attributes such as a knowledge base for engineering, problem solving, investigation and design through course learning objectives and graduate attribute indicators [9]. More specifically the accreditation process also requires that continual development of the curriculum is occurring, not just that a course meets the minimum calibration to learning outcomes and attributes. The data collected from the process is used to enhance and develop the course.

A brief comparison of this process can historically be considered. Appendix H.A illustrates two final exams that were obtained through a retired professor's personal library that was archived at Carleton University structures lab annex thirty years ago and found by the author during renovations in 2017. The former property of registered engineer W. Grueber was stored there and included educational materials dating back to the 1930s. This included textbooks and notes from his experience presumably as a student at the University of Saskatchewan in the 1930s. These materials predate the formation of CEAB by nearly 35 years. Among the articles present were two paper-based exams from the early 1930s. The exams and notes were digitized by the lead author. As observed, the exams were time-based and set for three hours, which today is still a common duration for exams. The examinations were based on the Structural Analysis course for which Civil Engineering Materials is traditionally a pre-requisite. On the topic of continual development, there is an opportunity to discuss that course within that context of an example, particularly how an equivalent course today uses experiential education as a method for developing the students' attributes. The contemporary course on structural analysis typically requires these attributes to be met: Knowledge Base, Problem Analysis, Investigation and the Use of Engineering Tools. The latter two were demonstrably not being met by the questions portrayed in Appendix H.A in these older exams. Though one might argue the use of engineering tables and 'slide rules' as being the tools for the day, the contemporary course utilises software and experiential engagement through lab-based exam problems. This is strictly an example of continual development within meeting attributes, however it does demonstrate that the development since 1930 is very marginal when one considers the pedagogy at achieving these graduate attributes and demonstrating continual development in education. Lab-based pedagogy for experiential learning was in use during the time these exams were prepared. Further, it can be remarked that the format and duration of civil engineering examinations has not demonstrably changed in nearly 100 years in Canadian engineering education.

H3.2. Experiential Learning Assessment

Motivated from lessons learned from student engagement, an experiential assessment was performed as a midterm for the author's Civil Engineering Materials course. The author has been teaching this course for ten years and this is not the first time this course has been reported at the Canadian Engineering Education Conference, previous activities to promote learning included the adaptation of case studies [11] and an experiential lab to promote learning of timber structures [12]. To continually improve the course, the midterm was conducted as an experiential assessment with the inclusion of an assessment analysis to determine if it positively impacted continual development.

Herein, an experiential midterm was constructed based upon the five learning outcomes as specified for a second year Civil Engineering Materials course: Knowledge Base, Problem Analysis, Design, Investigation and Communication (see Table 1 in Appendix H.C for details). The midterm was held during the fall semester's reading week and students had one week to complete the assessment. Appendix H.B details the midterm questions and format as it was given to the students. To ensure academic integrity of the midterm, all students had to physically film themselves at the site in question. These students were to visit an outdoor large central park in Toronto with written instructions to what they were to study on site. They were encouraged but not required to work in groups. Most students did form groups, with the exception of three students who chose to work individually due to personal preferences. The students would visit six sites which each contained a civil engineered structure and set of materials which made up said structure. These sites were identified on a map given to these students. Questions were based on the student's examination of materials at the site and related to the five learning outcomes of the course and were largely qualitative in nature as is the course, though light calculations were needed in some questions. The students were then to film their answers at the site and compile these videos for submission with a group presentation.

To account for accessibility and movement disabilities, those students were given the option of an alternative assessment if they identified as such. The site and grounds were accessible as defined by the park and transportation coming into the park and no students identified needing a related accommodation.

The midterm was designed for students to address the graduate attributes related to the course learning objectives. Some of the midterm questions fell under multiple graduate attributes (see Table H1 in Appendix H.C). For example, two of the graduate attributes are individual and teamwork abilities and communication skills which are assessed through the midterm format as students were able to work in a team and the submission format was a video presentation. As an experiential midterm, there was more freedom to evaluate graduate attributes such as investigation and communication skills than in a traditional written format. It has been found that authentic assessments allow for better evaluation of “soft” graduate attributes such as individual and teamwork, communication skills, and professionalism [13]. While, knowledge base and problem analysis can also be evaluated through traditional formats, as an experiential midterm, it allowed for students to be in the real-life environment to see the materials in use.

H3.3. Land Acknowledgement Significance

The midterm included two Indigenous sites where these students were instructed to film a proper and meaningful land acknowledgement as part of their submission. The land acknowledgement was worth one mark out of ten marks on the midterm. Land acknowledgements are an action to recognize the traditional territories of Indigenous peoples. The focus on land acknowledgements stems from the goal of reconciliation between settlers and Indigenous people, but simply acknowledging settler occupancy of Indigenous lands with a scripted sentence is considered void of connection, as well as any real action or change taking place [14]. A proper and meaningful land acknowledgement should bring to light the historical use of the land by Indigenous people and their stewardship, and the impact of settler colonialism including the forced suppression of Indigenous knowledge and the strength of Indigenous people [15].

One location included the site of a known Indigenous burial mound. The park also includes the rare Black Oak savannah ecosystem, which was the second location, which Indigenous peoples used for various purposes including food and medicine [16]. To preserve the savannah, the park has been conducting prescribed burns since 2000 (Figure 1), which encourages the growth of native species and reduces invasive species [17]. Prescribed burns, or Biinaakzigewok Anishnaabeg in Ojibway, are a form of Indigenous land management in fire-dependent environments [18,19]. Students were encouraged to use this knowledge as part of their land acknowledgment.

Introducing the detailed land acknowledgement requirement in the CIVL 2120 Midterm compelled students to pay tribute to the land and its original caretakers in a less superficial way as they were not allowed to use a scripted acknowledgement. By exploring the history of High Park without the ability to use the internet, students could clearly connect the past care of this land to how it is shaped today. Savannahs with prescribed burns, and burial grounds were first touched upon in class in order for students to elaborate on when they visited the site, as they executed self-guided learning. The exercise also offered the students the ability opportunity to move away from the concept of colonialized education methods, and towards a connection with the land and learning from it directly.

Figure H1: Prescribed burns at the park in 2023 a) during the burn and b) 6 days after the burn (courtesy E. Kennedy)

H4. Methods

Students were asked to provide voluntarily anonymous feedback about the midterm in order to improve future iterations and assess the immediate feasibility of a final exam of similar format. They were asked open-ended three questions: 1) what they liked about the midterm, 2) what they disliked about the midterm and 3) how the midterm could be improved. Student responses were recorded anonymously by the authors and then categorized under common themes for analysis for improvement of future iterations of the midterm as discussed herein. The collection of information was informal in nature and submitted without any identifiable information by physical paper in class.

To maintain consistency in evaluating grading, the midterm was not graded by the multiple teaching assistants as assigned in the class which can often be considered, in this case the professor performed all grading and compiling of assessment. The midterm grading was compared to past written exams in this course.

H5. Results

H5.1. Informal Midterm Feedback

Seventy-five students out of a maximum 82 students responded to at least one of the three questions. The majority of the students (48 responses) responded that they liked some part of the experiential aspect of the midterm. The students were familiar with the concept of experiential learning as in class they were briefed on the format of the midterm and how the structure takes an experiential form. These students indicated that they were able to visit the sites in-person. Students also specified that they enjoyed the applicability of the midterm and how they were able to see the engineered materials being used as part of an overall structure and recognize a system. The system aspect is beyond the scope of the current course but aligns with the design approach that they would see later in their studies. Students also enjoyed that the midterm was outside, with responses saying they liked that the site was a park, being in nature or getting “fresh air” in some form (13 responses). Some students who left the midterm for the last day would not respond in such a way as the grounds had heavy rainfall, which was mentioned in those survey responses. Other common responses were that they liked the midterm format, how it could be completed in groups and that it was a video submission that they had multiple days to work on. Five students remarked that they liked visiting and learning about the present and past Indigenous culture of the land which helped inform their land acknowledgement as part of their submission.

There were no mentions of disliking the experiential aspect of the midterm. There were some responses which students indicated that they disliked the video submission format. Some remarked that the unfamiliarity of the format discouraged them. Most responses that indicated dislike towards the midterm were related to the location of the site and the distance it takes to get to the site itself. Many students expressed they would have preferred a site closer to the campus. The time it takes to arrive at the site from campus via public transit is estimated as approximately 50 minutes. One site was located outside of the park and was specified by the students as a site they wished was replaced with a site in the park itself.

As reflected in the responses for what they disliked, the suggestions for improvements were largely focused on the location and suggesting having them closer to campus or for there to be less distance to travel. Five students specifically included the possibility of "accessibility" as a reason for their suggestion though indicated that this did not directly apply to them. While none of the responses stated they disliked the experiential aspect of the midterm, a few did suggest that they would prefer a traditional written assessment. Some stated that they believe the instructions could have been clearer with five students specifically saying they had difficulty finding the site locations from the directions included in the midterm alone.

H5.2. Midterm Grading and Academic Integrity

As part of the assessment, questions were based on the student's examination of materials at the site and related to the five learning outcomes of the course and were largely qualitative in nature in response. Marking of each of the questions technical content was based on five commonly used indicators of development of the assigned attribute: Poor, Below Expectations, Meets Expectations, Beyond Expectations, and Professional. Grading overall had the class on average be Beyond Expectations for the attributes measured. A portion of the grading was also assigned to the overall quality of the presentation communication of the response as it was a form of video learning following the same indicator scale. It was expected that the students demonstrate to teach the viewer about the attribute they were learning to show the comprehension. The graded results illustrated an increased student perception and significance of learning outcomes in the course compared to written in-class midterms in the same course prior to the Covid-19 online learning phase which demonstrated continual development of the course.

Academic integrity was a potential issue with one of the questions with the responses by the students, as they were not supposed to use external resources from the school. In the case of Question 4 (see Appendix H.B), ten students used a calculation procedure not taught in the course to describe the growth of wood in the environment (tree rings for example). The method was well referenced to online resources by the students. This was not considered exactly an integrity issue by the author but more of a communication barrier that the students were only to use their electronic classroom and not the internet for formulating answers. Subsequently following the midterm, the lecturer decided not to follow the experiential format for the final exam and instead assess the outcome of the midterm over a longer duration before utilizing the format again as planned in the future year. However, in addition to a final exam, students were required to complete an experiential final project where they would build a bridge out of popsicle sticks and glue.

H6. Discussion

This midterm was conducted in the context of the first full in-person semester since the Covid-19 pandemic began at York University. While the previous semester (Winter 2022) had began to transition back to in-person as of March 2022, the Fall 2022 semester was the first fully back to campus semester.

With regards to further effects of the Covid-19 pandemic on students, university students have reported an increase in stress and anxiety [20]. A study by Son et al. (2020) surveyed 195 students in higher education, and 71% of respondents reported that the pandemic had increased their levels of stress and anxiety overall. Even today, mental health of university students is questioned to be an overall concern in the return to fully on campus teaching and requires additional attention.

As such, the feedback from students indicated that they enjoyed the collaborative nature of the midterm as it was allowed to be completed in groups and seeing fellow students in their class in-person. The Covid-19 pandemic and subsequent public health restrictions negatively impacted students' socialization and their ability to interact with peers and instructors [21]. Some responses also remarked that it was the student's first time exploring that area of the city and many remarked enjoying being "in nature" and getting fresh air. As the midterm allowed for a week to work on it, some student responses noted that they found the midterm format less stressful than a traditional three-hour written exam. The lecturer determined that while the midterm was effective in achieving desired learning goals, the format needed at the time more careful feedback analysis before incorporation as a final exam which was not possible during the term. The final exam would remain a traditional format, it was decided by the lecturer not to hold the exam as three hours and reduce the length of the exam in size and timing to half of that measure. Additional research should be done into the educational pedagogical value of a three hour exam which has been the tradition in Canadian engineering education.

Five students mentioned in the survey that they enjoyed the inclusion of Indigenous sites which informed their land acknowledgement. Only one student responded that they disliked it, however, it was noted by them as to the inability to access external sources to inform the land acknowledgement, and not because of its inclusion as a requirement.

H7. Future Research and Conclusions

In conclusion, the use of an experiential midterm was found to be an effective method of assessing students' knowledge and understanding. Anonymous and informal student feedback found that many enjoyed the experiential format of the assessment, the extended duration to work on it and the ability to work in groups. However, many students disliked the amount of time it took to get to the specified locations and as such, their suggestions for improvement largely centered around choosing locations closer to campus.

The following recommendations are needed when considering a similar midterm format in the future, though these are not inclusive of all issues. Primarily, accessibility needs consideration in the selection of the site. In the case of this midterm, the site was connected to an accessible subway line, and the path into the site made accessible. This may not be the case for all civil engineering sites a lecturer may decide to rely upon. While students may feel that the site is accessible, the overall size of the site can bring kinesthetic barriers to those not used to walking for long periods. Weather can also be an issue. Accessibility should not be only limited to mobility but by the phrasing of questions, more visualizations in questions would aid this process for student engagement, particularly those who experience dyslexia or similar barriers in exams [22].

Academic integrity needs strong consideration in the future, though this is also a challenge with in-person assessments. While the physical visitation of the site and proof that the students did attend the site can help alleviate this concern, group-to-group communication is still possible as well as internet consideration. There is a parallel issue in physically being at the site all the time to proctor, in that if this is employed and the time on the site allowed to the students potentially reduced to ensure invigilation, the benefit of having open ended time is affected and the mental health gains will not be realized for the students.

A specific future recommendation is the use of a survey that is structured so that the responses are not as leading and would enhance academic assessment of experiential learning in general, though this was not the immediate goal of this study. Additionally, following the progress of students who take this course to determine long-term understanding and impact of experiential assessment is a future consideration, though, outside of the scope of this study.

H8. Acknowledgements

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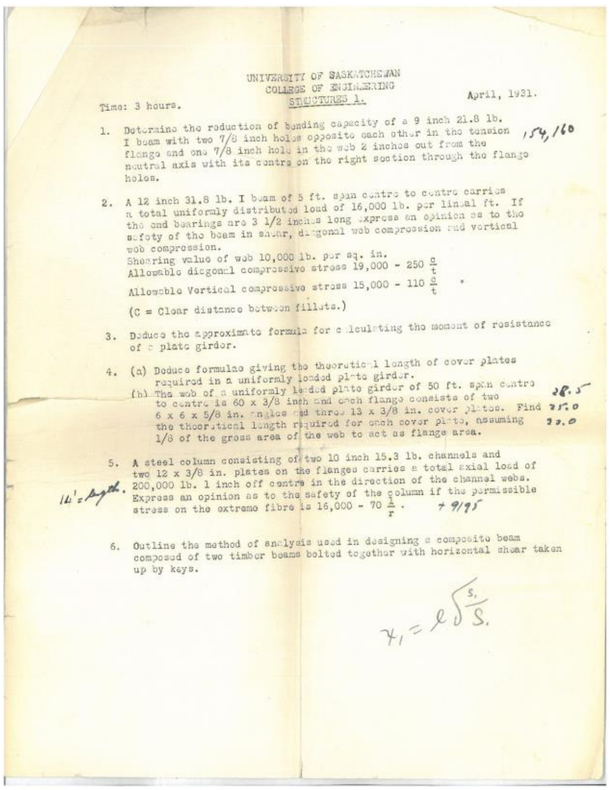
H10. Appendix H.A: Traditional Exam



UNIVERSITY OF SASKATCHEWAN
COLLEGE OF ENGINEERING
STRUCTURES 1.

Time: 3 hours. April, 1931.

1. Determine the reduction of bending capacity of a 9 inch 21.8 lb. I beam with two 7/8 inch holes opposite each other in the tension flange and one 7/8 inch hole in the web 2 inches out from the neutral axis with its centre on the right section through the flange holes.

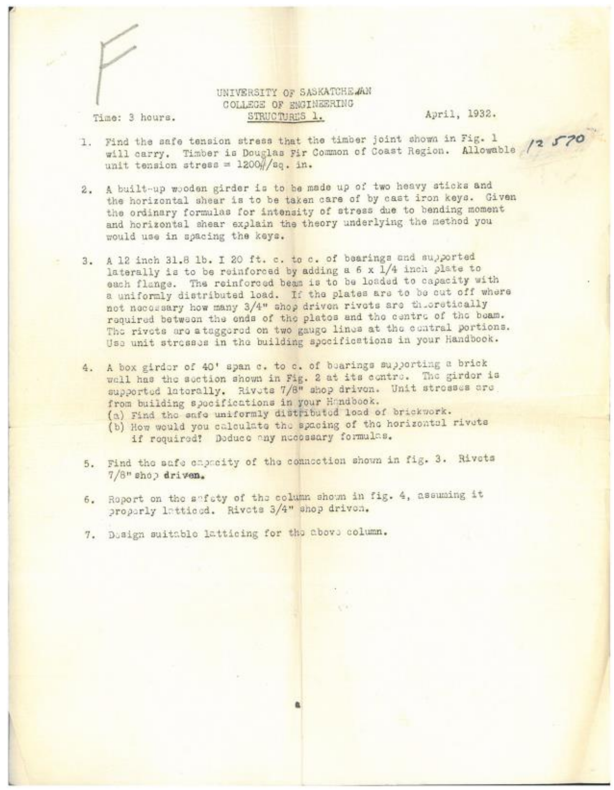
2. A 12 inch 31.8 lb. I beam of 5 ft. span centre to centre carries a total uniformly distributed load of 16,000 lb. per lineal ft. If the end bearings are 3 1/2 inches long express an opinion as to the safety of the beam in shear, diagonal web compression and vertical web compression.
Shearing value of web 10,000 lb. per sq. in.
Allowable diagonal compressive stress 19,000 - 250 $\frac{c}{t}$
Allowable Vertical compressive stress 15,000 - 110 $\frac{c}{t}$
(C = Clear distance between fillets.)

3. Deduce the approximate formula for calculating the moment of resistance of a plate girder.

4. (a) Deduce formulae giving the theoretical length of cover plates required in a uniformly loaded plate girder.
(b) The web of a uniformly loaded plate girder of 50 ft. span centre to centre is 60 x 3/8 inch and each flange consists of two 6 x 6 x 5/8 in. angles and three 13 x 3/8 in. cover plates. Find the theoretical length required for each cover plate, assuming 1/8 of the gross area of the web to act as flange area.

5. A steel column consisting of two 10 inch 15.3 lb. channels and two 12 x 3/8 in. plates on the flanges carries a total axial load of 200,000 lb. 1 inch off centre in the direction of the channel webs. Express an opinion as to the safety of the column if the permissible stress on the extreme fibre is 16,000 - 70 $\frac{l}{r}$.

6. Outline the method of analysis used in designing a composite beam composed of two timber beams bolted together with horizontal shear taken up by keys.



UNIVERSITY OF SASKATCHEWAN
COLLEGE OF ENGINEERING
STRUCTURES 1.

Time: 3 hours. April, 1932.

1. Find the safe tension stress that the timber joint shown in Fig. 1 will carry. Timber is Douglas Fir Common of Coast Region. Allowable unit tension stress = 1200#/sq. in.

2. A built-up wooden girder is to be made up of two heavy sticks and the horizontal shear is to be taken care of by cast iron keys. Given the ordinary formulas for intensity of stress due to bending moment and horizontal shear explain the theory underlying the method you would use in spacing the keys.

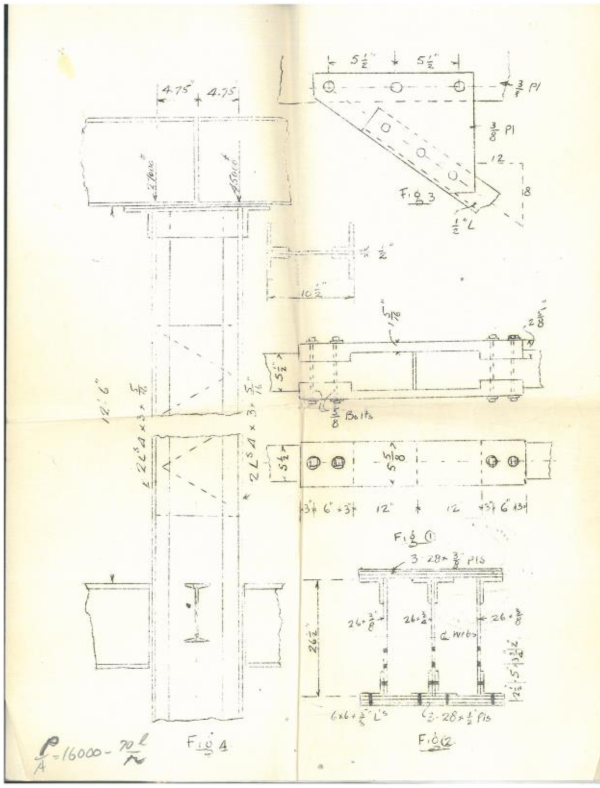
3. A 12 inch 31.8 lb. I 20 ft. c. to c. of bearings and supported laterally is to be reinforced by adding a 6 x 1/4 inch plate to each flange. The reinforced beam is to be loaded to capacity with a uniformly distributed load. If the plates are to be cut off where not necessary how many 3/4" shop driven rivets are theoretically required between the ends of the plates and the centre of the beam. The rivets are staggered on two gauge lines at the central portions. Use unit stresses in the building specifications in your Handbook.

4. A box girder of 40' span c. to c. of bearings supporting a brick wall has the section shown in Fig. 2 at its centre. The girder is supported laterally. Rivets 7/8" shop driven. Unit stresses are from building specifications in your Handbook.
(a) Find the safe uniformly distributed load of brickwork.
(b) How would you calculate the spacing of the horizontal rivets if required? Deduce any necessary formulas.

5. Find the safe capacity of the connection shown in fig. 3. Rivets 7/8" shop driven.

6. Report on the safety of the column shown in fig. 4, assuming it properly latticed. Rivets 3/4" shop driven.

7. Design suitable latticing for the above column.



H11. Appendix H.B: Experiential Exam

Introduction:

There are two main outcomes that the course gives you. The first is that it opens your eyes to civil engineering materials around you. The second is that it emphasizes why an engineered material would be chosen in a given design situation. The latter draws upon aspects of material and structural properties themselves as well as other aspects which may lead a designer to select a specific material - for example its economy and sustainability.

For this midterm you will visit High Park (Figure 1, and Figure 2) and Humber Bay Arch Bridge (Figure 3), both located in Central Toronto. The below maps exemplify several structures which would require specific selection or study of materials.

For High Park it is accessible by subway using Line 2 (disembark at Keele Station and head south). There are many lunch options nearby. It is recommended to start the midterm by entering in Site A.

Site D and G are not part of this version of the midterm. You do not need to document these sites. There are washrooms near Site E2 and the café.

Site E and E2 have significant indigenous history though lack significant markers. Site E represents a claimed burial mound called 'Snake' Mound. Site E2 represents a savanna and animal clearing called Hawks Hill. To maintain a savanna, controlled burns (wildfires) are held and are intended to create grassland where fruit/berries and vegetation for medicine would cultivate and suitable clearings for hunting would emerge. Without these carefully designed controlled burns, the savanna would grow to become a dense forest. The existence of the savanna gives evidence of indigenous past presence in the area. Visiting these sites may aid your creation of a proper land acknowledgement without the use of external resources as the exam is closed book.

You will answer the following questions in your filmed presentation (Q1-Q5).

Figure 1. High Park, Toronto

Take Home Midterm 2022

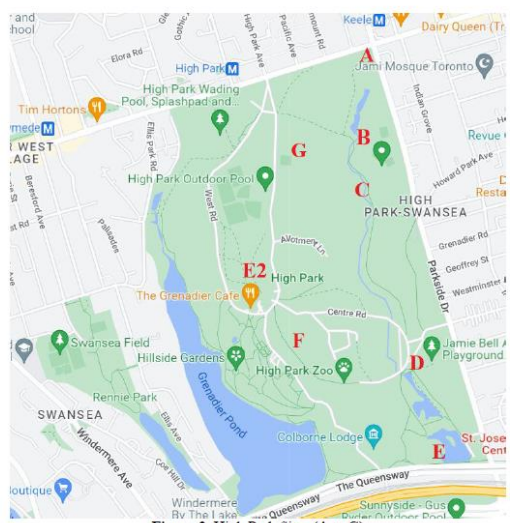


Figure 2. High Park Sites (A to G)

CIVL 2120: Civil Engineering Materials
Take Home Midterm 2022

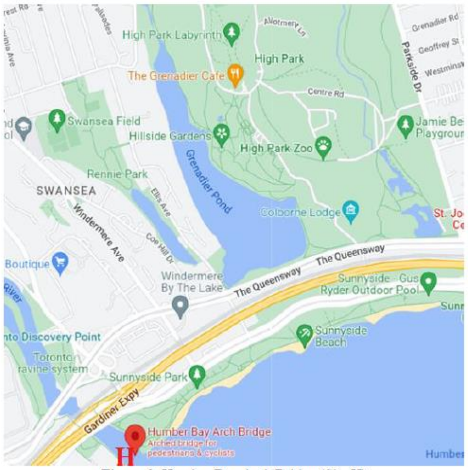


Figure 3. Humber Bay Arch Bridge (Site H)

Questions:

Q1. *(1 mark)* As you enter the park near Site A, a description pertaining to the soil conditions is present on a sign. What is the soil type that may be found at the park? *(Note: The soil type is important because it will determine the sizing of structures that may be found in the site. This will be discussed more at length in the module on soils in the second half of the course).*

Q2. *(1 mark)* For Site B, there exists a spillway near the retention pond which then drains under two bridges (a concrete and a timber bridge). A spillway controls the amount of water which drains down a stream. While observing the area (without entering the spillway) answer the following:
(a) What engineering materials besides concrete make this spillway? *(this does not include the bridges, there are at least two different materials besides concrete)*
(b) Describe why concrete would be used opposed to steel and timber as the primary engineering material of the spillway?
(c) Describe the mix design constituents necessary for this concrete to be used as a spillway. *(ex, type of cement, gradation of aggregate, and any admixtures/additives)*
(d) Produce a stress strain diagram of concrete that is properly formatted and labeled using realistic material property values that may be encountered in concrete of the spillway (*create this in excel as your own graph using known material properties and deformation trends assuming it is developed using load rate control in compression testing*).

Q3. *(1 mark)* For Site C, there exists a pedestrian bridge.
(a) What engineering materials is the pedestrian bridge deck made of?
(b) What is a benefit and disadvantage of these engineering materials in this use at Site C?

Q4. *(1 mark)* For Site F, there is a tree stump in the 'Zoo' on the east walk-way. The tree was cut down sometime in the last ten years due to internal rot. The tree is shown as it appeared in 2012 in Figure 4. The tree stump is of significant diameter and some actually climb into it today (don't do this its gross in there!). Hypothesize the former tree's age when it was cut down using a tape measure and a justifiable explanation to how you approximated its age.

Figure 4. Tree in question prior to cutting down. The inner portion should now be examinable

Q5. *(1 mark)* For Site H, there exists a pedestrian and cycling bridge *(Site H is a distance walk from the park though the shoreline area, the shoreline walk which gives excellent panoramas of high-rise concrete structures in the distance, refer to Figure 3 for location).*
(a) The deck of the Humber Bay bridge is being supported from above by what type of engineered material (*be as specific as you can*)?
(b) How is this engineered material made?
(c) What would the expected material properties of this supporting engineered material be? Include a stress strain diagram that is properly formatted and labeled to support your answer *(create this in excel as your own graph using known material properties and deformation trends).*

H12. Appendix H.C: Graduate Attributes and the Midterm

Table H1: Engineering materials graduate attributes and their associated midterm questions

CEAB Graduate Attribute	**CEAB Graduate Attribute Indicators**	**Corresponding Type of Midterm Question(s)**
Knowledge Base	• Identify the basic physical, chemical and other processes underlying engineering problems	• Identify the materials used in a given structure, or identify the soil type • Why would these materials be used • What are the benefits and disadvantages of the materials • How is a given material made

CEAB Graduate Attribute	**CEAB Graduate Attribute Indicators**	**Corresponding Type of Midterm Question(s)**
Problem Analysis	• Identify the problem variables, unknowns and constraints • Evaluate underlying assumptions and arguments used to simplify and formulate a problem	• Why would these materials be used • What are the benefits and disadvantages of the materials • Describe the mix design necessary for a specific purpose
Design	• Apply applicable codes and standards to an engineering design project	• Describe the mix design necessary for a specific purpose
Investigation	• Conduct and experiment to investigate complex problems • Evaluate incomplete and ambiguous data produced in experimentation • Draw valid conclusions that are supported by data and problem context	• Determine the age of a tree from its stump using a tape measure
Communication	• Clearly present information, professional engineering charts, tables, graphs and diagrams within a report or design document	• Answers to questions must be submitted in a video format with a specified total time limit