Transportation Vulnerability Analysis for Wildfire Evacuations

by

Abdullah Al Zahid

A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science

in

TRANSPORTATION ENGINEERING

Department of Civil and Environmental Engineering

University of Alberta

ABSTRACT

Wildfires are a natural part of Canadian ecosystems, but sometimes pose a threat to people. In Canada, when public safety is threatened by a wildfire encroaching into the wildland-urban interface (WUI), local authorities will typically recommend and lead evacuation of the area. During evacuations, roadway egress capacity has an important influence on evacuation efficacy. If the fire spreads quickly toward the community and egress capacity is insufficient, public safety can be compromised. We identify communities in Alberta (a province in western Canada) that are vulnerable to wildfire due to the configuration of the transportation network in relation to surrounding wildfire potential. Based on the existing literature, we first used metrics applied in Geographic Information Systems (i.e., GIS) to identify communities that are vulnerable for wildfire evacuation due to the geometric layout of their surrounding road network. Then to perform our analysis, 21 potentially vulnerable communities were selected based on expert input. We plotted fire hazard and transportation facility capacities for each community, and coupled and compared estimated fire travel times and evacuation travel times in a directional, scenario-based approach, to understand the potential for community egress against fire encroachment. Our results show that some communities (mainly within the boreal forest and Rocky Mountain foothills) have egress routes highly exposed to potential fire. Our findings also indicate that evacuation timing for some larger communities may be considered for further investigations, given relationships between estimated fire travel times and evacuation times. This work contributes an interdisciplinary assessment of community directional vulnerabilities for wildfire evacuation, bringing together wildland fire science and transportation engineering. To bridge research and practice, the results are presented in an interactive online map, and can be used to inform evacuation preparedness planning and proactive mitigation efforts.

Keywords: Wildfire, evacuation, remote communities, directional fire vulnerability, road network, Alberta

PREFACE

This thesis is an original work by Abdullah Al Zahid. The research included in Chapters 5 and 6 is currently submitted for presentation at the TRB Annual Meeting, entitled as "Directional Analysis of Community Wildfire Evacuation Capabilities" and co-authored by Abdullah Al Zahid, Dr. Amy M. Kim and Dr. Jennifer L. Beverly; this paper is currently under review. The author acknowledges the work of Air Forbes (manuscript in preparation) in providing radial graphs of directional fire exposure in the analysis described in Chapter 5, directional fire spread rates in the analysis described in Chapter 6 and in identifying the 21 communities suitable for the analysis in Chapters 5 and 6.

Disclaimer: *This work is one part of a larger academic work in progress, and was developed with many major assumptions as part of an academic study towards an MSc degree. It is not to be used for decision making.*

DEDICATION

I dedicate my contribution to this thesis work to my parents.

ACKNOWLEDGEMENTS

I am grateful for the guidance of my supervisors, Dr. Amy Kim and Dr. Jen Beverly. They gave me the freedom to explore new ideas and their guidance helped me to grow as a new researcher. They are always true inspirations for me and I couldn't expect more from them as mentors. Especially, at the very starting phase of this degree program, I lost my father and the Covid-19 pandemic started. So it was challenging for me to adjust mentally in a new country. I am extremely grateful to my supervisors for their relentless support during this difficult period. Without their support, it wouldn't be possible for me to continue my studies and complete this degree. I am grateful for the financial support from Canada Wildfire NSERC Strategic Network and Autonomous Systems Initiative. I would also like to thank Dr. Karim El-Basyouny, Dr. Tae J. Kwon, Dr. Tony Qiu, and Dr. Emily Grisé who through their courses enabled me to pursue this study.

I would like to thank Sabrena Jahan Ohi for her advice, help and guidance at various phases of this research. She was always the one whom I used to reach for any quick advice before reaching to my supervisors. Special thanks to Air Forbes for her contribution to this research. I am grateful to my fellow graduate colleagues for their social support during this research. In particular, I would like to thank Sudip Barua, Moein Sadeghi, Jianjing Jin, Kaleab Woldeyohannes Yirgu, Bryan Tran, Vivienne Li, Can Zhang, Mudasser Seraj Rafi, Tasnia Nowrin, Richard (Siqi) Mo, Sonja Leverkus, Brett Stewart, Kennedy Korkola, Sidra Ijaz Khan, Jared Randall and Andrew Stack.

I would like to thank my parents and sisters, who have always been there for me. I would also like to convey my gratitude to Almighty Allah. Finally, University of Alberta is located on Treaty 6 territory, traditional meeting ground and home for many indigenous peoples. I respect the histories, languages, and cultures of First Nations, Métis, Inuit, and all First Peoples of Canada, whose presence continues to enrich the vibrant community in Alberta.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1. INTRODUCTION

1.1 Background and Motivation

Wildfire is a natural phenomenon in Canadian ecosystems that sometimes poses a threat to public safety. Scientists are predicting more frequent and intense wildfires due to a growing prevalence of extreme fire weather, in turn, induced by climate change (Barbero et al., 2015; Wotton et al., 2017; Hanes et al., 2019). As a result, the number of wildfire evacuations is also increasing. In Canada, annual evacuee numbers have increased since 1980, with 0.713 homes lost for every 100 people evacuated (Beverly & Bothwell, 2010; Government of Canada, 2021). Wong et al. (2020) reported that over one million people had to evacuate from California wildfires in 2017 and 2019. Most fire management agencies in Canada aim to ensure the protection of people and rely on evacuations when public safety is threatened due to wildfire (Beverly & Bothwell, 2011). Not all wildfires pose a threat to communities and prompt evacuations. Only a small fraction of fires cause safety issues, typically due to their proximity to populated areas coupled with fire intensities and rates of spread that exceed suppression capabilities.

Accordingly, it is important for communities to understand their vulnerabilities during wildfire emergency situations that prompt evacuation – specifically considering roadway configurations and transportation accessibility in relation to surrounding wildfire potential. This information is necessary for developing evacuation plans, but can also inform community fire protection and transportation infrastructure investment strategies towards community safety. Road network capacity can be critical to how evacuations unfold and whether or not residents are successfully and safely evacuated. If a fire moves quickly towards a community and available road capacity is insufficient to accommodate citizens' egress, possibly reduced due to fire-induced road closures, this can lead to travel delays (Zimmerman et al., 2007), gridlock, or, in the worst-case scenario, entrapment (Grajdura & Niemeier, 2022). In 2016, the Horse River Fire (also called the Fort McMurray Wildfire) in Fort McMurray, Alberta caused an estimated 88,000 people to evacuate. Despite unplanned contraflow and extensive use of air evacuation, a report published on the event indicated that the evacuation would have been even more complex if Highway 63 had not been expanded to four lanes and improved a few weeks before the fire (*Institute for Catastrophic Loss and Reduction*, 2019).

The transportation capabilities of other communities beyond Fort McMurray should be assessed, in relation to the potential for wildfire in the surrounding landscape, in order to determine which communities need further resources and attention to expand their evacuation capabilities, possibly through expansion of evacuation capacity or “Fire Smart” measures such as vegetation management and fire precautionary measures (*FireSmart,* 2001). This is challenging as both evacuation and wildfires are uncertain, dynamic, and dependent on many factors. Also, when a fire encroaches on a community, it can prompt road closures that restrict or eliminate possible evacuation routes. Wildfire evacuation decisions in Canada involve the interaction and coordination of multiple agencies that will depend on the characteristics of the fire and the location and size of the population to be evacuated, thus making it administratively and operationally complex (Beverly & Bothwell, 2011). Different agencies engaged in wildfire need to know how road closures could affect evacuation, and for a specific community, which fire spread directions could cause road closures, leading to longer egress durations and requiring earlier evacuation orders.

1.2 Research Questions

Wildfire impacts on a community will depend on the trajectory and size of a fire as it encroaches on the built environment. If the fire environment (i.e., fuel, weather and topography) supports fast rates of spread along the fire’s trajectory, the time available to evacuate will be limited, causing a short to no-notice evacuation order. This sudden rush to leave the community can create traffic gridlock, resulting in delays (Chen et al., 2020). In this study, the following research questions were investigated within that context:

1) Which communities may have less potential to quickly and safely evacuate due to the geometric layout of the surrounding road networks, combined with wildfire potential, thereby rendering them more vulnerable?

We will answer the above question by performing a GIS-based analysis using metrics describing the road network and wildfire potential. From this step, we identify communities in fire-prone areas that would be suitable for transportation analysis of evacuation scenarios in the following steps (i.e., locations where future evacuations are possible due to the high levels of hazardous fuels surrounding the community, combined with limited evacuation routes). This work is contained in Chapter 4.

2) Which fire trajectories (i.e., from which direction) into a given community will necessitate a rapid or time-limited response due to road closures and resulting reduced community roadway capacity?

We will answer the above question by plotting roadways and their capacities together with potential fire pathways identified in a prior study. From this step, we will identify roadways that are most likely to be under threat of closure due to proximity to fire pathways, and their contributions to the total community egress capacity. This work is contained in Chapter 5.

3) For a given community and a given situation (i.e., trajectory of encroachment, fire weather conditions) and assuming the fire is a given distance away from the community and an evacuation is ordered, can the fire reach the community before it is evacuated?

We will answer the above question by coupling minimum fire travel time along all possible trajectories into the community with simulated evacuation times. From this step, we will identify if a fire encroaching along a given trajectory can reach the community before it has been evacuated. Details of the approach are provided in Chapter 6.

1.3 Main Research Objective and Tasks

The main objective of this research is to develop tools that can be applied to identify communities that are vulnerable during wildfire evacuation, due to the directional orientation and capacity of the transportation network combined with surrounding community fire exposure and potential fire travel times. Research questions are answered in three steps, which each correspond to Chapters 4, 5 and 6. A simplified conceptual diagram of the steps involved in different chapters is presented in Figure 1.1. Chapter 2 reviews the related literature and Chapter 3 describes the data sources used for the analysis. The thesis is concluded in Chapter 7.

Chapter 4 addresses our first research question. We performed an analysis in GIS to identify communities in Alberta that are both highly exposed to potential wildfires and potentially vulnerable during evacuations due to limited road capacity. In total, 21 communities were selected for analysis based on the analysis described in Chapter 4 (10 communities) combined with those chosen with expert input (11 additional communities, personal communication [Air Forbes, May 18 2021]).

Chapter 5 addresses our second research question. Circular plots of 360 degrees showing fire exposure identified in a previous study (Beverly & Forbes, *in review*) and road capacities are plotted to identify directional vulnerability with respect to evacuations. Our analysis from this step shows that some communities (e.g., Rainbow Lake and Swan Hills) have directional zones around them with limited evacuation routes and high fire exposure. The analysis identifies directions around the community where wildfire safety improvement measures can be prioritized.

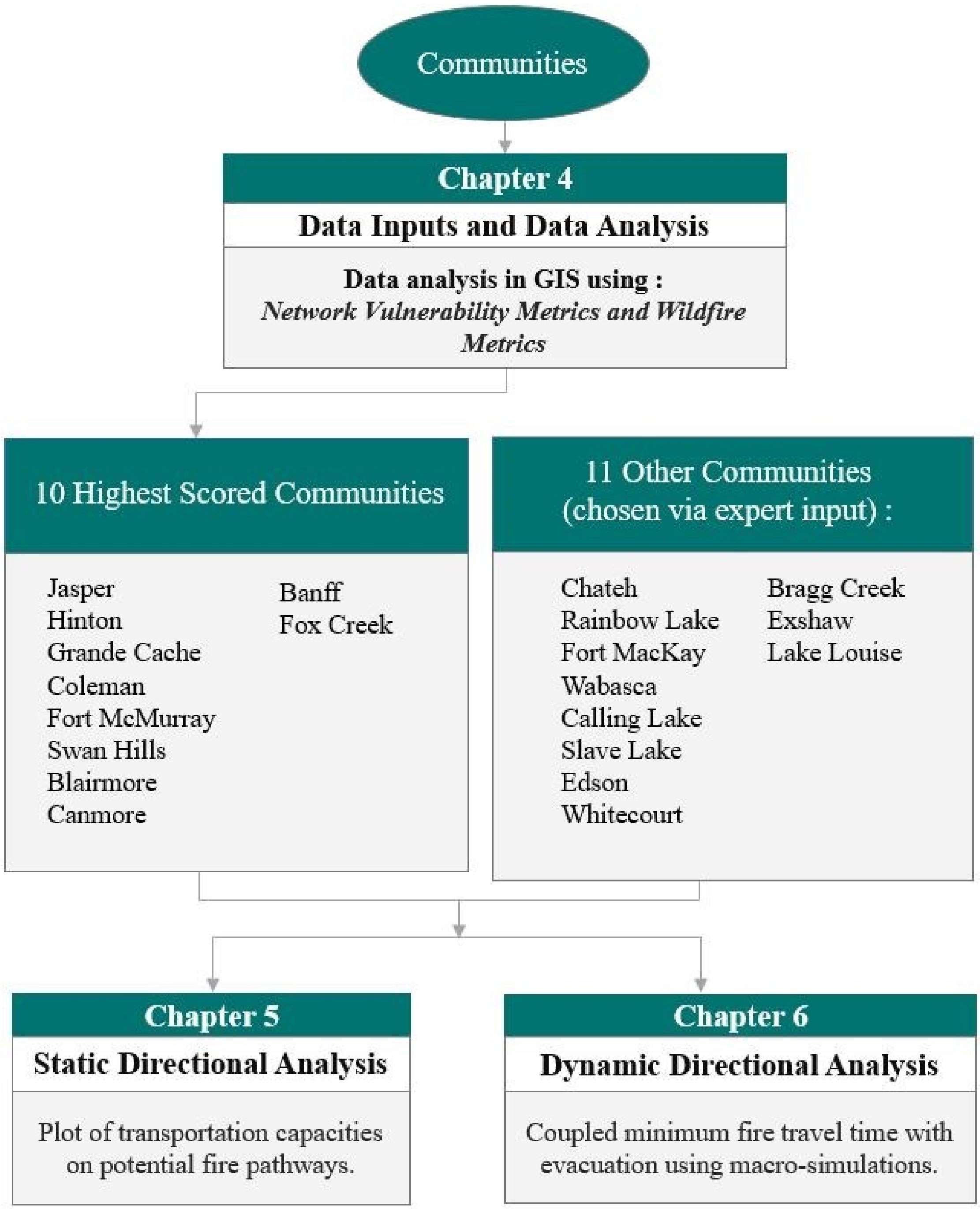

Figure 1.1: Thesis Overview

To answer our third research question (Chapter 6), we compared the results of macrosimulation against minimum fire travel times from 5 km radial distance to the community center (10 km to 5 km for larger communities).

Finally, the results of these three steps are combined, compared, and represented in an interactive web platform, which can help decision-makers evaluate and prioritize community safety measures.

CHAPTER 2. LITERATURE REVIEW

Section 2.1 briefly discusses the differences in emergency planning and evacuation studies for different disasters, with a focus on wildfire evacuation studies. Section 2.2 provides definitions of the key terms in the literature. Section 2.3 discusses different measures of transport evacuation modelling and 2.4 discusses fire hazards modelling. Finally, Section 2.5 summarizes and shows the gap in the literature where our work contributes to wildfire evacuation studies.

2.1 Introduction

In an emergency, the standard protective actions are to either shelter in place (SIP) or evacuate (Cova et al., 2011). The type of protective action taken varies by geographic region, hazard type, context and local conventions. For example, in Australia, the primary protective action is to "Stay and Defend" (McNeill et al., 2015; Tibbits & Whittaker, 2007), whereas in North America, evacuations predominate (Drews et al., 2014; McCaffrey et al., 2017). Evacuations can be classified as mandatory, recommended or voluntary (Rasid et al., 2000).

Evacuation of a community can be caused by many reasons, including but not limited to hurricane, nuclear accident, flood, earthquake, volcanic eruption, or wildfire. Early evacuation studies were focused on nuclear power plant emergencies due to the 1979 Three Mile Island reactor incident that occurred in Pennsylvania, US (Pel et al., 2012). However, after a series of devastating hurricanes in the 1990s impacted coastal communities in the US, many evacuation studies shifted to hurricane contexts. Likewise, after the 9/11 terrorist attack, mass evacuation due to terrorist attacks became a focus (Pel et al., 2012). In recent years, climate change has shifted the focus yet again to flood and wildfire-related contexts (Intini et al., 2019b; Jolly et al., 2015) .

Duration and other elements of an evacuation will vary due to the underlying cause. Hurricane evacuations usually encompass larger areas than wildfire or flash flood evacuations. Also, in hurricanes, emergency management and weather agencies are able to provide evacuation warnings several days to weeks prior, whereas wildfire or nuclear accidents cause evacuation with a shorter lead time. Wildfire evacuations are usually within hours or without any notice (called no-notice) due to uncertainties associated with fire ignition and spread (Demange et al., 2020). Thus, evacuation studies that address different evacuation contexts can be expected to differ and models developed for one evacuation context would not necessarily be appropriate for another.

2.2 Definitions

Our study focuses on the transportation network in evacuation studies and some terms are commonly used in the literature, such as transportation network vulnerability and resilience. Also, in different chapters of this thesis, we used wildfire evacuation related terms such as wildland urban interface (WUI) and trigger buffer. There are many definitions of these terms in the literature. Below we define some of the common ones used in emergency planning and evacuation studies referenced in our literature review.

Vulnerability: Multiple factors can influence the vulnerability of an affected population, and collectively, contribute to the community's overall vulnerability. These factors will vary depending on community size, evacuee’s response and fire behavior.

Erath et al. (2009) defined road network vulnerability as the multiplication of the probability of experiencing a critical situation and the induced consequences, and they focused on transportation link failurerelated consequences across the road network. Furno et al. (2018) defined transportation system vulnerability as the limitation of the road network to absorb and react to the situations brought on by adverse events. These definitions acknowledge that community vulnerability with respect to transportation system and service varies based on the purpose of the work. For our analysis, we are looking to ascertain the vulnerability of a community with respect to wildfire evacuee transport, based on the possibility of facing a critical situation while evacuating due to limited capability of the available roads to accommodate evacuation – particularly in the event of a wildfire blocking roadways.

Wildland-Urban Interface (WUI): WUI is defined as the area where built environment and the wildland vegetation meet (Butler, 1974), or where human inhabitants and the wildland vegetation start to interact (Radeloff et al., 2005). Due to the presence of people and human developments, WUI areas are associated with an increased likelihood of human-caused fire ignitions, and wildfires in these areas pose a threat to public safety and values (Calkin et al., 2014; Radeloff et al., 2018; Syphard et al., 2007). The WUI area is increasing with growing populations, causing amplification of the wildfire-related human risk in North America (Bénichou et al., 2021; Intini et al., 2020).

Trigger buffer: A trigger buffer results when lines are drawn to connect a predefined set of fixed points encircling a community. When a spreading fire front arrives at any point on a community's trigger buffer line, an evacuation recommendation is activated (Cova et al., 2005). Trigger buffers often consist of prominent geographic or landscape features such as rivers, bridges, or roads used to define the timing of a recommended evacuation order.

2.3 Transport Evacuation Modelling

The earliest evacuation models calculated trigger point distances, forming a buffer around a community called a "trigger buffer." The U.S. Federal Emergency Management Agency (FEMA) developed a GIS model to estimate the trigger buffer for coastal areas for hurricane-caused evacuations (FEMA 2000). They applied the "decision arc" concept to identify the trigger buffer boundary. Similarly for wildfire, Cova et al. (2005) used fire spread modeling, GIS, and evacuation timing assumptions from interviewed experts to estimate evacuation trigger buffers. In another paper, the Wildland-Urban Interface Evacuation (WUIVAC) model was applied in different scenarios (Dennison et al., 2007). Larsen et al. (2011) evaluated the WUIVAC model using the 2003 Cedar Fire (Larsen et al., 2011). However, these approaches were still lacking to address how the evacuation time can vary based on the urgency to evacuate.

Later, the WUIVAC model was combined with a spatiotemporal GIS approach with traffic simulation (Li et al., 2019). First using traffic simulation to estimate the total evacuation time, then producing probability-based trigger buffers, and finally combining the results of the two. In that study, the evacuation traffic simulation was done independent of the fire modeling, although the urgency to evacuate or type of evacuation notification (i.e., alert or mandatory order) depends on the fire's proximity and rate of spread.

2.3.1 Simulation of Transport Movement in Wildfire Evacuation Studies

A common approach to model and assess a community evacuation due to wildfire is to use simulation, which are used for both wildfire spread and traffic evacuation models (Gwynne et al., 2019; Intini et al., 2019). These models are used for evacuation planning purposes, modelling the potential outcomes of different fire and evacuation scenarios. Traffic simulations are used to estimate how the evacuation may occur based on evacuee decisions and response, hazard characteristics, transportation infrastructure, and evacuation decisions (Wahlqvist et al., 2021).

Traffic models are classified as macroscopic, mesoscopic, and microscopic. Microscopic simulations represent individual vehicles, with models of how vehicle behave in the presence of infrastructure, other vehicles, and how they change lanes. Because these models are computationally intensive, they are typically applied when focusing on small geographic areas or specific transportation facilities, when greater detail about vehicle movements is desired (Intini et al., 2019; Burghout, 2005). Macroscopic models are usually preferred for large and/or complex spatial contexts where individual vehicle characteristics are less important, as they are computationally less intensive. Vehicles are represented on an aggregate level, such that vehicle representation is simplified and level of detail is low (Burghout, 2005). Macroscopic traffic simulation models represent vehicles in homogenous groups by the basic descriptors of speed, flow and density – and do not consider vehicles individually. Often this is analogous to fluid or gas flow phenomena, and the equations derived for these flows are used. The most common macroscopic model used in the traffic stream analysis is the Lighthill, Whitham, and Richards (LWR) model, also called a hydrodynamic model (Lighthill & Whitham, 1955). The LWR model can be used for analytical solutions for a single segment of a roadway; however, when temporal and spatial interaction of traffic flow exists, the solution method is typically simulation.

Wahlqvist et al. (2021), in the WUI-NITY platform, used the LWR model by discretizing the modeling process into small time steps. In our analysis, similar to Wahlqvist et al.'s (2021) approach, we also used the LWR model with discretized time step due to the simplicity of its implementation, alignment with our purpose of analysis, and the fast computation time.

2.3.2 Coupling Fire Spread and Evacuation Simulation

Simulation-based approaches to model fire spread and traffic evacuations are prevalent in the literature. Ronchi et al. (2020) introduced the WUI-NITY simulation model on the Unity3D game engine, using FARSITE for fire modeling (Finney, 1998b) with trigger buffers calculated using a second sub-model and the LWR model for evacuation movement (Lighthill & Whitham, 1955). Pedestrians are also included in the evacuation simulation. The sub-models allowed for a dynamic interchange of information between the fire spread and evacuation models and thus, corresponding decision processes.

FARSITE is an American fire growth simulation software model, whereas in Canada, the Canadian fire growth simulation software “Prometheus” is used (Tymstra et al., 2010) . Despite many similarities between these two fire growth models, fuel type and some other inputs used in FARSITE are different and should not be applied to the Canadian landscape. A separate study by applying these two models in Sweden showed that these two models behave differently while predicting fire spread (Hagelin & Cluzel, 2016). Thus, there is still no coupling fire spread and simulation method for Canada, Australia, or other parts of the world. Our directional analysis (Chapter 5) involving the coupling of minimum fire travel time (worst case scenario) with macroscopic evacuation simulation is a basic first initiative in the Canadian context.

2.4 Fire Modelling

Wildfire is a dynamic process controlled by fuel, weather, ignition, climate, and human activities. Fire weather and behavior prediction is used to predict how a fire might behave depending on the weather conditions (Hély et al., 2001).

The Canadian Forest Fire Behavior Prediction (FBP) System (Forestry Canada Fire Danger Group, 1992a) is widely used in Canada to predict fire behavior. The FBP System calculations can be computed in bulk using openly distributed code (cite the paper that documents the R package for the CFFDRS). Individual or small numbers of calculations can also be easily output with a simple FBP System calculator available as a downloadable computer application called "Red App." The application outputs predicted fire behavior characteristics based on user inputs and were used to generate fire spread rates described in Chapter 5. The "Canadian Forest Fire Weather Index (FWI) System" and "Canadian Forest Fire Behavior Prediction (FBP) System" are the sub-systems widely used by the fire managers and practitioners to predict fire danger.

2.4.1 Wildfire Risk Assessment in Canada

Fire risk is typically defined as the product of the likelihood and the potential impacts of wildland fire (Johnston et al., 2020). The Canadian Forest Fire Danger Rating System (CFFDRS) and its components Canadian Forest Fire Behavior Prediction System (FBP) (Stocks et al., 1989) and Canadian Forest Fire Weather Index (FWI) System (Van Wagner, 1987) are widely used for day to day operational fire management. These tools predict the danger of a fire but do not explicitly model fire risk (Johnston et al., 2020).

In the past, the focus was primarily on fire response and suppression. (Johnston et al., 2020). However, after the Okanagan Mountain Park Fire (Sandink, 2009), which caused the evacuation of around 27,000 population and 239 homes lost, it brought national attention that fire research is not only important for the forest industry but also for the general interest of public safety and the decision horizon should be for long-term mitigation actions.

2.4.2 Fire Modeling Frameworks

In recent years, the advancement of computing power, graphics, and storage capacity has enabled researchers to produce spatial fire growth simulation models, such as FARSITE (Finney, 1998a) and Prometheus (Tymstra et al., 2010). Prometheus is an automation of the FBP Systems equations executed on a spatial land cover/fuel layer using weather inputs. These simulation models and software can help understand continuous fire behavior in case of a fire.

Burn probability measures are extensively used in past research (Parisien et al., 2005). Burn probability simulation models are different than fire growth simulations. But their validity and accuracy is questioned due largely to the highly stochastic nature of wildfire events (Beverly & McLoughlin, 2019) and discussed in Section 2.5.3.

2.4.2.1 Prometheus and FARSITE Fire Growth Model

Prometheus is a deterministic fire growth simulation model developed in 2002 based on the Canadian Fire Forest Fire Behavior Prediction (FBP) System of the Canadian Forest Fire Danger Rating System (CFFDRS) (Forestry Canada Fire Danger Group, 1992; Tymstra et al., 2010). This model is used extensively to predict probable fire behavior and helps to inform ire management decision making. It uses topographical features, fuel types, and weather to simulate fire growth using Huygens' Principle of wave propagation. FARSITE is a similar American model based on the U.S. fuel types and is widely used by U.S. practitioners (Finney, 1998a). As mentioned before, a study applying these two models in Sweden showed that these two models behave differently while predicting fire spread (Hagelin & Cluzel, 2016).

2.4.2.2 Burn Probability Simulation

Burn probability models are based on the Monte Carlo Simulation approach, which involves repeated simulation of individual fire events using Prometheus or other fire growth models. Similar to our static analysis approach described in Chapter 3, Dye et al. (2021) used the outputs of burn probability simulation to develop fire metrics in their analysis. This approach is widely used in research and fire management planning to identify locations most likely to burn (Braun et al., 2010; Parisien et al., 2006; Beverly et al., 2009). Beverly & McLoughlin (2019) investigated the correspondence between burn probability heat maps and burned areas observed in subsequent years for five study areas in Alberta, Canada. They found greater than 70% of the burned areas were located in the burn probability range where it was considered the least likely to burn. This essentially questions the validity and reliability of these simulation models. The study also showed that the choice of classification methods for mapping probability values in GIS is a subjective judgment that can alter the map's appearance and accuracy.

2.4.3 Fuel as a Fire Hazard

Beverly et al. (2009) found that high or extreme simulated burn probability in west-central Alberta was primarily determined by the fuel composition in the area immediately around a location. Based on these findings, Beverly et al. (2010) assessed the exposure of the built environment with respect to vegetation, to ascertain its potential as an ignition source. Beverly et al. (2021) used the proximity of hazardous fuel as the basis for assessing wildfire exposure at both community and landscape scales. Wildfire exposure is a numeric rating that describes the potential for fire transmission to a location irrespective of weather conditions or other fire controls. The metric is reliable for identifying fire-prone locations across a region, with 70% of burned areas occurring in locations with fire exposure over 60%. For Static Metric Analysis in Chapter 4, we used wildfire exposure as one of the two static metrics of wildfire potential. A directional assessment of community exposure to hazardous fuel was introduced by Beverly & Forbes *(in review)*. We build on this work by combining directional exposure assessments with fire travel times and a directional analysis of the roadways serving a community. The results of this combined fire and transportation analysis are communicated through a simple data visualization that can be used as a communication medium with government and local communities.

2.5 Summary of Literature Review

Dye et al. (2021) presented a static analysis of basic road network characteristics to characterize evacuation vulnerability of communities in the rural Pacific Northwest, in GIS. In Chapter 4.2, we used a similar approach but using a different metric for the transportation network (minimum lanes to population ratio) and different biophysical wildfire inputs including wildfire exposure, and historical patterns of human-caused ignition points (see details in Chapter 4).

Some recent studies, for example Ronchi et al. (2020), model fire spread as an input to evacuation transportation simulation; however, their focus was on overall risk, not directional vulnerability. Our approach of relating minimum fire spread rate in each 45 degree direction of a rural community, with evacuation traffic simulation (in Chapter 6) provides a directional vulnerability assessment that their study did not. Macroscopic simulation with the discretized LWR model is appropriate for our analysis, due to its ability to generate results in seconds due to computation simplicity, matching the computational detail of the fire spread model, and thus suitable to assess many rural communities quickly.

Fire hazard and the perception of risk are considered to be the most influential factors in evacuation behavior (McNeill et al., 2015; Lovreglio et al., 2019; Mozumder et al., 2008). Accordingly, we relate minimum fire travel time with our mobilization curve using Tweedie et al.'s (1986) Rayleigh distribution (in Chapter 6). Given that burn probability simulations may not be representative or useful for informing fine-scale activities in landscapes (Beverly & McLoughlin, 2019), we have used the landscape fire exposure metric (Beverly et al., 2021) as the primary basis of our network vulnerability analysis (in Chapter 5).

This literature review demonstrates that the impact of the directional vulnerability of the transportation network for wildfire evacuation has received little or no attention. As current wildfire evacuation planning does not include directional assessments of transportation vulnerability, this thesis develops a method to assess directional transportation vulnerability due to wildfire encroachment, and subsequent evacuation.

CHAPTER 3. DATA SOURCES

In this chapter, we introduce the data sources used to build the representation of Alberta communities and Alberta highway network. For the wildfire risk assessment part, the data sources used for calculating the "Wildfire Metrics" (used in Chapter 4) are introduced.

3.1 Data for Communities and Transportation Network

3.1.1 Communities

The most current community population data were obtained from the 2016 Canadian Census (Statistics Canada, 2017a), using a downloadable tool called *GeoSuite* 2016. These data included information such as population centre (PC) name, PC type, population count, and representative PC point coordinates. Using definitions provided by Statistics Canada, the identified population centres are communities with a population of at least 1000 and a population density of 400 persons or more per square kilometer. Population center boundary files were obtained in a shapefile format and population counts were downloaded in *.csv files. The ArcGIS "Join Tool" was used to connect the boundary shapefiles with the population count data, making it a single shapefile with population count data. Finally, community centroids were determined by converting the polygons into point features in ArcGIS. The location of communities and the road network in Alberta is shown in Figure 3.1.

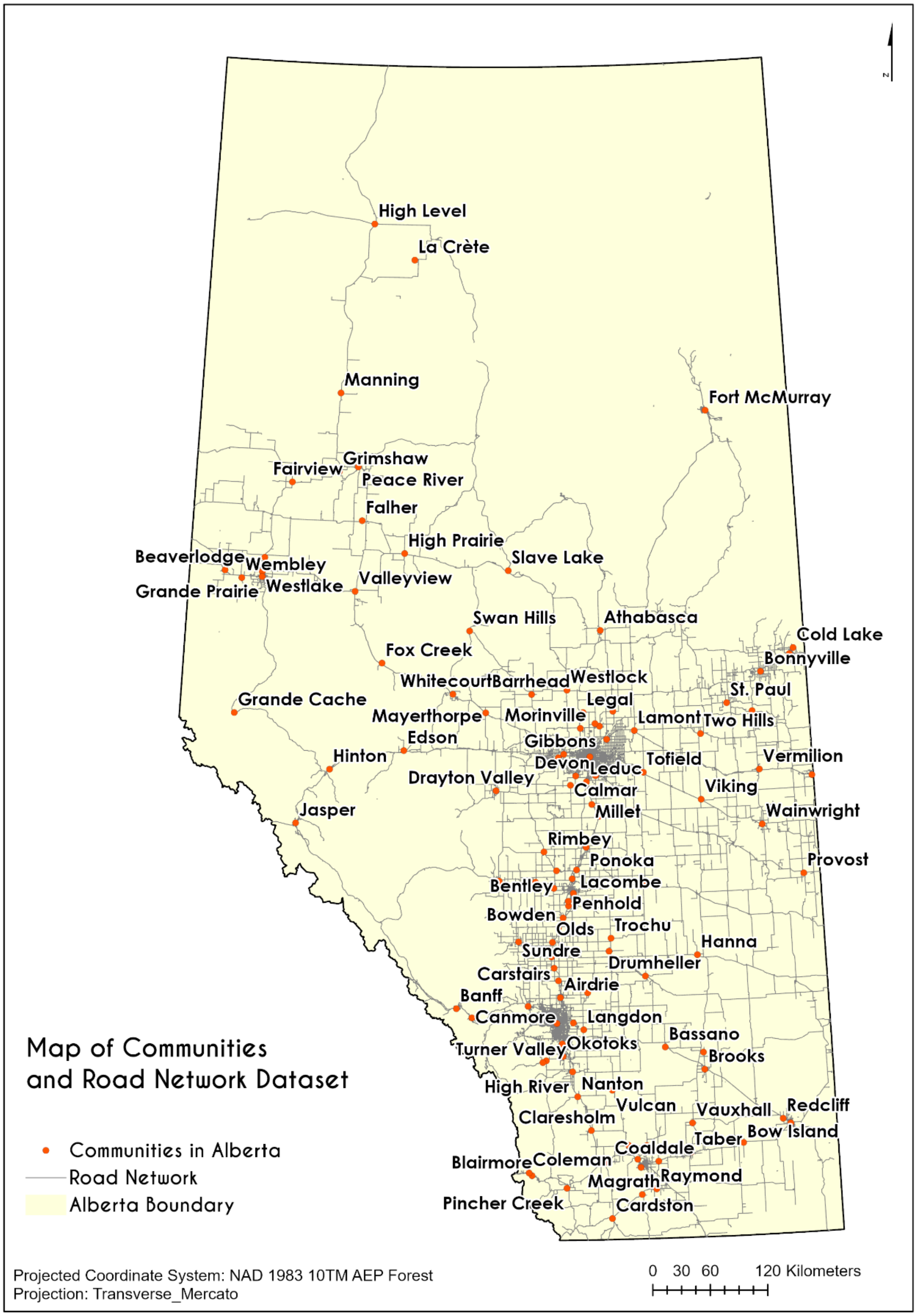

Figure 3.1: Population centre (community) locations and provincial road network. All communities are not shown; at this scale, some would be shown as overlapping.

3.1.2 Road Transportation Network Data

For the Chapter 4 analysis, we considered the paved road network consisting of freeways, controlled access highways, arterials, collectors, municipal and local roads. We assembled a complete network database of these road types from the ABMI Wall to Wall Human Foot Print Inventory. We did extensive manual corrections to integrate the different attributes from the Metadata file. The resulting integrated network contains 249,144 line segments with the minimum attributes required to assess the static metrics.

The Alberta highway network, obtained from Alberta Transportation as part of a previous related study, was used for the analysis of Chapters 5 and 6. Based on attributes including, but not limited to, annual average daily traffic (AADT), highway length, and vehicle composition, the hierarchical classification of Alberta's highway network consists of four classes designated as Levels 1-4 (Stantec Consulting Ltd., 2007):

1. *National Highway System (Level 1) facilities:* Inter-provincial and international movement of people, goods and services are accommodated by these facilities. These Level 1 facilities are generally only connected with Level 2 facilities. The total length of Level 1 facilities throughout Alberta is around 5,689 km, or 18.4% of the Alberta network.
2. *Arterials (Level 2) facilities:* These are similar to Level 1 facilities but only serve intra-provincial routes. These Level 2 facilities generally only connect Level 1 and Level 3 facilities. The total length of Level 2 facilities throughout Alberta is around 8,494 km, or 27.4% of the network.
3. *Collectors (Level 3) facilities:* These facilities connect local roads and arterials. Access to these facilities are more frequent than Level 1 and 2 facilities and can serve traffic from communities or industrial developments. The total length of Level 3 facilities throughout Alberta is around 12,216 km, or 39.6% of the network.
4. *Locals (Level 4) facilities:* Local roads primarily serve country residential and rural homesteads. The total length of Level 4 facilities throughout Alberta is around 4,097 km, or 13.3% of the network.

We used roadway capacities contained in the Alberta Transportation dataset in the analyses described in Chapters 5 and 6.

3.2 Wildfire Data and Inputs

3.2.1 Fire Exposure Data

Our analysis makes use of a readily available map of wildfire transmission potential called landscape fire exposure (Beverly et al., 2021), hereafter referred to as *fire exposure* or *exposure*. Exposure has been calculated for the entire province of Alberta (Beverly et al., 2021) and a recent study characterized the amount and configuration of exposure around communities in Alberta (Beverly & Forbes, *in review*). Outputs of the latter study by Beverly and Forbes *(in review)* were obtained as inputs for analyzing transportation vulnerabilities with respect to wildfire evacuation in Chapter 5.

Beverly et al. (2021) showed that most burned areas in Alberta occurred in locations with ≥ 60 % exposure. Beverly & Forbes *(in review)* therefore consider locations with ≥ 60 % exposure as "critically exposed." Critically exposed areas around the town of Jasper are shown in Figure 3.2, along with the road network. The colored polygons denote locations that have exposure of 60 percent or more. As the exposure assessments are based on proximity to hazardous fuels, they account for the mechanisms by which fires transmit from one location to another: radiant heat and ember transport. This exposure map is used while calculating the wildfire metric in Chapter 4. One limitation of the data is each cell is 100m x 100m or 1 hectare (ha) in resolution of the land cover raster file. The resolution is relatively coarse and fuels may not be well representative as FBP fuel system fuel types are simple categories (Forestry Canada Fire Danger Group, 1992).

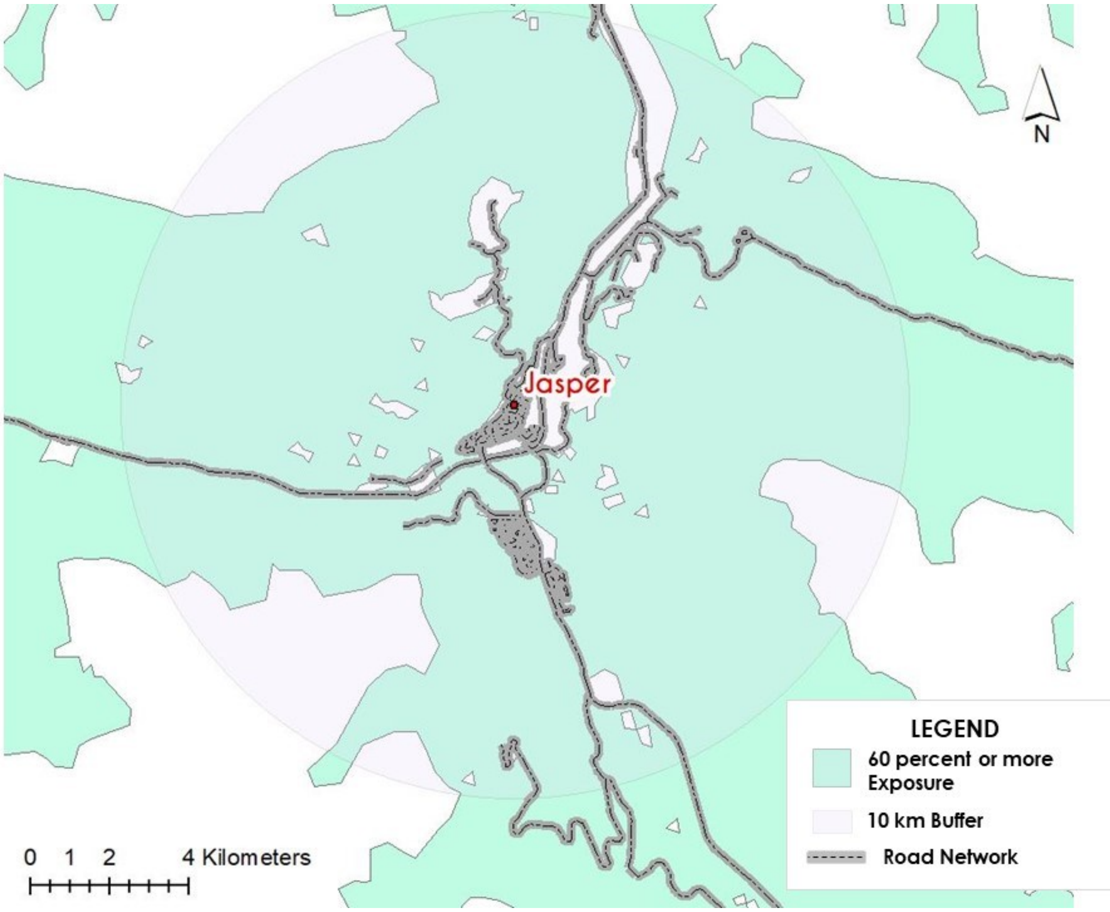

Figure 3.2: Fire Exposure (60 percent or more) map of 10 km buffer distance around Jasper Alberta.

CHAPTER 4. DATA ANALYSIS

This chapter includes the wildfire data inputs that we used for our analysis in Chapter 5 and 6. The data analysis section of this chapter also presents a framework for assessing transportation vulnerability in relation to wildfire evacuation using GIS-based metrics. Results are used to identify ten vulnerable communities for further analysis in the following chapters. Also, the data inputs for the analysis in Chapter 5 is also included in this chapter.

Disclaimer: *This work is academic work in progress and not to be used for decision making*

4.1 Data Inputs

4.1.1 Proportion Exposed Plots in Chapter 5

As mentioned in the previous chapter, Beverly et al. (2021) reported that areas burned by wildfire aligned with locations that had ≥ 60% exposure. Beverly & Forbes (*in review*) therefore defined critical exposure areas as those with ≥ 60% exposure and developed a method to quantitatively describe the directional pattern of fire exposure around a community using radial graphs. We use the results of that directional exposure assessment to explore if exposure pathways into communities align with road directions, which could result in loss of road capacity in the event of a wildfire, which was investigated in Chapter 5. By overlaying the roads with directional exposure Beverly & Forbes (*in review*), road network directions vulnerable to wildfire can be identified.

Radial graphs of directional fire exposure from Beverly & Forbes (*in review*), were provided by the authors. Beverly & Forbes (*in review*) assessed directional fire exposure in one-degree transects extending outwards from the community centroid for 15 km. This analysis was completed for 21 fire-prone communities in Alberta. The resulting radial graphs show the proportion of a given transect that is critically exposed. For example, if one-third of the transect intersects lands where exposure met or exceeded the critical threshold of 60%, then the directional exposure is 33%, whereas if the entire transect intersects critically exposed lands, the directional exposure is 100%.

4.1.2 Directional Fire Spread Rate as Data Input in Chapter 6

Potential fire travel times along each one-degree transect were calculated for spring and summer conditions for each community. This procedure was conducted by a fire modeler (A. Forbes, personal communication [July, 2021]) and involved estimating fire spread rates by fuel type using the FBP System, given assumptions about weather conditions. The time required for a fire to travel along a 5 km increment of the transect was estimated from the composition and amount of the intersecting fuel types. No attempt was made to account for barriers that could potentially arrest fire spread, those areas were simply assigned a spread rate of zero. Fire travel times were estimated for two 5 km increments extending out from the community centroid – 10 to 5 km, and 5 km to centroid (0 km). The calculated fire travel times were then used to determine minimum fire travel time (t_1) for each of the 8 directions of a community (see Section 6.1Figure 6.1 for model details).

Several assumptions are associated with these fire spread calculations. First, the fire spread rate is calculated using an assumed weather condition with Fine Fuel Moisture Code of 92.5, a Build-up Index of 92.7, and an Initial Spread Index of 14.7. These values represent the 95th percentile fire weather for fires occurring between 2006 and 2018, and thus a worst-case scenario (Beverly et al. 2021). Second, the spread rate along a transect is calculated by taking a weighted average of individual spread rates of different percent of fuel types that intersect the transact. In reality, the presence of a continuous patch of non-fuel/water/vegetated non-fuel land that are all assigned a rate of spread (ROS) of 0 m/min for the purposes of this study, might affect the progression of the fire by completely arresting fire spread. Likewise, it is possible that a fire could jump over non-fuel portions of a transect, such that ROS is not slowed at all. More complex spatial fire growth simulation approaches such as Prometheus were not used because these models do not model how fire can potentially jump over non-fuel patches.

4.2 Data Analysis using GIS

In this chapter, GIS analysis is used to perform the initial identification of the vulnerable communities for their limited evacuation roadway geometric network in relation to the wildfire potential. The analysis included 122 communities in Alberta that had a population of at least 1000 and population density of at least 400 persons per square km, as described in Section 3.1.1. The

GIS model consists of five network metrics for evaluating evacuation roadway vulnerability, which are combined with two wildfire potential metrics.

An assessment of transportation vulnerability was based on five metrics: exit road capacity, road directionality, travel area, connectivity, and evacuee load (the latter including population). Four of these metrics (i.e., exit road capacity, road directionality, travel area, connectivity) are similar to those developed by Dye et al. (2021). The aim of these transportation vulnerability metrics (including Dye et al.'s (2021) four metrics) is to characterize each community's surrounding road network, on the potential to quickly and safely evacuate the community.

Wildfire potential was gauged according to the amount of highly exposed land in the surrounding landscape, calculated in a separate study. Wildfire potential focusses on which parts of the surrounding landscape are capable of hosting a wildfire incident. By combining the scores from the transportation and wildfire metrics, an overall vulnerability score is calculated for each community. The result is that ten highly vulnerable communities are identified for further assessment in the following chapters.

4.2.1 Network Vulnerability Metrics

While calculating the metrics, the circular buffers drawn from the community centroid extend outwards 15 km. This is because most of the communities show clear route directions for evacuating from or leaving the community at a 15 km distance. If a buffer smaller than 15 km (i.e. 10 km) is used, it results in inclusion of local roads in the metric calculation, which are eventually merged into the highways. However, we also conducted a simple sensitivity analysis by performing the same calculations of the network metrics for 10 and 20 km buffer distances of each community.

4.2.1.1 Exit Capacity (Dye et al., 2021)

The number of lanes for each road intersecting the 15 km circular buffer perimeter is counted for each community.

4.2.1.2 Travel Area Metric (Dye et al., 2021)

The travel area metric describes the curviness or indirectness of roads within a 15 km circular buffer. "Network Analyst" tool from ArcGIS is used to calculate the travel area metric. The travel area metric provides the maximum number of places that can be reached by traveling

15 km distance starting from the community centroid. If the road is straight, the resulting travel area will be larger than if roads are meandering or winding. Communities with larger travel areas are considered less vulnerable, because evacuees can travel faster away from the community than they would on a meandering road, assuming all other factors such as time and speed are equal.

4.2.1.3 Connectivity (Dye et al., 2021)

Connectivity was measured using the "Line and Junction Connectivity tool" in ArcGIS. It consists of the number of lanes approaching intersections within a community, within a 15 km circular buffer distance. The number of lanes in each intersection is summed using the "Join" tool for each community. This metric is based on the expectation that a well-connected network provides more flexibility for evacuation route choices. A higher number of connections means more efficient access for emergency responders and more options to possible destinations and directions.

4.2.1.4 Road Directionality (Dye et al., 2021)

This metric represents the directional routing options for an evacuating community. Road directionality is computed by the circular variance of the road network, based on the positions of available exit points along the circumference of the 15 km community buffer. Higher variance means more diverse alternatives to choose from.

4.2.1.5 Evacuee Load

This metric indicates the location (in radial distance from community centroid) and size of a roadway bottleneck for a community, determined against the community population. To calculate, circular buffers lines were drawn at 1 km intervals from the community centroid out to 15 km distance. Intersection points between the buffer lines and the roadway network were identified using the "Intersect" tool for each buffer polygon. Out of these 15 buffer lines, the buffer line which contains the smallest number of intersection points was selected. Then the corresponding total number of lanes on intersecting roads was found, and this was divided by the population of the community (in thousands) to find the community's minimum number of lanes per evacuee. Figure 4.1 shows an illustration of how the metric is calculated; orange dots are the intersecting points of the roadway network with the circular buffer.

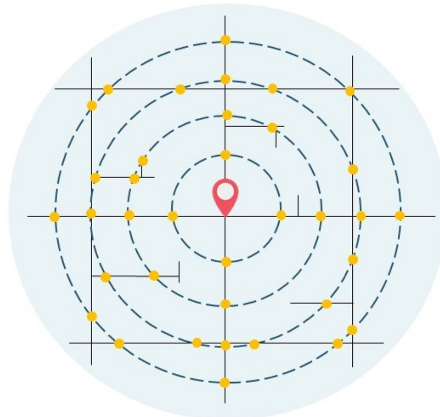

Figure 4.1: Evacuee load metric

If the number of lanes to population ratio is small, the community has a more restrictive roadway bottleneck, and possibly greater congestion in egress. Thus, the ratio gives us some understanding of community size versus roadway capacity.

4.2.2 Wildfire Metric

Dye et al. (2021) used two metrics to ascertain wildfire potential: a burn probability map generated using wildfire simulations, and mean fireline intensity. As discussed in Section 2.4.2.2, Beverly & McLoughlin's (2019) study showed that simulated burn probability had limited value for mapping fire potential in Alberta's forest ecosystems. Accordingly, we used an alternate wildfire metric, landscape fire exposure, which is based on grid cells' proximity to nearby hazardous fuel and has been successfully validated in Alberta.

As mentioned in Section 3.2.1, the exposure data used in this study was provided by Beverly & Forbes (*in review*). In that study, the characteristics of landscape fire exposure mapped by Beverly et al. (2021) were described for each community using a series of metrics; however, the magnitude of exposure was selected for use in this study because it provides an overall indicator of fire potential in the landscape surrounding the community. Also, Beverly et al. (2021) showed that between 2007 and 2019, most of the area burned by wildfires in Alberta occurred in locations with ≥ 60% exposure, and this was consistent for 10 of the 11 ecological units included in the study. In order to calculate the metric, a circular buffer of 15 km is drawn around the selected communities. The area with exposure ≥60% within the 15 km buffered area is calculated using the "Intersect" tool in GIS. Finally, area values are normalized between 0 and 1.

4.2.3 Evacuation Vulnerability Score

The calculation for the transportation vulnerability score is shown in (Eq. **4.1)**, which combines all five network vulnerability metrics introduced previously. The weighting for the "Evacuee load" metric is 0.5, as the index is biased toward larger populations. For each community, the normalized transportation vulnerability score was combined with the normalized wildfire potential score by taking an average using (Eq. **4.2)** to produce an overall rating of transportation vulnerability to wildfire, which we defined as evacuation vulnerability score. The final scores calculated using (Eq. **4.2)** are normalized between 0 and 1 for comparison purposes.

$$\begin{aligned} &Transportation\ Vulnerability\ Score \\ &\quad = (Exit\ capacity) + (Road\ directionality) \\ &\quad + (Travel\ area\ metric) + (Connectivity) \\ &\quad + 0.5\ (Evacuee\ load) \end{aligned} \qquad \textbf{(Eq. 4.1)}$$

$$\begin{aligned} &Evacuation\ Vulnerability\ Score \\ &\quad = (Transportation\ Vulnerability\ Score \\ &\quad + Wildfire\ Metric\ Score)/2 \end{aligned} \qquad \textbf{(Eq. 4.2)}$$

According to the above metrics, communities that exhibit the greatest vulnerability with respect to wildfire evacuation due to the geometric layout of road network are listed in Table 4.1. As expected, Table 4.1 shows that the most vulnerable communities are those with small populations, with the exception of Fort McMurray.

Table 4.1: Communities with the Highest Evacuation Vulnerability Scores

Ranking	*Community Name*	*Evacuation Vulnerability Score*	*Population*
1	Grande Cache	1	3,571
2	Jasper	0.96	4,590
3	Hinton	0.93	9,882
4	Coleman	0.87	1,475
5	Fort McMurray	0.84	66,573

The locations of all communities for which an evacuation vulnerability score was calculated are shown in Figure 4.2. Results show that these communities are mainly located in areas with high fuel exposure, north of Edmonton or along the western border of Alberta with British Columbia. The color symbols use “Jenks natural break” symbology tool in ArcGIS.

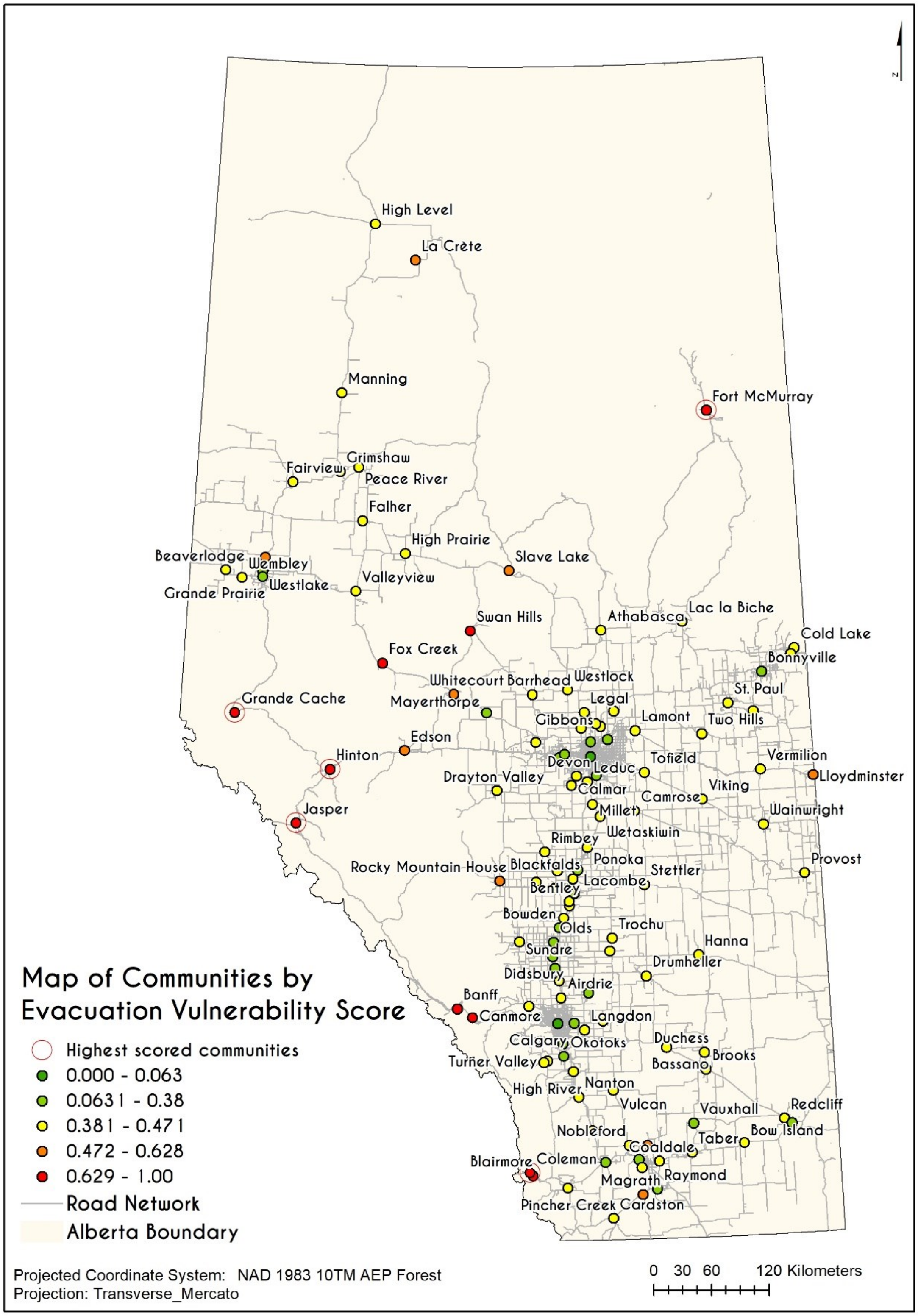

Figure 4.2: Map of evacuation vulnerability metric scores. The scores are the normalized values of the averages of the transportation vulnerability metric (Eq. 4.1) and wildfire metric (Eq. 4.2).

The highest community scores are summarized in Figure 4.3. Results indicate Grande Cache's transportation vulnerability is high, but wildfire potential is lower compared to other communities; the overall vulnerability is ranked 5th. On the other hand, Hinton's wildfire potential score is higher than Grande Cache but transportation vulnerability is lower, and thus ranked 3rd.

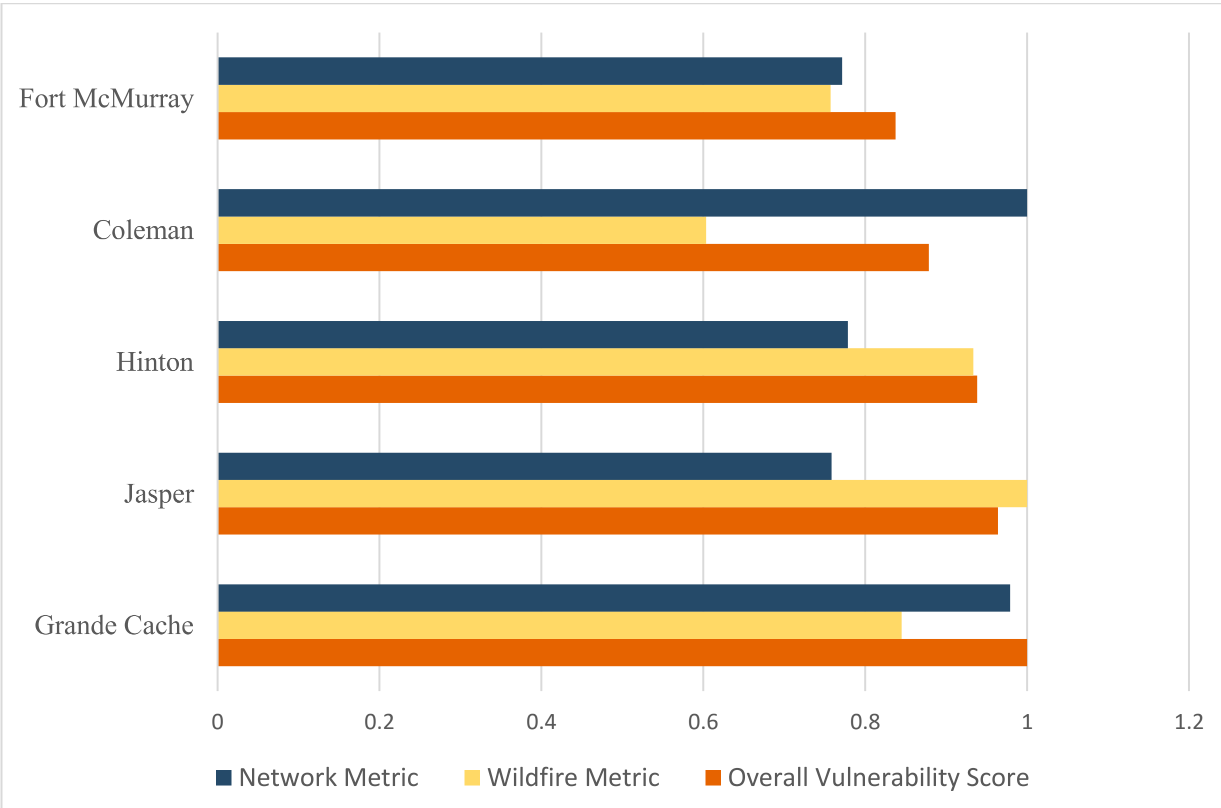

Figure 4.3: Comparison of the communities exhibiting the highest levels of transportation vulnerability with respect to wildfire evacuation

The geographical positions of these highly scoring communities are mostly aligned with high fuel exposure areas, which is expected because this scoring is specifically focused on wildfire evacuation. However, a low vulnerability score does not mean that a community is not vulnerable for wildfire evacuation – i.e., low fire hazard and/or sufficient road network to accommodate evacuation. Rather, the focus of our analysis was to identify communities which potentially may be flagged as more vulnerable compared to others, and thus require further analysis – specifically, the directional analysis of Chapters 5 and 6.

4.2.4 Discussion of the GIS-Based Data Analysis

The goal of our analysis in this chapter was to answer the first research question: Which communities may have less potential to quickly and safely evacuate due to the geometric layout of their road networks, combined with wildfire potential, thereby rendering them more vulnerable?

The communities with the highest transportation vulnerability scores were Grande Cache, Sexsmith, La Crète, Duchess and Magrath. Results show that remote communities are most vulnerable as they have limited routing options. However, some communities close to Edmonton also show high transportation vulnerability scores, possibly due to their large populations in relation to their available transportation network. Lloydminster was also shown to be vulnerable, but it is on the eastern border with Saskatchewan (i.e., the bounds of our geographic scope) and road layout data is not available, and thus requires further analysis beyond this one.

Fort McMurray, Coleman, Grande Cache, Hinton, Jasper show high evacuation vulnerability scores. Some communities with high transportation vulnerability scores are not included in the final list of high scoring communities due to their low wildfire scores. These communities may require further attention for other types of natural disasters (if any), as they could face critical situations while evacuating. We emphasize that low vulnerability does not mean zero fire hazard – a community with low wildfire potential can still face quick spread surface fire and prompt evacuation.

For communities with high transportation vulnerability, further detailed evacuation movement studies are recommended, in order to determine community evacuation plans that lead to more efficient evacuations, and in some cases, investments in transportation infrastructures. For communities more vulnerable to wildfire, additional evacuation considerations for people with different access levels and mobility should also be considered. Planned alternative solutions that are well communicated to the public are essential for safe evacuations.

CHAPTER 5. STATIC DIRECTIONAL ANALYSIS

In this chapter, directional wildfire trajectories into communities are assessed with respect to their potential for disrupting the transportation network and their corresponding loss of capacities due to this disruption.

Disclaimer: *This work is an academic work in progress and not to be used for decision making. Also, we did not estimate any likelihoods or probabilities; rather, the* ***possibility*** *of approaching fire from a direction with road closure.*

5.1 Introduction and Background

Most communities are connected to the larger transportation network by at least one roadway (if not, they are termed "fly-in, fly-out communities). When a wildfire encroaches into the built environment, it can interact with the surrounding transportation infrastructure. In some cases, this can create a compound impact, where the community must evacuate due to the fire but the fire itself is obstructing the use of some transportation facilities. If a fire impacts an important, high capacity road, it can cause significant loss in overall evacuation capacity and may prolong evacuation time. For example, during the 2018 Camp Fire in California, at least seven deaths resulted from evacuees becoming entrapped in their vehicles during evacuation due to traffic gridlock (Ramsey et al., 2020).

By examining the characteristics of roadways, including where they are located and their capacities, in relation to the directions in which fires can enter the built environment, variations in vulnerability to wildfire can be assessed. Thus, we assess a community's directional transportation capacity given possible closures due to fire exposure pathways (Beverly & Forbes, *in review*). To this end, we assess 21 communities in Alberta, Canada, identified as potentially high risk for fire (Beverly & Forbes, *in review*) and with limited roadway facilities, and thus deemed appropriate for investigation (Figure 5.1). Directional fire exposure assessments presented in radial graphs in Beverly & Forbes (*in review*) were used to explore how fire exposure pathways into each of the 21 communities align with roadways, and thus identify which roadways are vulnerable and how community egress capacity is impacted when a roadway is inaccessible due to fire. Figure 5.1 shows the locations and populations of these 21 communities. Most of these communities have limited roadways (in terms of the number of roads and carrying capacities) connecting them to the larger provincial transportation network.

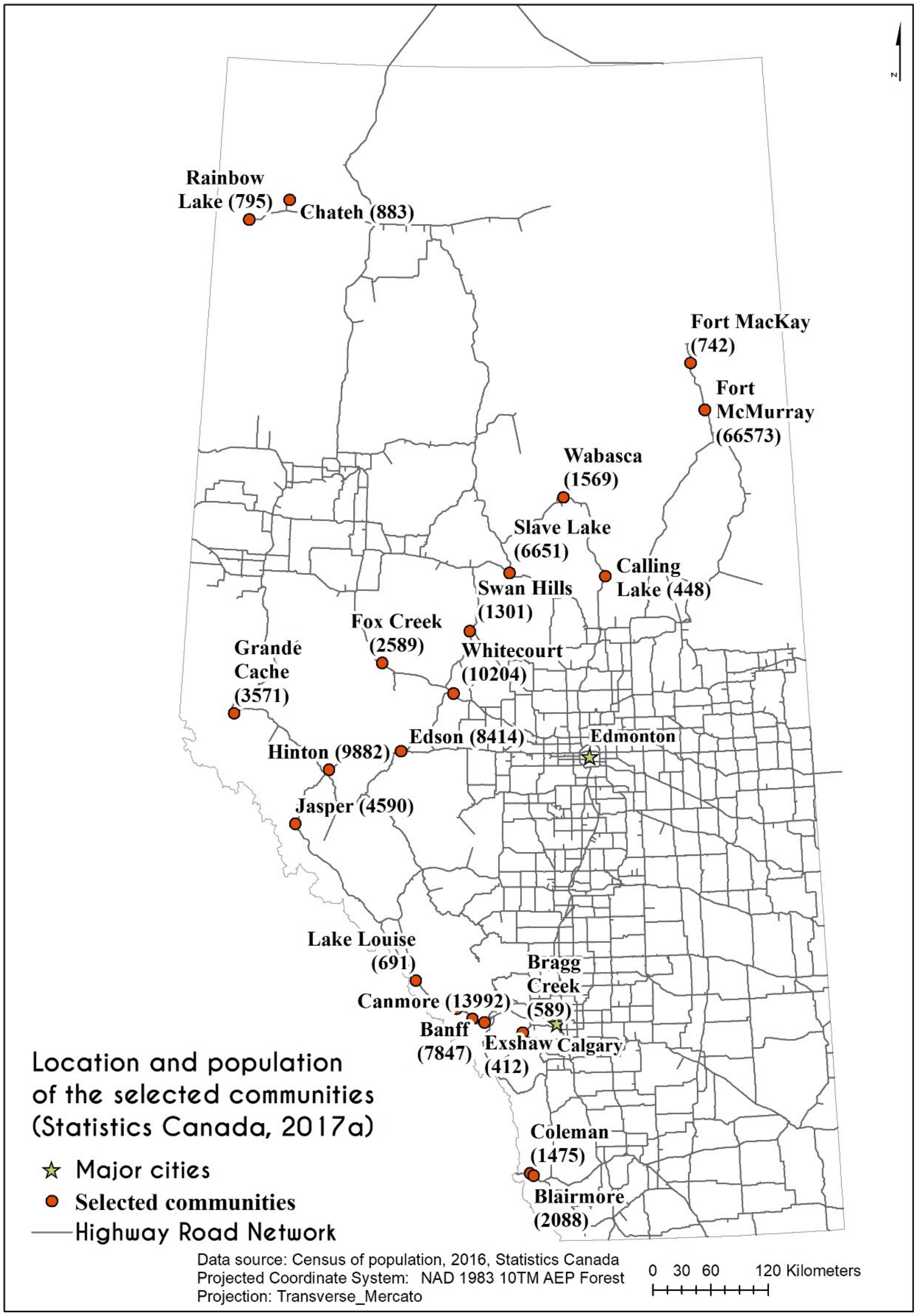

Figure 5.1: Locations of the selected 21 communities throughout Alberta, Canada

5.2 Modelling Framework

A community's total evacuation capacity is simply the sum of all available roads' outbound capacities. We determine the radial locations and capacities of all roadways at 5, 10 and 15 km from the community centroid. These points were chosen for several reasons. First, Beverly & Bothwell (2011) reported that for evacuations between 1980 and 2007 documented in Canada, 29% of the evacuations had wildfire distance data and 80% of those evacuations were prompted by a wildfire that had travelled within 10 km of the evacuated community. We also chose 5 km because even some small communities can be nearly 10 km across, which means a fire at 5 km would mean imminent danger for residents. These few discrete points were selected to make the resulting plots clear and understandable, with the assumption that roadway cross sections, and thus operational capacities, are not changing significantly between points.

It was also possible to take continuous capacities from 0 to 15 km. However, this would make the plots more complex with possibly too much information, rendering important features more difficult to identify. So, it was decided that to calculate capacity every 5 km was a compromise to keep plots simple and useful, accepting some loss of information. To understand how critical a road closure incident is, we also calculated the capacity that remained after the road closure. As the basis of our analysis, directional fire exposure plots were merged with road capacities. As an example, the steps used to produce the combined plots of directional fire exposure and roadway capacity is shown for the community of the Slave Lake (Figure 5.2; see Figure 5.1 for the location of Slave Lake within Alberta).

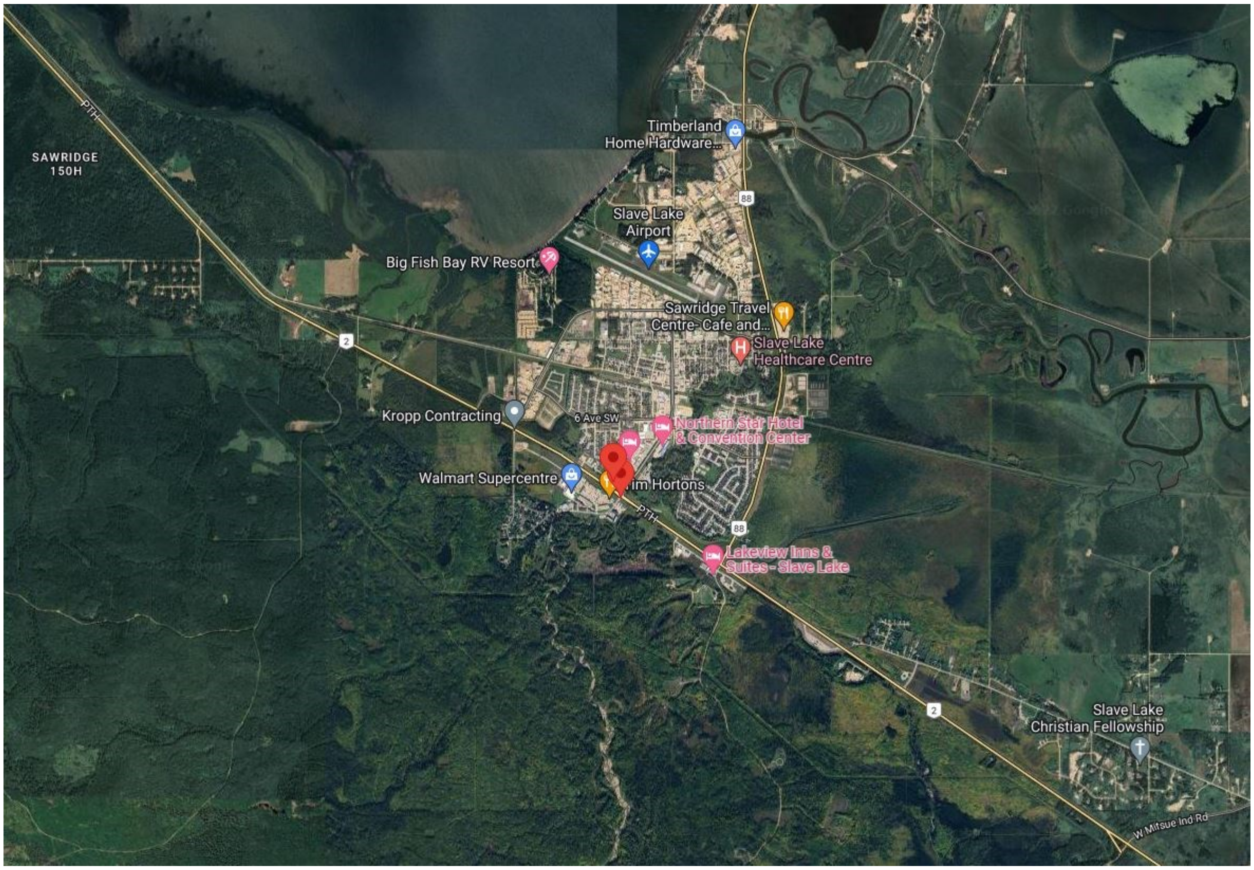

Figure 5.2: Map of Slave Lake (Google Earth). Slave Lake is a town of approximately 6,651 residents located on the southeast shore of Lesser Slave Lake in central Alberta, at the junction of Highway 88 and Highway 2.

Step One: Using the circular buffer tool in ArcGIS, 5, 10, and 15-km circular buffers are drawn from the community centroid (as per the Statistics Canada community polygon (*Statistics Canada*, 2021, details in Section 3.1.1)), as shown in Figure 5.3. The road network is then intersected with the buffers using the "Intersect" tool from ArcGIS. Descriptive attributes of the intersecting points included road capacity, speed limit, pavement condition, and number of lanes. Figure 5.4 shows the road capacity values for each intersecting point for Slave Lake.

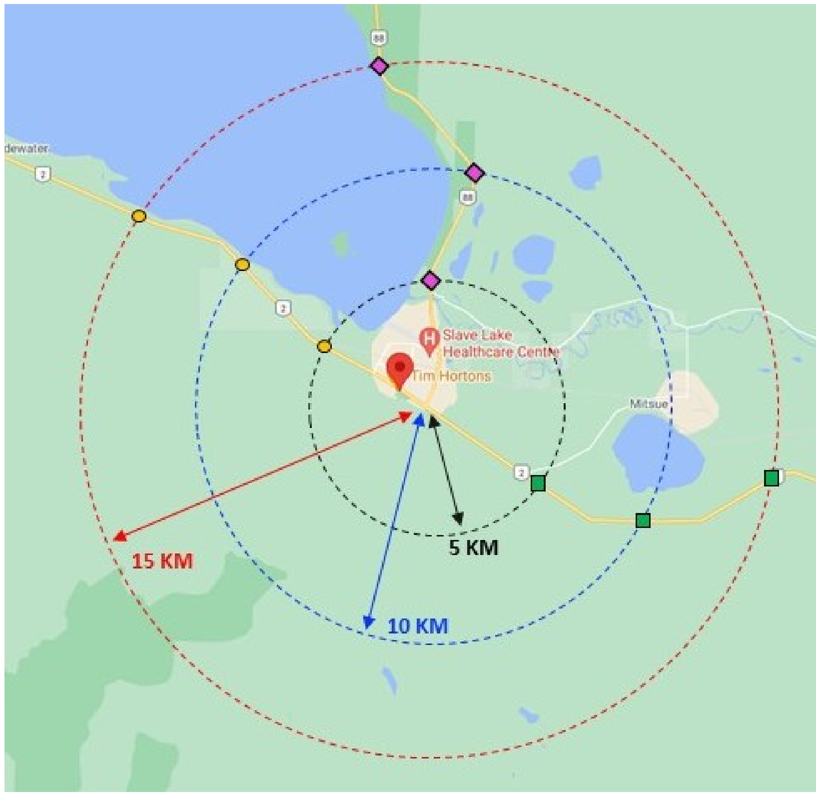

Figure 5.3: 5, 10, and 15-km circular buffer lines are drawn from the centroid

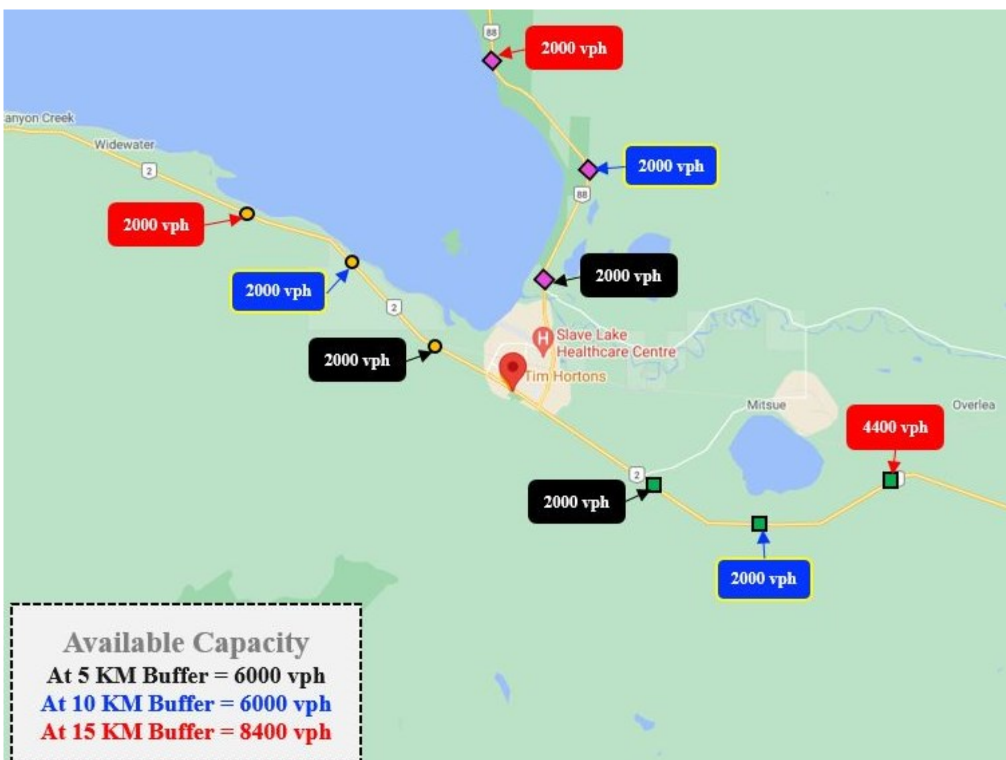

Figure 5.4: Intersecting points of buffer lines with roads, Slave Lake

Step Two: Using the geoprocessing tool "Generate Near Table" in ArcGIS, the angular direction of each intersecting point in relation to the community centroid was calculated. Note that the angles are given with respect to the horizontal x-axis, which we recalculated from the north in Excel using the "Table to Excel" tool from ArcGIS.

Step Three: With the roadway capacities at the intersecting points on each buffer and their corresponding radial direction, we found the total capacity for each buffer distance (5, 10, and 15 km). Then for each road, we calculated the total roadway capacity remaining if that particular road was closed, for each of the three buffers. If two roads were less than or equal to 5 degrees apart, we assumed a potentially encroaching fire would block both.

Step Four: Using R Studio, we plotted the total road network capacities at buffer distances of 5, 10, and 15 km, and displayed the remaining (reduced) capacity at a road location as a "spike," should that road be closed due to fire. The length of each "spike" indicates the contribution of the road in question to the total roadway capacity, at each buffer distance.

A sample plot showing only total roadway capacities for Slave Lake, Alberta is shown in Figure 5.5. The y-axis on the right side of the figure measures total community egress capacity, while the rings represent capacity and how it decreases should a given roadway facility be unavailable. As an example, let us observe the red line. It shows that at 15 km distance from community centroid, total community egress capacity is around 8400 vph if all roadways are available. However, say northbound Highway 88 (represented by the pink diamonds) is closed due to wildfire encroaching from that direction. Then, total community egress capacity decreases to 6400 vph at 15 km (which is indicated by a pink diamond at the radial location of the roadway at 15 km), because Highway 88 contributes 2000 vph capacity to Slave Lake's total egress capacity at 15 km. A similar observation is made for the capacities of Highway 88 at 5 and 10 km (identical) – total community egress capacity would drop from 6000 to 4000 vph should a wildfire encroach from the north and cause Highway 88 to be shut. This indicates that Highway 88 at 15 km has a sizable contribution to the total egress capacity of Slave Lake, and should a wildfire encroach from that direction and cause closure of Highway 88, a proportional reduction of this capacity occurs. Another point to note is that the total egress capacity is the same at 5 and 10 km but larger at 15 km; it appears that Highway 2 (green squares) expands to an additional lane between 10 and 15 km as indicated by the longer red "spike."

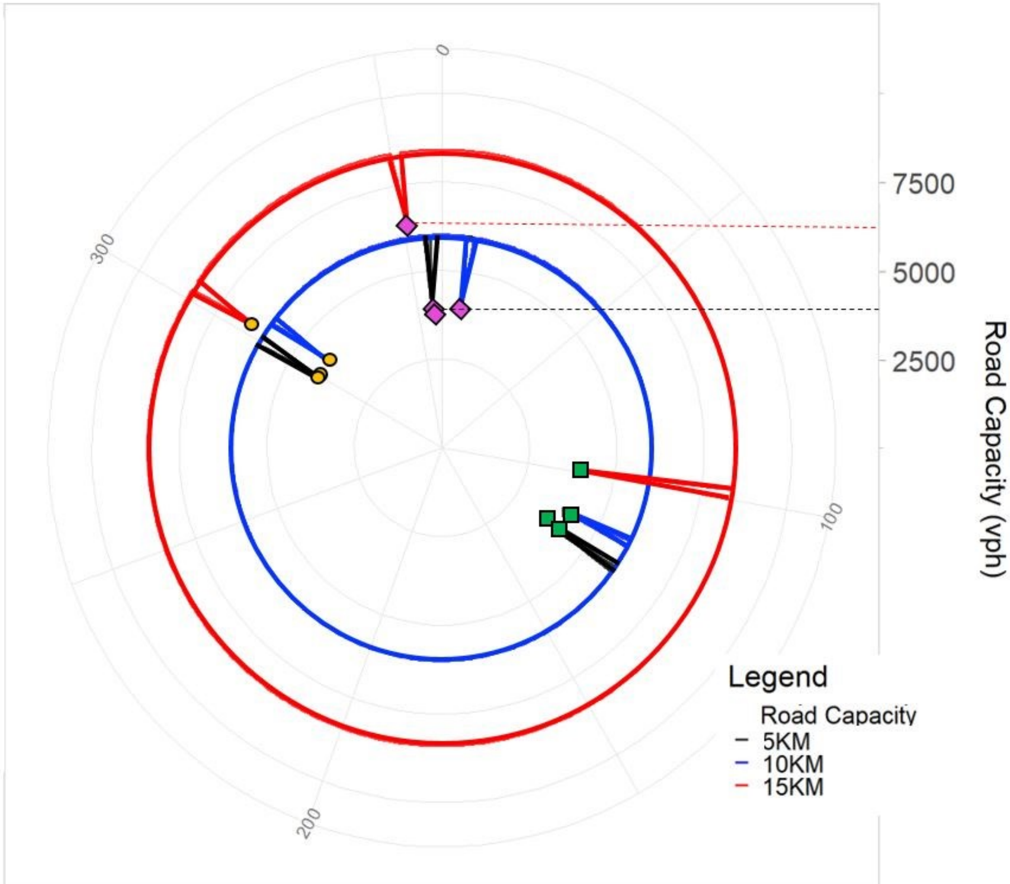

Figure 5.5: Community egress capacity (Slave Lake)

Recall that Beverly & Forbes (*in review*) measure the proportion of the one-degree transect that has fire exposures over the 60% threshold, which is shown on the left-hand y-axis in Figure 5.6. Lobes on the exposure radial graph delineate potential fire pathways, with colors again corresponding to the buffer distance analyzed. Small or absent lobes in a given direction indicate little potential for fires to encroach on the community from that direction, at that buffer distance. Long and wide lobes indicate prominent potential fire pathways into the community. A road is most vulnerable to possible closure if it intersects a large exposure lobe. The exposure lobes are all relatively small in the case of Slave Lake, and all directional transects have less than 50% critical exposure, suggesting potential fire pathways into the community are limited (Beverly & Forbes, *in review*). This is not surprising given that the community is situated along a large lake, and a large wildfire in 2011 eliminated fuels to the southeast of the community. Also, the largest exposure lobes are to the south and southwest of the community, whereas the three roadways into

Slave Lake are to the north, northwest, and southeast. They also do not change direction appreciably between 5 and 15 km. This indicates that Slave Lake's egress capacity is not highly threatened by wildfire. However, the graphs are not able to indicate whether the total egress capacity is sufficient for the community population.

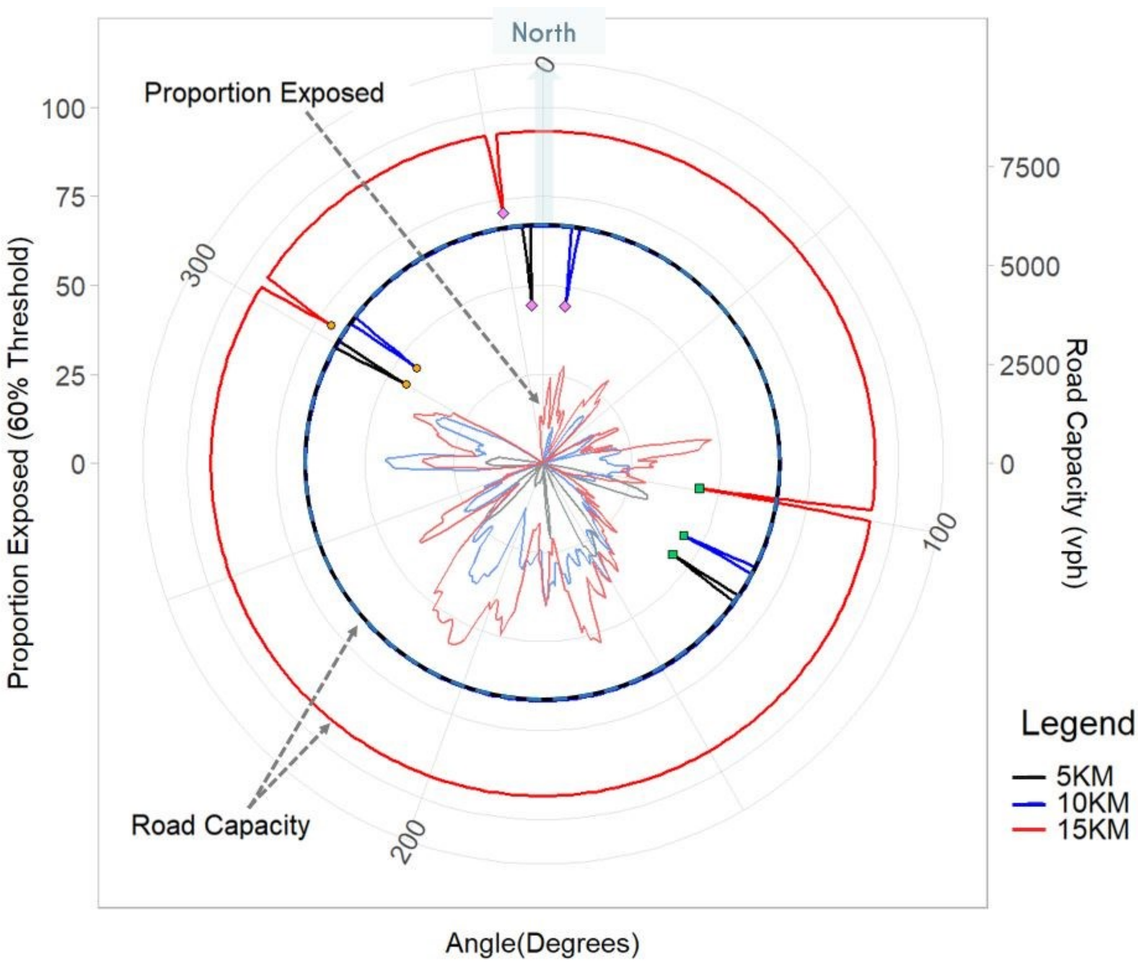

Figure 5.6: Community egress capacity and critical fire exposure levels (i.e., proportion of directional transect with ≥ 60% exposure), Slave Lake

Figure 5.7 shows results for Fox Creek. Highway 43 is the only major roadway serving this community, and its capacity remains the same at all buffer distances. Highway 43 leading southeast out of town (green box marker) aligns with a large and broad critical exposure lobe, indicating a fire pathway that extends into the community from 15 km (and likely, beyond). This suggests that the community is more vulnerable to a fire that encroaches from the southeast and at the same time, induces closure of Highway 43 from that same direction. Should that occur, evacuation must occur northwest out of the community on the only other roadway available, at half the total community egress capacity.

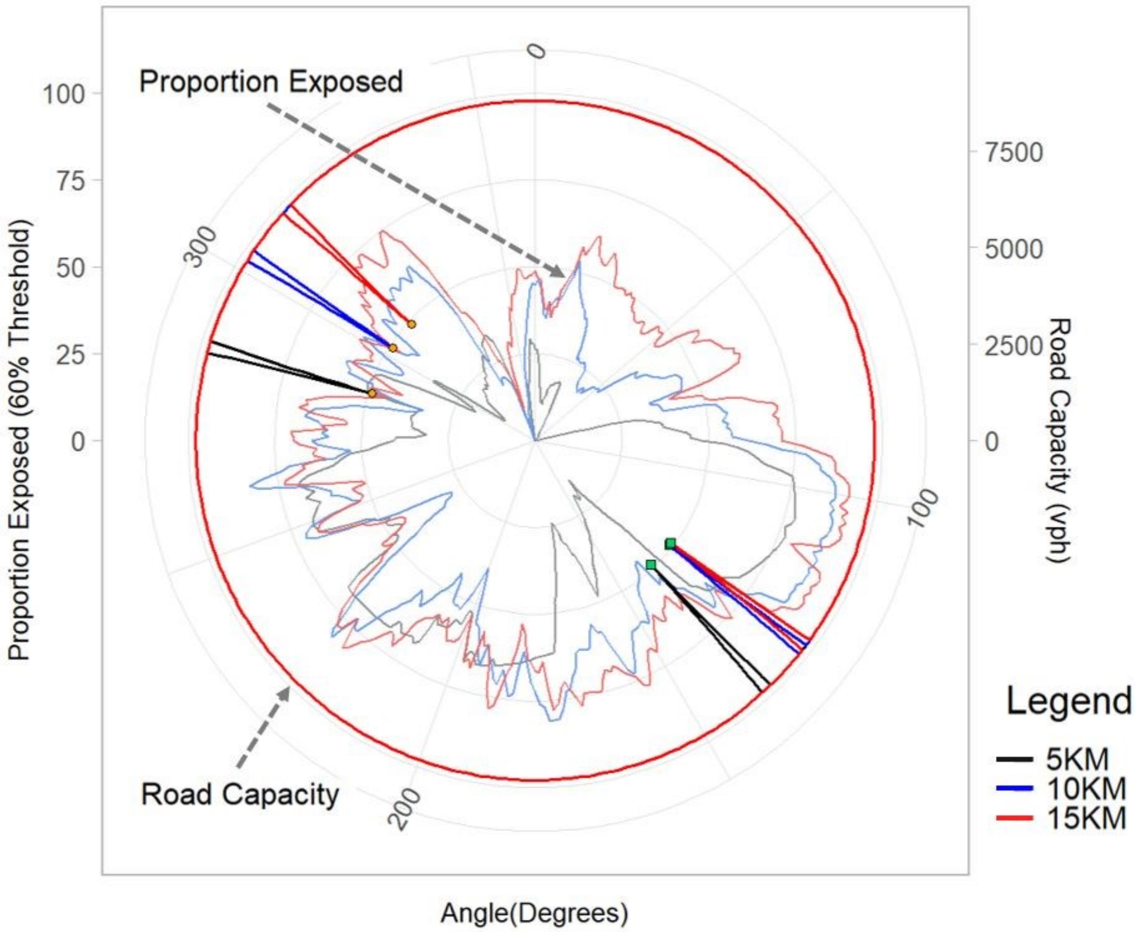

Figure 5.7: Community egress capacity and critical fire exposure levels (i.e., proportion of directional transect with ≥ 60% exposure), Fox Creek

5.3 Interpreting Directional Road Vulnerability Plots

The radial graphs displaying directional capacities of the road network provide a standardized approach to assess communities and compare vulnerabilities across them. We present the results for five additional communities, to demonstrate how the graphs are interpreted and to highlight notable aspects of the plots. Plots for all 21 assessed communities are included in Appendix A.

5.3.1 Rainbow Lake

The community of Rainbow Lake (Figure 5.8) has only one egress route via Highway 58. There are nearly continuous unbroken fire pathways into the community from west to northeast in the clockwise direction. Critical fire exposure levels are more limited between the southeast and east. The eastward egress route is aligned with a somewhat limited fire pathway, but because this is the only way out of the community, via Highway 58, a fire encroaching from the east can create a critical situation for the community.

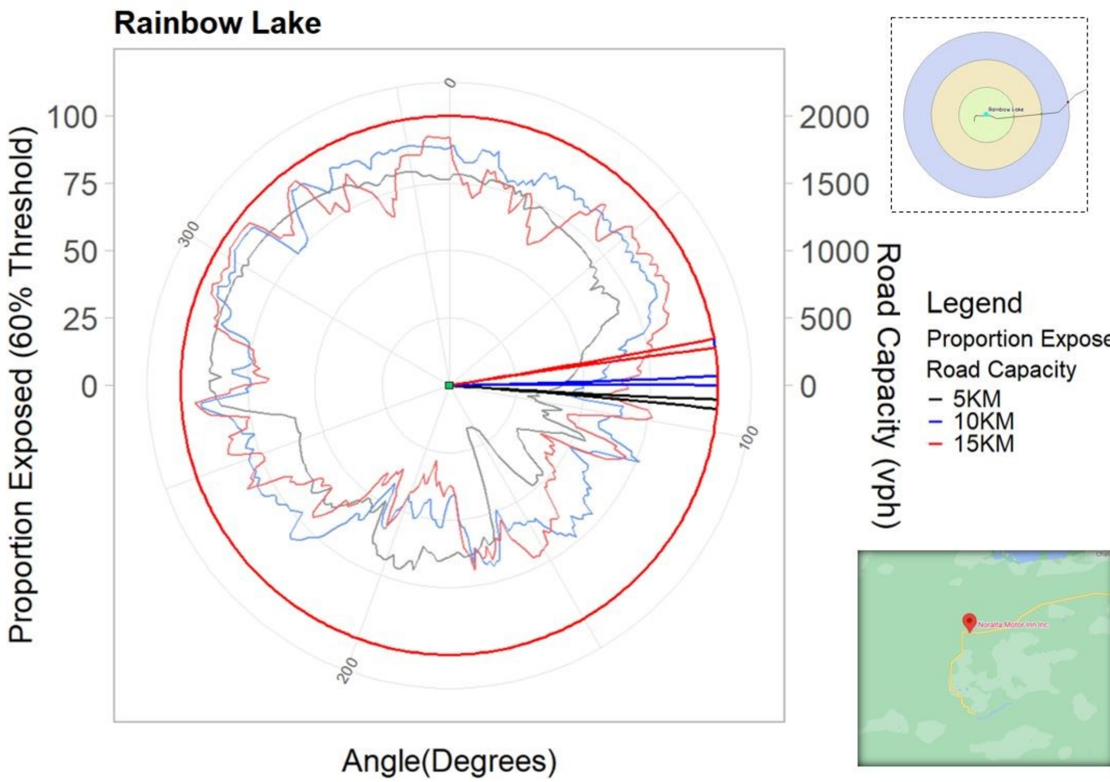

Figure 5.8: Plot of directional road capacity for Rainbow Lake in relation to critical exposure levels (i.e., proportion of directional transect with ≥60% exposure)

Fires to the east of Rainbow Lake should be prioritized for detection and suppression action, even if the areas to the north or west might seem more of a priority based on the amount of critical fire exposure, independent of evacuation vulnerabilities.

5.3.2 Lake Louise

All egress routes available for the community of Lake Louise (Figure 5.9) are located within large exposure lobes delineating potential fire pathways into the community, extending out to the 10 km buffer, and in some directions, to 15 km. If a fire encroaches from the southeast or from the west or northwest, it will block a road and overall capacity will decrease. However, given that there are three available directions of egress and two are almost 180 degrees apart, it would not be possible for one fire to impact all three roads at once. The spikes in the radial graph show that a fire approaching from the southeast will cause a large reduction in capacity, as two roads (i.e., Highway 1 denoted by orange dots and Highway 1A denoted by green dots) are co-aligned and proximate in a single direction.

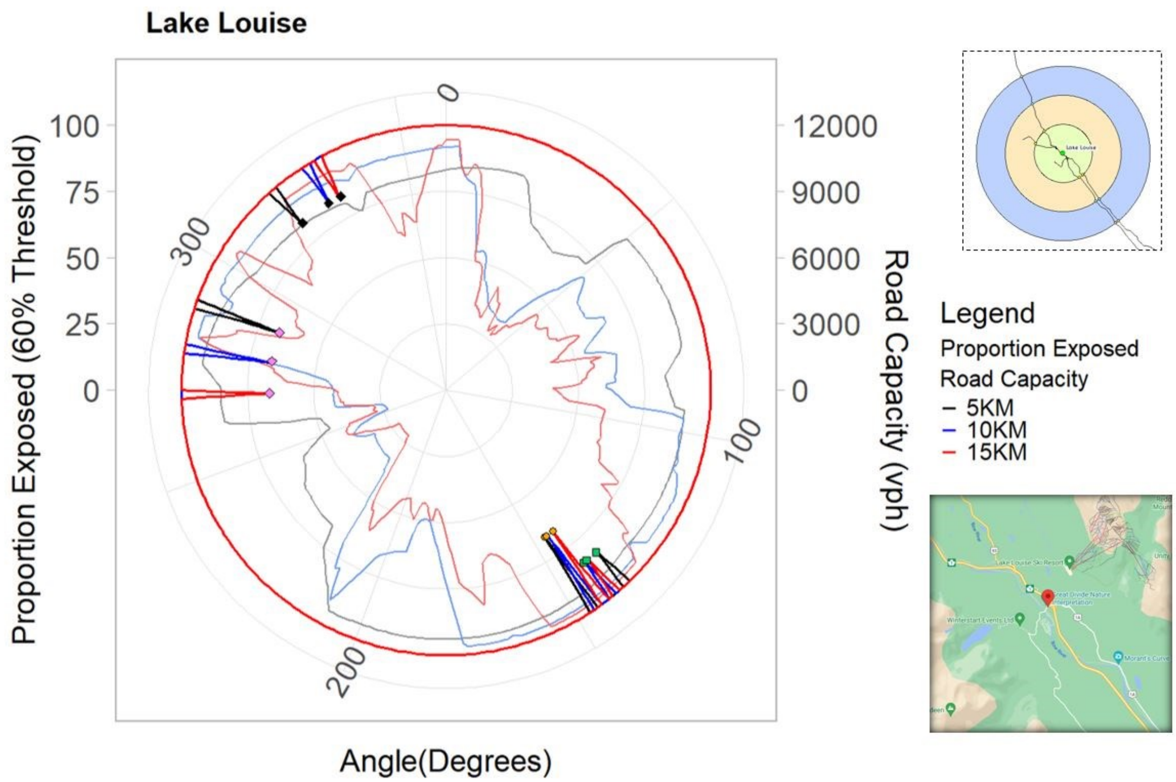

Figure 5.9: Plot of directional road capacity for Lake Louise in relation to critical exposure levels (i.e., proportion of directional transect with ≥60% exposure)

5.3.3 Blairmore

Highway 3 in Blairmore provides two egress routes in opposing directions (Figure 5.10), neither of which overlaps with exposure lobes delineating potential fire pathways into the community. This shows that a fire approaching the community within the most prominent fire pathways (i.e., from the north and northeast) will not block any roads, as the road network is oriented west to east.

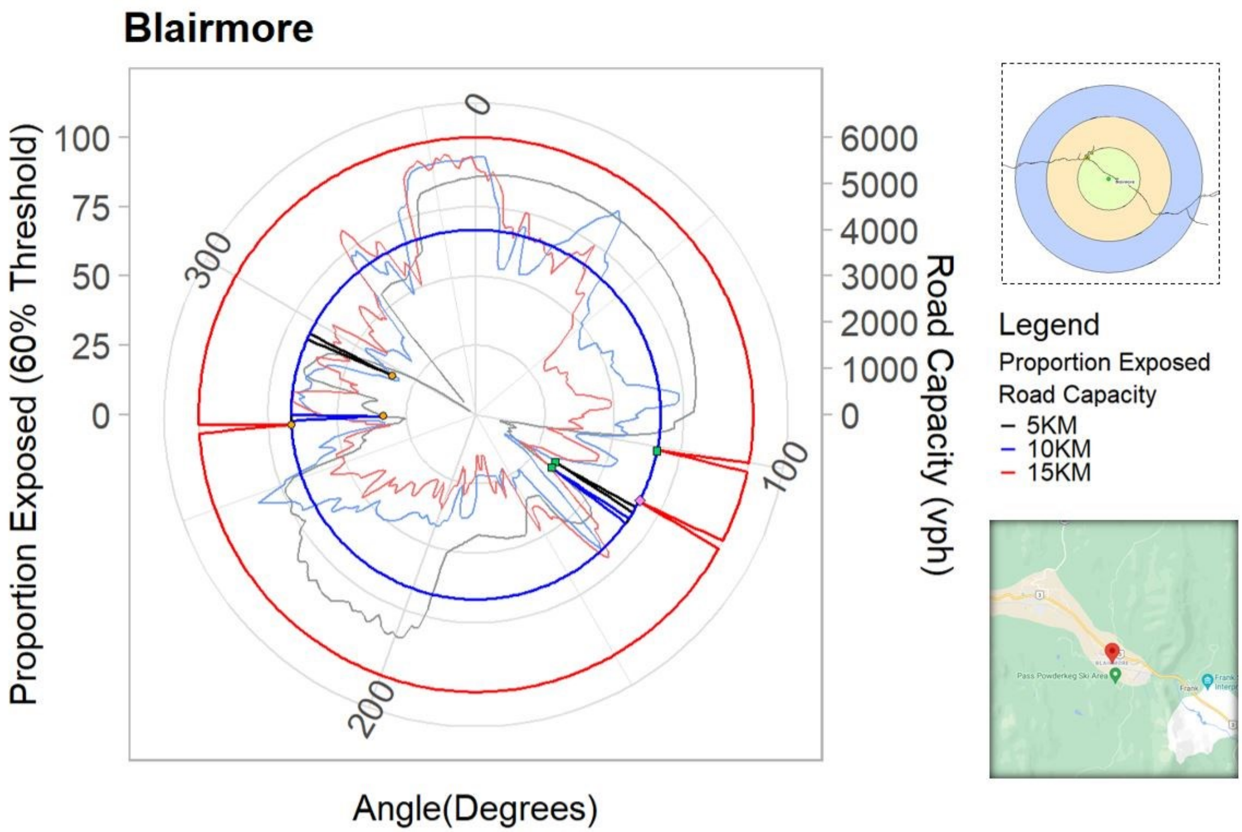

Figure 5.10: Plot of directional road capacity for Blairmore in relation to critical exposure levels (i.e., proportion of directional transect with ≥60% exposure)

5.3.4 Swan Hills

The community of Swan Hills (Figure 5.11) has three evacuation routes with the same capacities, but all are within large exposure lobes delineating fire pathways into the community. However, as the directions are diverging, an advancing fire towards the community will possibly not block all routes at once. A fire encroaching from the southwest, west, northwest, north or due east would not impact the road network directly. Road network exposure is limited to fires encroaching from the south, southeast and north-northeast.

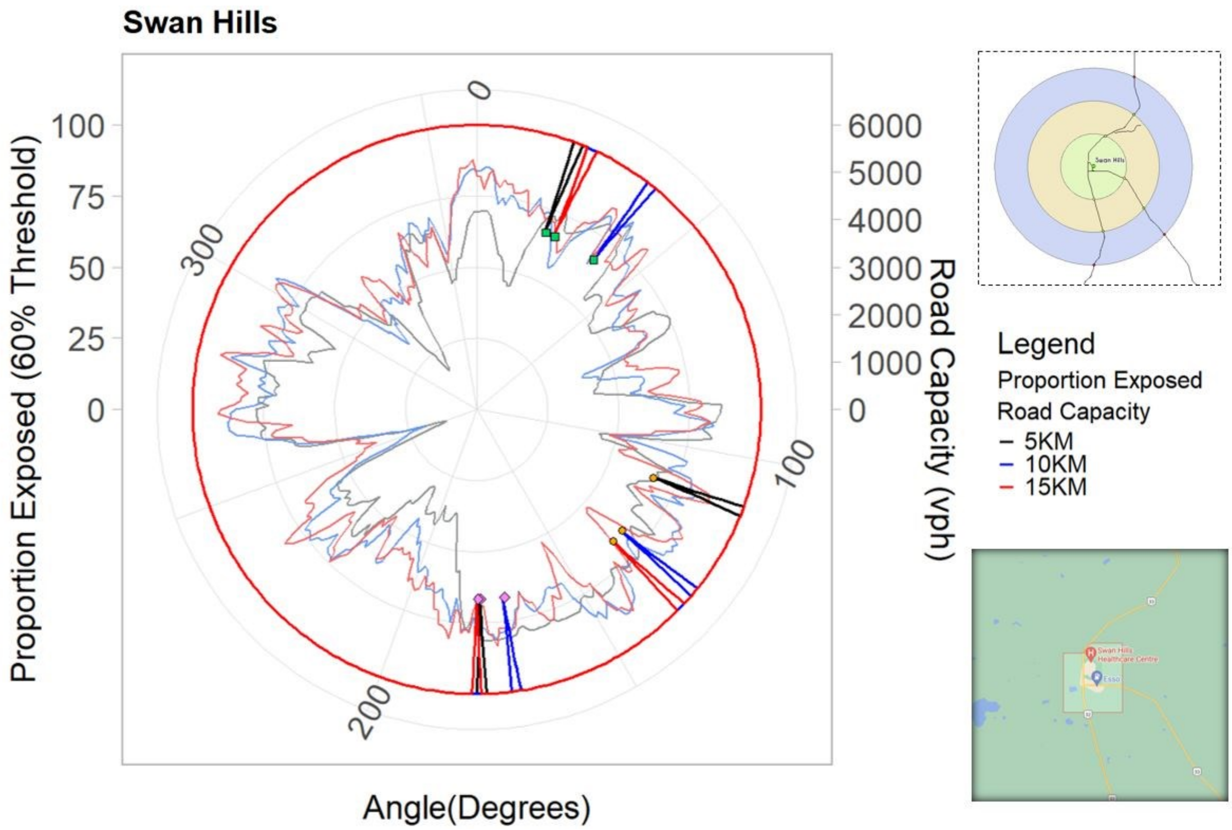

Figure 5.11: Plot of directional road capacity for Swan Hills in relation to critical exposure levels (i.e., proportion of directional transect with ≥60% exposure)

5.3.5 Calling Lake

Like many communities, Calling Lake is located next to a water body, which eliminates fire exposure over a broad surrounding area to the west and northwest of the hamlet and also limits routes in and out. There is one prominent exposure lobe at 160 to 180 degrees. This south-southeast fire pathway does not directly overlap with any roads. It is evident from the radial graph that the road network is not vulnerable to disruption from fires encroaching on the community within the available fire pathways.

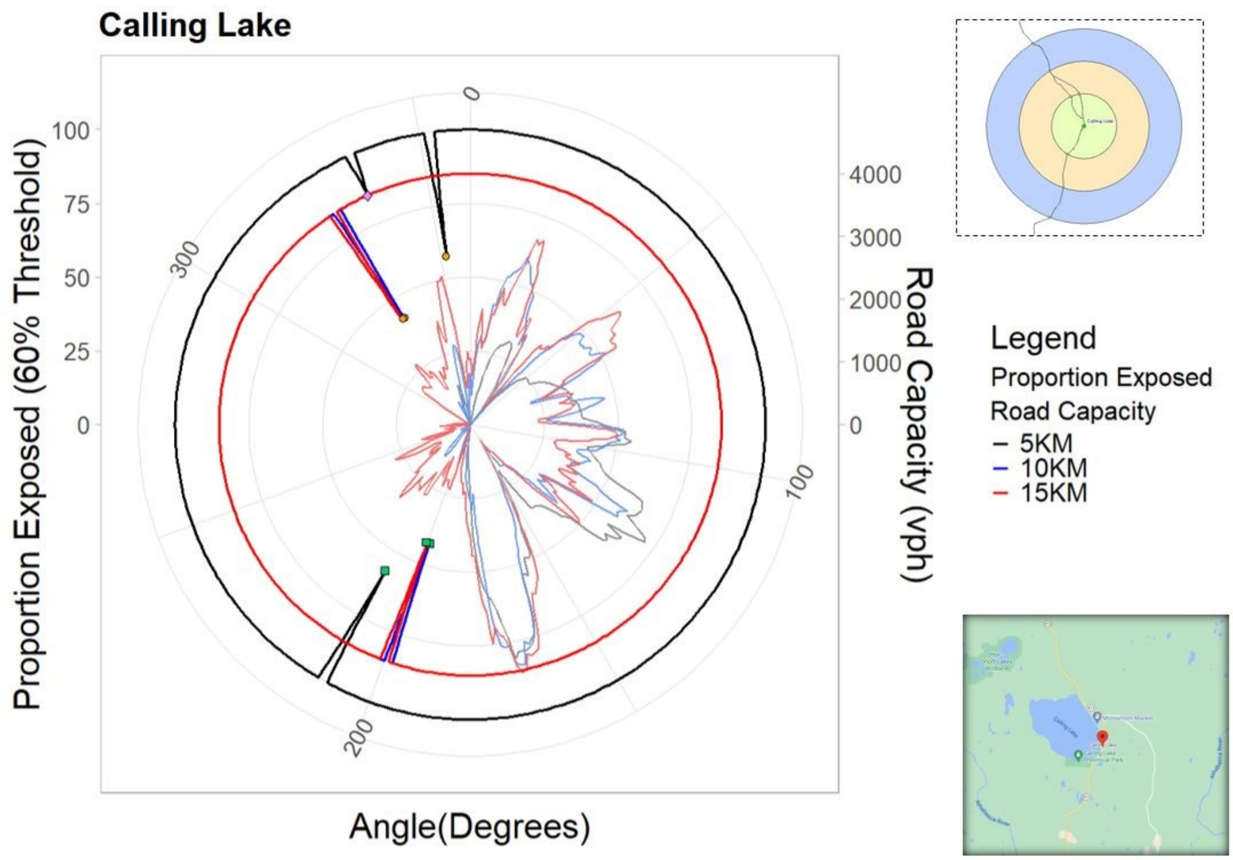

Figure 5.12: Plot of directional road capacity for Calling Lake in relation to critical exposure levels (i.e., proportion of directional transect with ≥60% exposure)

5.3.6 Discussion of Results

We now discuss some notable findings from the radial graphs of the remaining communities. Communities with highly limited transportation connections – such as one roadway connecting to a larger highway– may be highly vulnerable to wildfire, depending on directional fire exposure and how it aligns with available roadway(s). The communities of Fort MacKay and Rainbow Lake are shown in Figure 5.13; each have only one connecting road. The point of concern, however, is that these roads appear to align with high fire exposure.

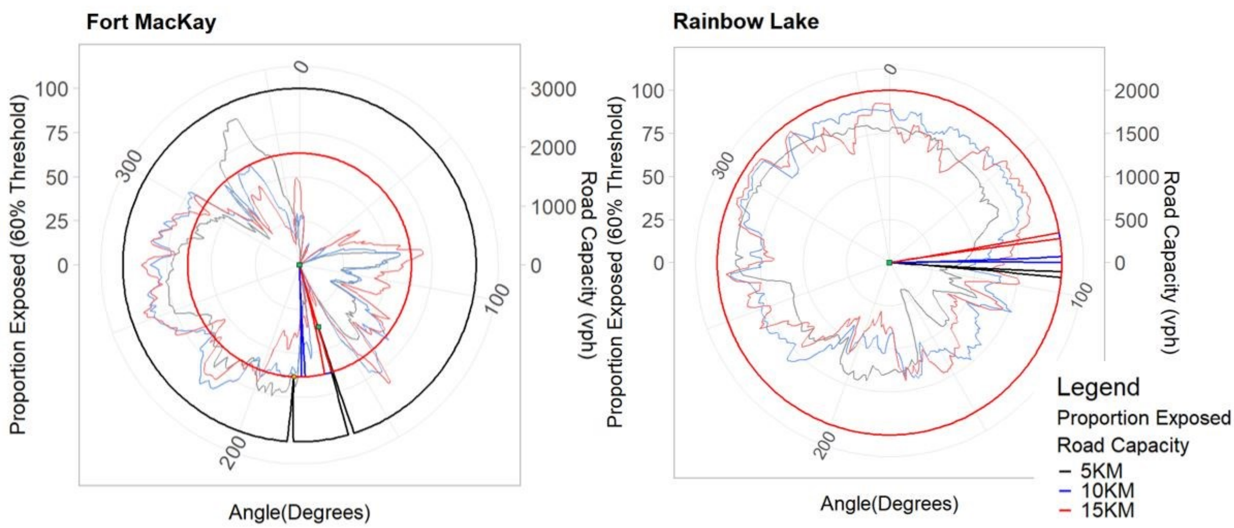

Figure 5.13: Community egress capacity and critical fire exposure levels (i.e., proportion of directional transect with ≥ 60% exposure), Fort McKay and Rainbow Lake (each with only one egress route)

In both Grande Cache and Wabasca (Figure 5.14), roadway egress capacity is directionally clustered (i.e., roads are proximate to each other, with radial positions that differ by less than 90 degrees). Large fires in the vicinity of these communities could potentially obstruct all egress routes – from northeast to southeast in Grande Cache, and southeast in Wabasca. Grande Cache has relatively high exposure values along the northern egress route and in proximity to the northeast route. Wabasca has one egress route eastbound that aligns with an exposure lobe delineating a potential fire pathway, while the southwest route does not. This suggests that Grande Cache is potentially more vulnerable to egress route disruption than Wabasca.

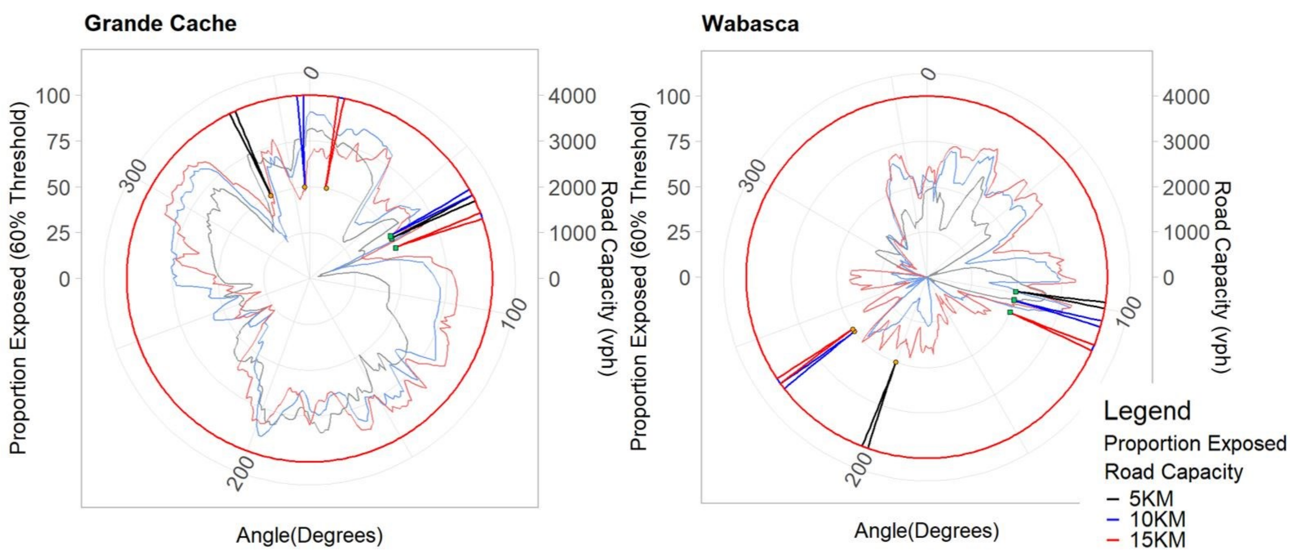

Figure 5.14: Community egress capacity and critical fire exposure levels – communities with roads grouped in limited directions

Some communities, such as Edson and Slave Lake, have egress routes with limited potential wildfire exposure (Figure 5.15), compared with the other communities discussed above.

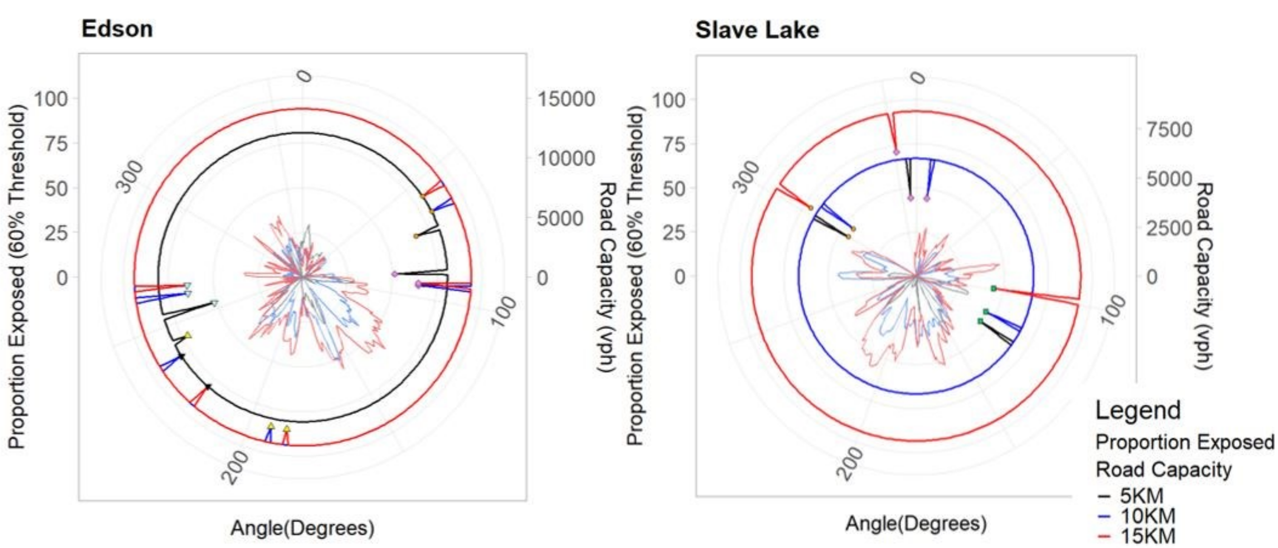

Figure 5.15: Community egress capacity and critical fire exposure levels - communities with limited directional fire exposure

5.4 Summary and Conclusion

In this chapter, we have presented an approach to plot directional transportation capacities in order to identify road network vulnerabilities caused by fire exposure pathways into communities. Our analysis shows that some communities – like Rainbow Lake, Chateh and Fort MacKay – have limited evacuation routes that are also vulnerable to fire-induced closures due to their alignment within exposure pathways. Fire exposure lobes or pathways might be limited in a given direction, but the presence of a road with high capacity (in absolute value or as a proportion of the total community egress capacity available) or that is the only community egress route can make it a direction of concern to consider and prioritize for mitigation measures.

Overall, this combined analysis of fire and transportation directional vulnerabilities identifies critical directions in which roadways are vulnerable to disruptions from wildfire, and provides some guidance towards decisions to prioritize community safety improvement measures towards wildfire evacuation capabilities and inform decisions about where to focus fire prevention, detection and suppression efforts. For example, FireSmart vegetation management treatments could be used to reduce or remove fuels along fire pathways that align with important egress routes. Banff, Canmore, Swan Hills, Lake Louise, Jasper, and Grand Cache were communities identified to potentially face road closures and thus reduced egress capacity should they experience wildfire encroachment, given that some of their routes are situated within very high fuel exposures. However, with multiple evacuating routes, they are potentially not as vulnerable as Rainbow Lake, Chateh or Fort MacKay.

CHAPTER 6. DYNAMIC DIRECTIONAL ANALYSIS

This chapter presents a dynamic framework for analyzing a community's directional vulnerability in a wildfire evacuation scenario. The same 21 communities of the previous chapter are used for analysis. The work of this chapter addresses the third research question: When a fire is a certain distance away from the community and an evacuation order is placed, will the fire reach the community before it can evacuate?

Disclaimer: *This work is an academic work in progress and not to be used for decision making. Also, we did not estimate any likelihoods or probabilities; rather, the* ***possibility*** *of approaching fire from a direction with road closure.*

6.1 Introduction

Timely evacuation of a community does not depend solely on egress capacity and fire exposure; the relationship between population size and egress capacity must also be considered, among other human behavioral factors (discussed in Aguirre (2005), Grajdura et al. (2021) and Wong et al. (2020), amongst others), as well as fire travel times. We capture and compare these within two features: the minimum travel time of a fire into a community, and the estimated time for the community to evacuate considering a possible road closure and corresponding reduction in total community egress capacity.

6.1.1 Model Setup

A circular buffer around a community is divided into eight equal pie-shaped sections, each spanning 45 degrees, and the minimum fire spread time in each section was calculated. Estimated fire travel times were generated using the Canadian Forest Fire Behaviour (FBP) Prediction system (Forestry Canada Fire Danger Group 1992) for different fuel types present under assumed weather conditions. The fire travel time is t_1^s, where $s = 1 \dots 8$ are the pie-shaped sections starting from due north marked as 0°, continuing clockwise such that $s = 1$ is the section from 0-45 degrees, $s = 2$ is 45-90 degrees, and so on. Then, we used a macroscopic traffic simulation model (Lighthill Whitham and Richards, or LWR model) to estimate the time for evacuees to travel a safe distance (10 km) away from the community, t_2^s. Finally, we compare t_1^s and t_2^s for each community as an indicator of potential community vulnerability to wildfire, for $s = 1 \dots 8$. Segments spanning 45 degrees were chosen because larger segments omit spatial detail, whereas smaller segments introduced unnecessary detail and complexity in land cover data and roads. The difference between t_1^s and t_2^s , $\Delta t^s = t_2^s - t_1^s$, was calculated for each directional segment.

We consider the decision of when an evacuation is called. 29% of the evacuations between 1980 and 2007 documented in Canada had distance data; of these, 80% were prompted by a wildfire that had travelled within 10 km of the evacuated community. To account for the spatial extent of the built environment, we classified communities into two categories: larger and smaller. A 5-km buffer was plotted around each community and assessed visually. Communities with limited development within the 5 km buffer were classified as smaller, whereas those with extensive development were classified as larger. Figure 6.1 indicates whether a community is classified as smaller or larger and Table 6.1 shows the list of these two community categories.

Table 6.1: Smaller and Larger Communities

Smaller (5 km buffer)	Larger (10 km buffer)
Assumption/Chateh	Banff
Bragg Creek	Canmore
Calling Lake	Edson
Exshaw	Fort McMurray
Lake Louise	Hinton
Rainbow Lake	Slave Lake
Swan Hills	Whitecourt
Wabasca	
Blairmore	
Fox Creek	
Grande Cache	
Jasper	
Fort McKay	
Coleman	

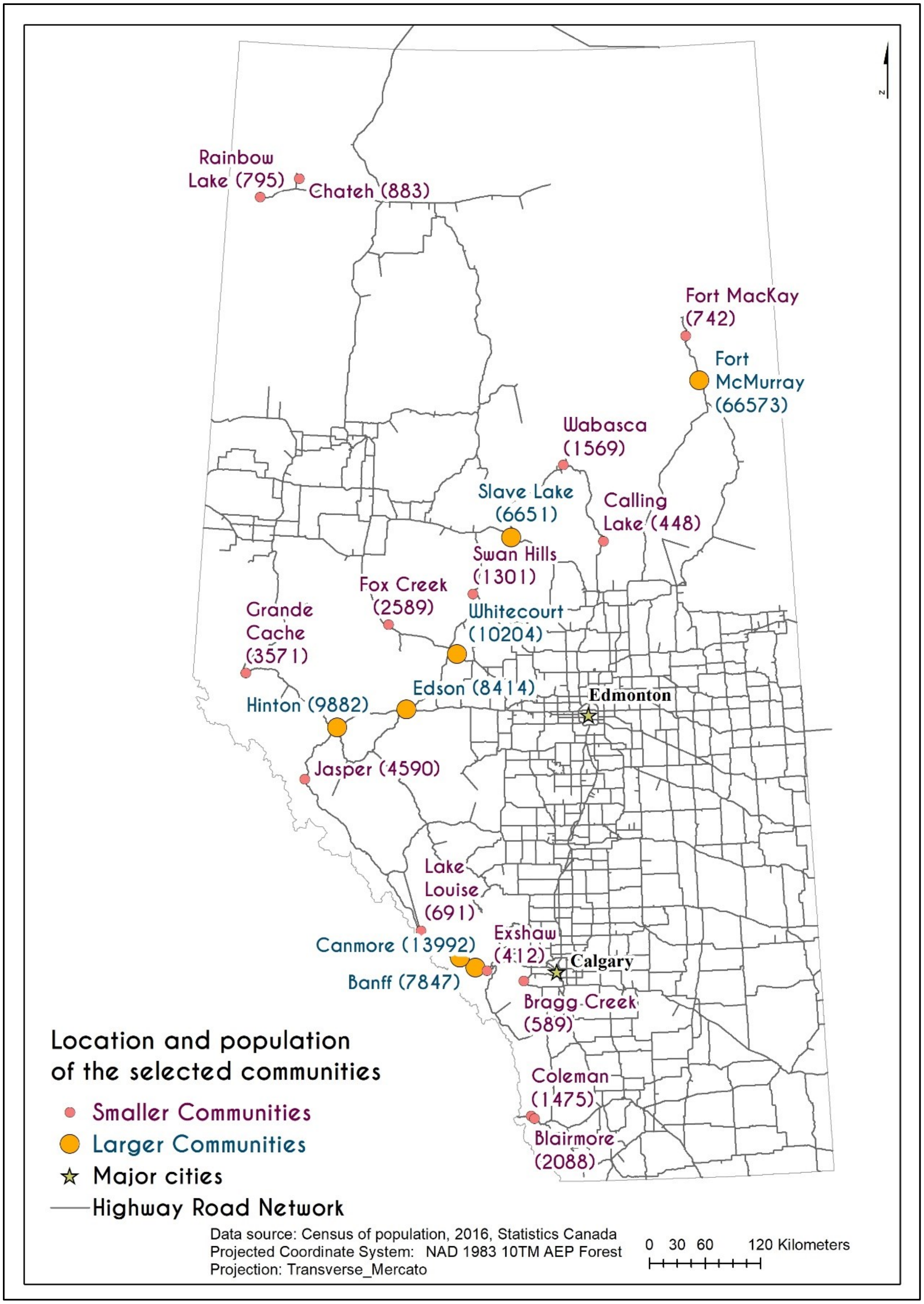

Figure 6.1: Selected communities for analysis in Alberta, Canada. Community populations are taken from the 2016 Canadian Census (Statistics Canada, 2017) are shown next to community names.

As an illustration, let us focus on Fox Creek (designated smaller) and Hinton (larger), shown in Figure 6.2. The pink and white circles delineate 5 and 10 km buffers, respectively, from the community centroid. For Hinton, the 5 km boundary contains extensive developed lands, whereas Fox Creek has minimal developed lands beyond a small core. A fire that reaches the 5 km buffer edge at Fox Creek would have to continue further before reaching the built environment. The default 5 and 10 km buffers utilized in this study were adopted as a simplified approach for assessing multiple communities across a large provincial jurisdiction in a standardized manner, and may not be suitable for all communities. We recommend developing more refined, customized buffer distances for individual community assessments to reflect the varied spatial footprint of the built environment.

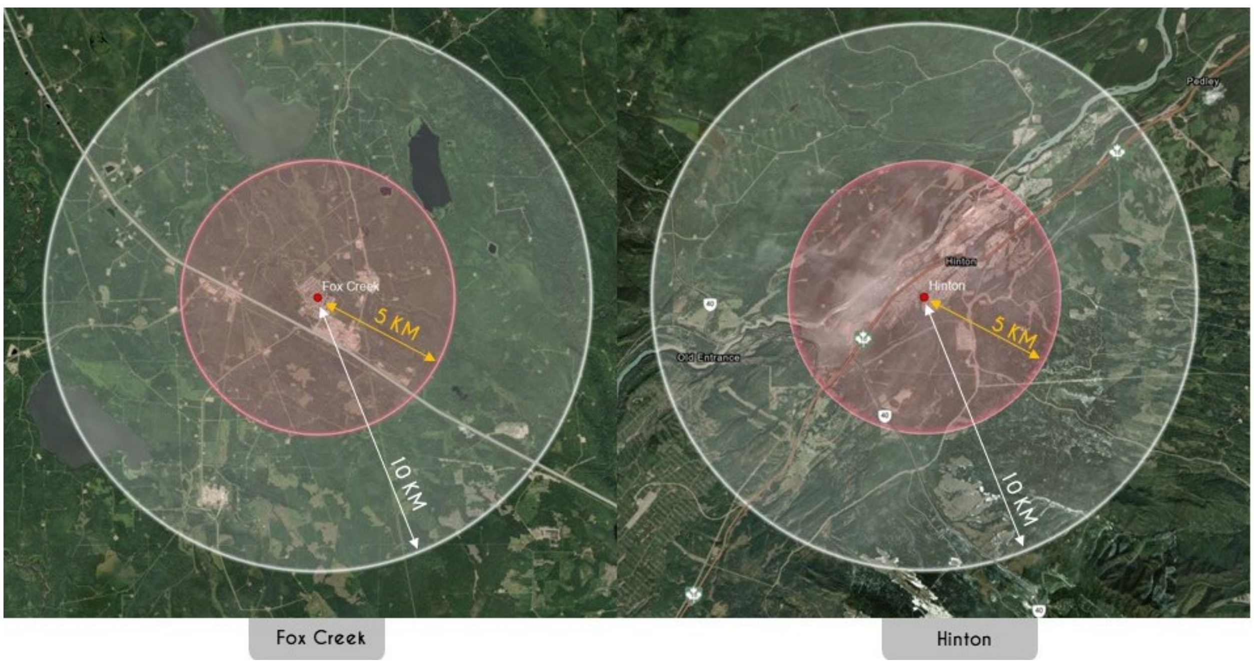

Figure 6.2: Variation in community sizes and their boundaries

When the fire is 5 km from a smaller community, we assume a mandatory evacuation order is called; and for larger communities, orders are assumed to occur when the fire is 10 km away. For smaller communities, t_1^s is the minimum possible time for the fire to travel from 5 km to the community centroid, for segment s (and assuming residents should have evacuated before the fire reaches the community at 0 km). For larger communities, we assume an evacuation order is called at 10 km, and t_1^s indicates the minimum time required for the fire to travel from 10 to 5 km in s (assuming residents evacuate before the fire reaches 5 km).

6.1.2 Evacuee Travel Time, t_2

The evacuation time t_2^s required for residents to travel 10 km away from the community (assumed a safe distance for both smaller and larger communities) depends on whether segment s contains a roadway that would be obstructed by a fire in that segment, rendering the egress capacity provided by that road unusable. In our scenario-based analysis, as evacuation is assumed to begin when a fire is 10 km (for larger communities) or 5 km (for smaller communities) away from the community centroid. We calculate t_2^s using the LWR model together with an evacuee mobilization time curve following the Rayleigh distribution. The parameter used for the Rayleigh distribution is related back to fire travel time, explained in the following section.

6.1.2.1 Mobilization Curve

Evacuation mobilization time is the period between when an evacuation order is issued and the time that evacuees depart (Yazici & Ozbay, 2008; Li et al., 2013). Before evacuees depart, several critical decisions and actions take place, including the decision to evacuate, preparation time, and loading into vehicles. Mobilization time includes all these decisions and actions, and assumes people are mobilized once they are in their vehicles and moving (Li et al., 2013).

Mobilization time curves are also known as "S"-curves because of their shape. Various mathematical models including Artificial Neural Networks, sigmoid "S"-Curves, the Rayleigh distribution, and sequential logit model (Tweedie et al., 1986; Yazici & Ozbay, 2008; Radwan et al., 1985) are used to represent mobilization curves. Mobilization curves are widely used in the literature irrespective of the evacuation type, because they are not data intensive to produce and are mathematically simple in representing evacuee movement. However, these curves usually cover a shorter evacuation period (i.e., evacuation duration of less than a day) and do not capture variations with evacuation order type, time of the day variation, or disaster characteristics (Ozbay & Yazici, 2006). The mobilization curve represents a count of vehicles, for example, that are actually moving past a point/cordon, rather than evacuation demand (or an intention curve).

In defining a mobilization curve for input to the traffic simulation, we make some assumptions. First, the mobilization curve must be defined for the mode of transport based on whether evacuees are traveling on foot, or by vehicle, for example. In this study, evacuees are assumed to travel by vehicle. Second, Wahlqvist et al. (2021) assumed 14% of evacuees leave before an evacuation order is placed, while 5% never evacuate at all; the remaining 81% evacuate after the evacuation order is called. Third, we assumed an evacuee vehicle occupancy of two, following Woo et al. (2017). With these assumptions, the estimated vehicular evacuation demand of a community such as Fox Creek is computed as 1,048 vehicles, given a population of 2,589 and assuming 81% of residents evacuate with two persons per vehicle, and all residents leave by vehicle (*Statistics Canada*, 2021). Finally, we assume the curve follows the Rayleigh distribution.

Rayleigh distribution

Tweedie et al. (1986) first used the Rayleigh distribution to define a mobilization time curve ("S"-curve), which was used to perform a Monte Carlo simulation of the evacuation of Oklahoma's emergency planning zone required by the U.S. Nuclear Regulatory Commission (NRC). This curve represents the cumulative percentage of evacuees at each time period, which is also true for all S-curves. The equation is as follows:

$$F(t) = 1 - \exp\left(-\frac{t^2}{MMT}\right) \qquad \textbf{(Eq. 6.1)}$$

$F(t)$ is the cumulative percentage of total trips generated at time t

t is time, in minutes

MMT is the maximum mobilization time, in minutes

The maximum mobilization time is the assumed time available to mobilize the last evacuee/vehicle. This time will vary for different communities and disaster types. Tweedie et al. (1986) took MMT as 1800 minutes based on expert opinion. This S-curve is based on a single parameter and simple to use. In the case of an evacuation due to wildfire, the time when the fire hits a trigger buffer point to the time when all evacuees' vehicles must be mobilized can be considered the maximum mobilization time, or MMT. Figure 6.3 shows the proportion of cumulative mobilized evacuees over time, for different maximum mobilization times. The curve represents moving vehicles generating evacuation demand.

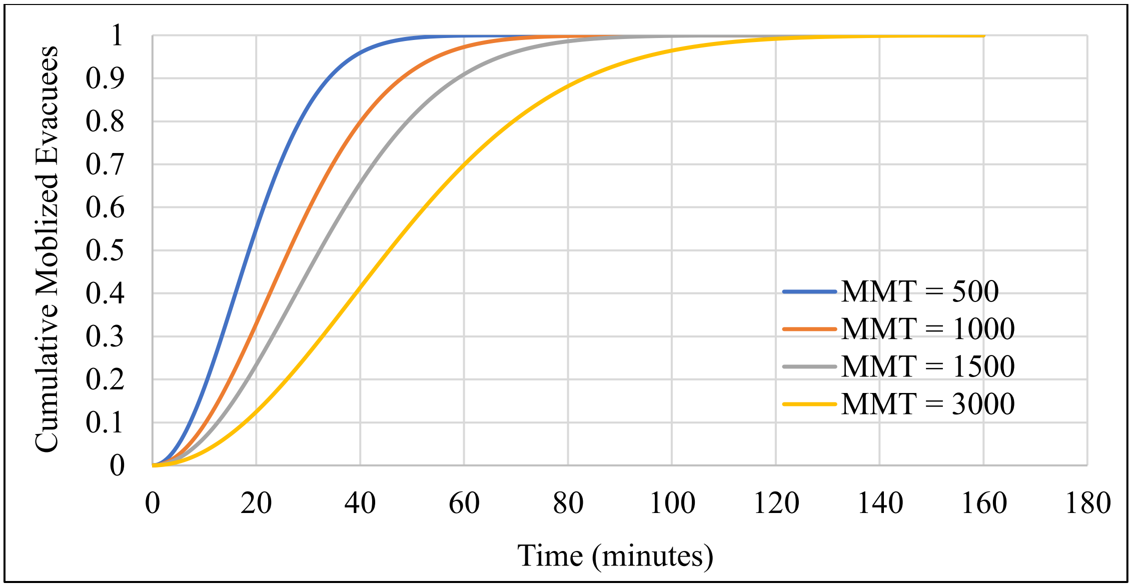

Figure 6.3: Cumulative mobilization curve for Tweedie's approach (Rayleigh Distribution) with changing maximum mobilization time.

Radwan et al. (1985) S-Curve

Radwan et al. (1985) proposed an evacuation mobilization S-curve based on half loading time (H) and public response (α), shown in Eq. 6.2. H represents the time at which half the vehicles in the system have been loaded onto the highway network, and α represents the response of the public to the disaster, which affects the slope of the curve.

$$P(t) = \frac{1}{1 + \exp\big(-\alpha * (t - H)\big)} \quad \textbf{(Eq. 6.2)}$$

Where:

$P(t)$ is the cumulative percentage of total trips generated at time t

α is the shape parameter defining the curve's steepness

H is half loading time, in minutes

This formula is used in evacuation simulation packages like TEDSS and MASSVAC too. However, it is difficult to determine half-loading time (H) or curve steepness (α) parameters without empirical knowledge. Figure 6.4 shows the variation of percent cumulative mobilized evacuees with time for different α values. It shows that a slight change in α value changes the steepness of the curve sharply, indicating the equation is very sensitive to the assumptions.

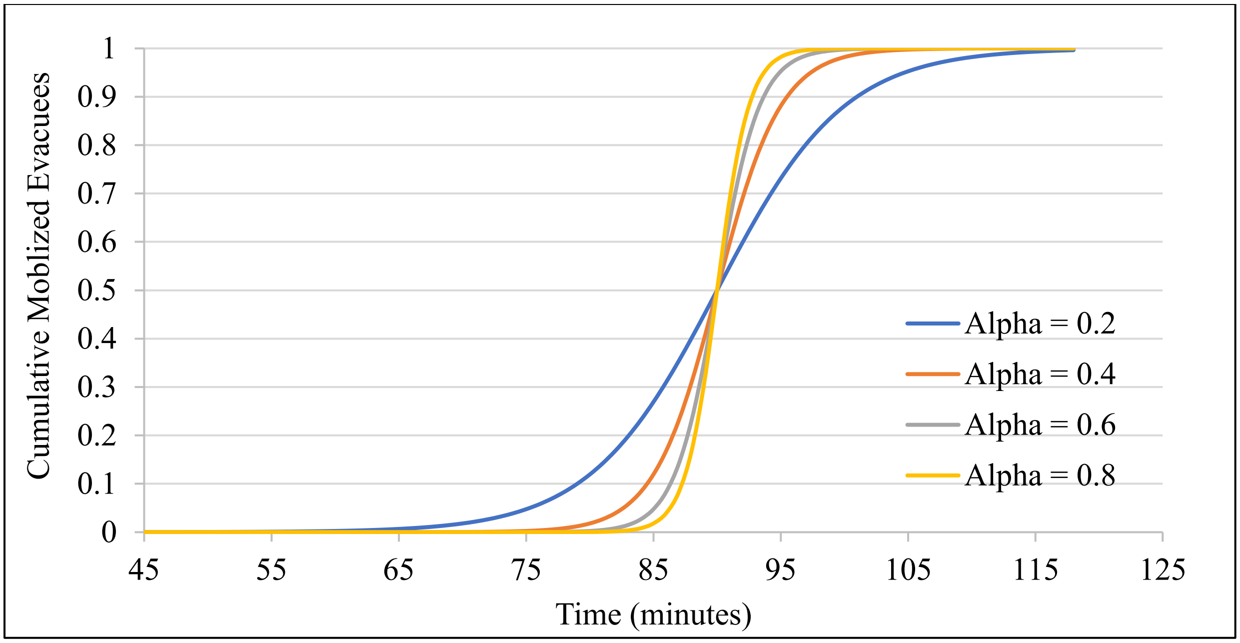

Figure 6.4: Radwan et al.'s (1985) cumulative mobilization curve with different values of α

Sequential logit model

Fu (2004) and Fu et al. (2007) used the sequential logit model to develop a response curve model for hurricane evacuation. In the sequential logit model, the random utility function U_i^c represents a household's utility not to evacuate at time i, while U_i^s is the utility of the household to evacuate at i. These utility functions consist of a deterministic component represented by $\beta x'$, where β are parameters on explanatory variables x', and a random error term ε; i.e., $U = x'\beta + \varepsilon$. $P(i)_{s/c}$ in Eq. 6.3 indicates the probability of a household to evacuate at the time i, if it has not already evacuated:

$$P(i)_{s/c} = \frac{e^{\boldsymbol{x}'\boldsymbol{\beta}}}{1 + e^{\boldsymbol{x}'\boldsymbol{\beta}}} \qquad \textbf{(Eq. 6.3)}$$

Where:

$P(i)_{s/c}$ is the probability of a household to evacuate at the time i, given that it has not evacuated

$\boldsymbol{x}'$ are explanatory variables which can include distance to shelter location, time of day, speed, road condition, risk or hazard, and others

$\boldsymbol{\beta}$ are estimated parameters

Lognormal distribution

Ronchi et al. (2020) used a lognormal distribution to define the Wildland Urban Interface & Unity 3D (WUI-NITY) platform's mobilization curve (Ronchi et al., 2020). The lognormal curve has two parameters, μ and σ, which are not assigned particular physical meaning like the parameters introduced for the previous evacuation mobilization curves. It is not realistic to assign any single specific μ and σ values for all communities, as parameters will vary with the duration of the evacuation, population, and evacuation order type (mandatory or voluntary).

We chose to use the Rayleigh distribution following Tweedie et al. (1986) because of its simplicity in the absence of data. Other approaches rely on parameters that lead to various difficulties. For example, the lognormal distribution is defined by parameters u and σ, which we are unable to define. In addition, the two parameters would require calibration for each community based on their particular attributes. A similar problem arises with Radwan et al.'s (1985) formula –any fixed H and α cannot be predefined for all communities, rather they must be calculated for each community individually based on its attributes. Thus, we deemed the Rayleigh distribution most suitable for our analysis over other distributions given its simple, intuitive, and single MMT parameter, and thus moved forward with its use in our analysis.

In this thesis, MMT is defined as the fire spread time towards the community, for each directional segment s. It is the time between when the fire intersects the trigger buffer and mandatory evacuation is called (i.e., at a distance of 5 or 10 km, depending on the community size category of "smaller" or "larger"), and when the fire is assumed to reach the community (0 or 5 km, for smaller and larger communities, respectively). Thus, $MMT = t_1^s, s \in 1 \dots 8$.

6.1.2.2 Traffic Simulation

The simulation is based on the principles of the Lighthill-Whitham-Richards (LWR) model, a hydrodynamic model defining the relationship between vehicle density and flow (Lighthill & Whitham, 1955). The model is based on the hypothesis that at any point on a roadway, flow q (in vehicles/hour) is a function of density, d (vehicles/km). The model is shown in Eq. 6.4, showing that flow and density are related to a law of conservation of vehicles. Here, $d(x,t)$ and $q(x,t)$ represent density and flow, respectively, as a continuous function of space and time.

$$\frac{n(x) * \partial d(x,t)}{\partial t} + \frac{\partial q(x,t)}{\partial x} = 0 \qquad \textbf{(Eq. 6.4)}$$

Where:

$n(x)$ is the number of lanes at roadway distance x

$d(x,t)$ is traffic density at roadway distance x and time t, in vehicles/lane/km

$q(x,t)$ is traffic flow at roadway distance x and time t, in vehicles/hour

The LWR model includes continuous functions, and thus we discretize time in intervals M to perform a simulation. We assume time interval M to be 0.01 minutes or (0.6 seconds). Although smaller M leads to a better approximation of the continuous equations, the results are similar whether M is 0.01 or minutes. The 10-kilometer distance is discretized into 10 cells and each cell is considered as 1km. The discretized version of the equation is shown in Eq. 6.5.

$$d_i(m+1) = d_i(m) + \frac{M}{l_i * n_i} * \left[q_{in,i}(m) - q_{out,i}(m)\right] \qquad \textbf{(Eq. 6.5)}$$

Where:

m is the iteration number for M

$d_i(m)$ is the average traffic density in section i at m

l_i is the length of section i

n_i is the number of lanes in section i

$q_i^{in}(m)$ is the inflow in section i at m

$q_i^{out}(m)$ is the outflow in section i at m

We also use Greenshield's linear speed-density relationship (Greenshields et al., 1935):

$$v = v_f * \left(1 - \frac{d}{d_j}\right) \qquad \textbf{(Eq. 6.6)}$$

Where:

d is density in vehicles/lane/km

d_j is the maximum or jam density

v_f is the maximum (or free-flow) speed of the roadway in question.

Although the speed at jam density is zero in Greenshields' model, we follow Ronchi et al. (2020) and use 5 kph (kilometers per hour), assuming that vehicles will still be moving very slowly at very high densities. In addition, as part of the simplification of the traffic simulation, we assume that vehicles cannot enter the downstream section if jam density is reached on that section. As with all macroscopic traffic models, intersection operations and vehicle dynamics like overtaking are not considered. It is important to note that we distributed demand amongst available roadways proportionate to each road's capacity – a major assumption that should be revisited in future work.

6.2 Sensitivity Associated with Seasons

To explore the variation between the two seasons most fire-prone in Alberta, the same calculation is performed separately for spring conditions. The results show that although some communities show differences in the results of Δt values for each segment s, Δt^s, between the different seasons, their highly vulnerable directions (red colored) remain the same. Moreover, the relative rankings of the directions with respect to evacuation vulnerability remain the same for most communities. Specifically, for the smaller communities, 88% of the directions are ranked as the same for both seasons. For the larger communities, 75% of the directions retain the same rank. There are some small differences in rankings; for the smaller communities, for example, 99% of differences are only one step (i.e., ranked 5 in summer condition and ranked 4 in spring).

As spring conditions are drier than summer, the relative wildfire rate of spread is higher and shows smaller Δt values. For most directions, the differences are small and remain very close for these two consecutive seasons. The results indicate that road and fuel positions remain unchanged during seasons; the most vulnerable directions remain the same. The overall seasonal calculation indicates that although we performed the analysis for the worst seasonal condition (spring) of the year, this analysis can also be used to prioritize critical evacuation directions in other seasons.

6.3 Results

The difference between the minimum fire travel time t_1^s and evacuation time t_2^s , Δt^s, was calculated for each directional segment s, and for both spring and summer conditions (the most fire-prone seasons of the year in Alberta), with comparison facilitated by normalizing Δt^s values between 0 and 1 separately for each community. These normalized values are to compare directions for each community individually. The results are presented in an interactive online map created with ArcGIS Pro version 2.9.1, which can be accessed via email request to the author's co-supervisors.

Simulation results change with the fire travel times in different seasons, because the mobilization curve's MMT parameter depends on fire spread rate. As spring conditions are drier than summer, the relative wildfire rate of spread is higher and thus Δt values are often slightly smaller than for summer. Despite this, we note that the most vulnerable segments, and relative rankings of directions with respect to evacuation vulnerability, remained largely similar for each community. For the smaller communities, 88.4% of the directions are ranked the same for both seasons; for the larger communities, this was 75%.

Figure 6.5 shows example outputs for three communities classified as "larger" (results will be discussed in 6.3.1). A direction is deemed vulnerable if a fire from that direction is estimated to reach the community before or close to when the community can evacuate fully (which of course depends on whether roadways are also contained within the directional segment in question). When Δt^s is small or negative (shown in red) for directional segment s, it indicates high vulnerability, with fire reaching the community in a close or even shorter time than residents can evacuate 10 km away. When Δt^s is large, vulnerability is low (green – up to 250 minutes additional time for evacuees to reach 10 km compared with fire travel times). The colours are chosen using the Symbology tool in GIS, and represent direct Δt^s values, and not the normalized values. Details of the results are discussed in the following sections.

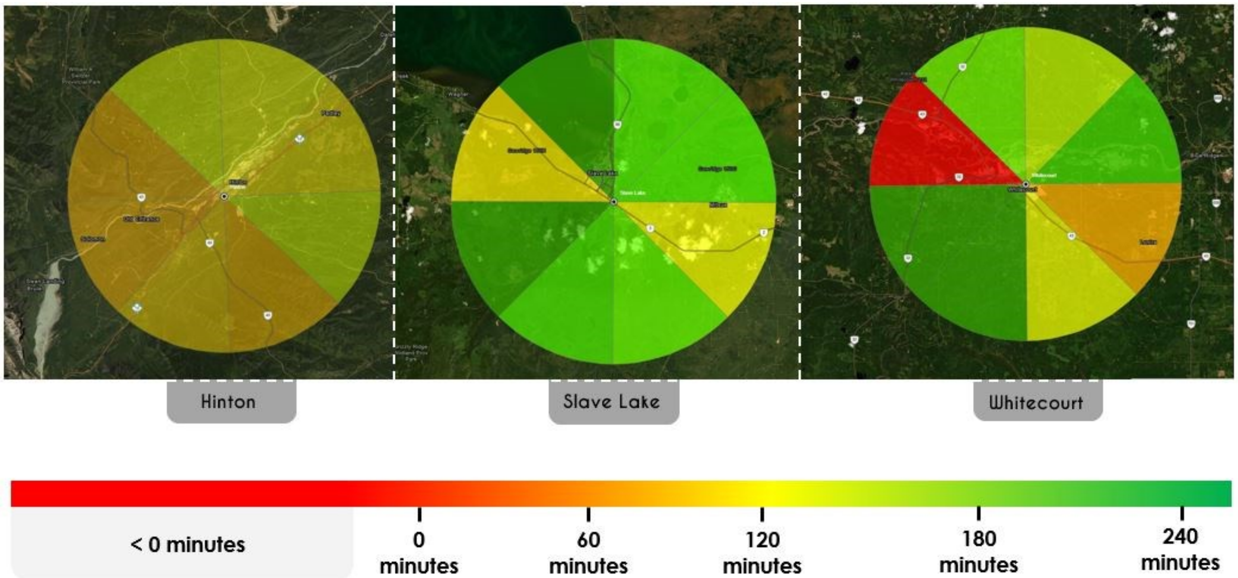

Figure 6.5: Dynamic directional analyses for Hinton, Slave Lake and Whitecourt

6.3.1 Larger Communities

Our analysis shows that fires entering communities from certain directions pose greater threats. For example, for Slave Lake, a fire coming from west or east will impact roads that are limited for this community (Figure 6.5). Although potential road closures make these directions more vulnerable, the directional segment containing a northbound road is green. This suggests that potential road closure alone does not indicate vulnerability, but rather depends on a combination of wildfire travel times and roadway egress capacities.

For Whitecourt, the west-northwest directional segment $s = 7$ is red, with $\Delta t^7 = -53$ minutes, indicating that a potential fire entering the community from that direction could enter 53 minutes faster than evacuation to 10 km can occur, considering that the road leaving the community in the west-northwest direction is closed due to fire encroachment. The results also indicate that the other directions are not critical, suggesting that this community could further investigate and prioritize fire mitigation measures in this direction, and evacuation planning measures with this in mind. For Hinton, the results show that all directions may be of some concern to the community, particularly those spanning 135 to 315 degrees (segments $s = 4,5,6,7$). Overall, however, no direction is clearly flagged like that of Whitecourt.

Of the seven larger communities, Fort McMurray, Whitecourt, Banff, and Canmore have directional segments shown in red, indicating fast fire travel times combined with sizable roadway capacity shortfalls, suggesting concern for community evacuation. Of the 56 total directional segments associated with these larger communities (i.e., eight per community), 13 segments (23%) were assessed as highly vulnerable (red) and of evacuation concern. Of these 13 segments, Banff and Canmore share nine. This is expected due to the fact that both communities have relatively large populations (7847 and 13992, respectively) compared to their egress capacities, and both are situated in landscapes with high fire exposure. In addition, both are popular summer recreation and tourist destinations, and populations swell in the summer season.

We now compare our static and dynamic analyses results, and discuss the relationship between the results. Plots of the static analysis for Hinton and Whitecourt are shown in **Error! Reference source not found.**, to compare against the results of the dynamic analysis shown in Figure 6.5. The two communities have similar total road capacities and populations. From **Error! Reference source not found.**, it appears that Hinton (population 10,200) has continuous fire pathways or lobes to the southwest at all three buffer distances assessed (5, 10, and 15 km), which coincide with one of the four egress routes available. Large lobes exist at 10 and 15 km distances to the northwest and southeast, which also overlaps egress routes, but less so at 5 km. However, Figure 6.5 provides a comparison of the times which fire can enter the community and people are able to egress; results suggest that community evacuation should be able to occur in a relatively timely fashion, given estimated fire travel times, potential roadway closures, and subsequent throughput capabilities on the remaining open roads. However, one hour may not be a sufficient buffer between evacuation to 10 km and the fire reaching the community at 5 km. The community may consider fire mitigation actions between 135-315 degrees around the community.

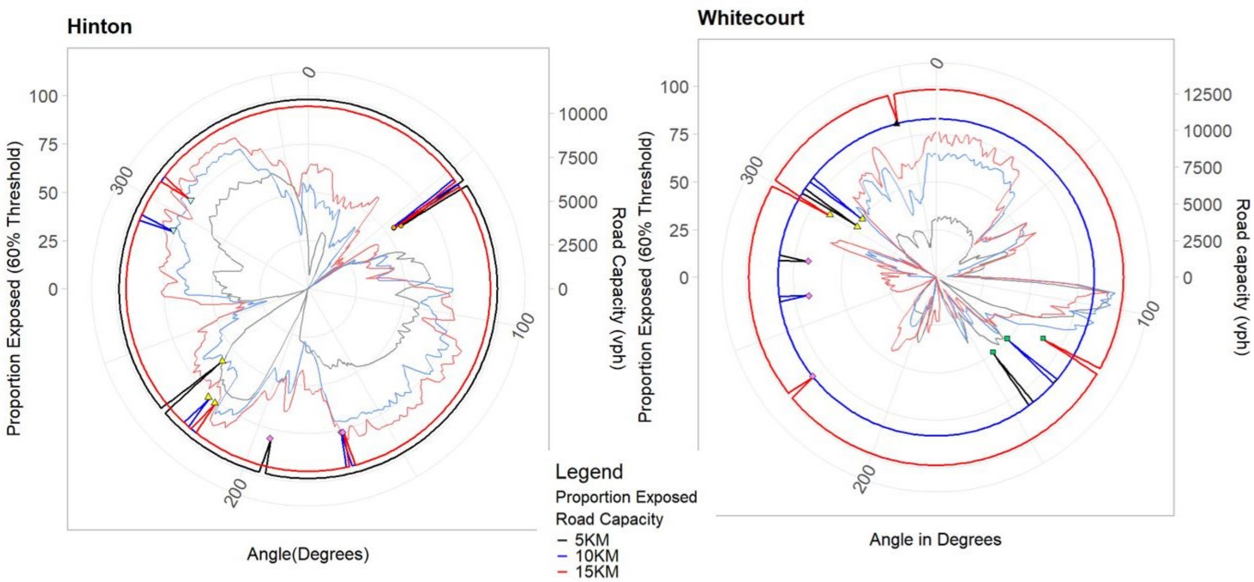

Figure 6.6: Comparing results from Ch. 5 analysis, Hinton and Whitecourt

For Whitecourt (population 9,900), Figure 6.6 indicates that the main continuous fire pathway is to the east/southeast, with large lobes at all three distances. Figure 6.5 reinforces the observation from Figure 6.6 but also reveals another direction of major concern to the northwest. It is shown in red due to negative Δt values, which results from the fact that fire travel times in that direction are small compared with community egress capabilities resulting from closure of the road towards the northwest (Highway 43, which provides significant capacity to the community as shown in Figure 6.6).

The static and dynamic analyses are based on different fire (exposure versus travel times, respectively) as well as transportation metrics (roadway capacity versus throughput times, respectively). As a result, the results show different perspectives on community vulnerability, with the first reflecting vulnerability based on static observations of the infrastructure and biophysical environment, and the second considering the movement capabilities of both fire and people. The results of the static analysis could be used to inform fire mitigation and vegetation management (such as FireSmart) approaches, while the dynamic analysis may be more informative towards considering and eventually designing community early warning systems.

6.3.2 Smaller Communities

The smaller communities assessed show less evacuation vulnerabilities compared with the larger communities, due to their very small populations (i.e., often in the hundreds). Only four of the 14 small communities (Rainbow Lake, Chateh, Fort MacKay, and Grand Cache) exhibit concerns, shown in Figure 6.7. As with Hinton, static analyses of Rainbow Lake and Fort MacKay (Figure 5.13) suggest considerable vulnerabilities, particularly Rainbow Lake, due to critical fire exposures overlapping only one egress route each. The dynamic results of Figure 6.7 appear to mirror the static results, which is somewhat different from what we observed for the large communities of Hinton and Whitecourt. Figure 6.7 indicates that the travel times of fires entering Fort MacKay and Rainbow Lake in the same segments in which their egress routes are located are smaller than or close to community evacuation times, which is cause for concern. Other than those segments, however, the rest are light to dark green indicating more than adequate capability for the community to evacuate via the sole egress route available.

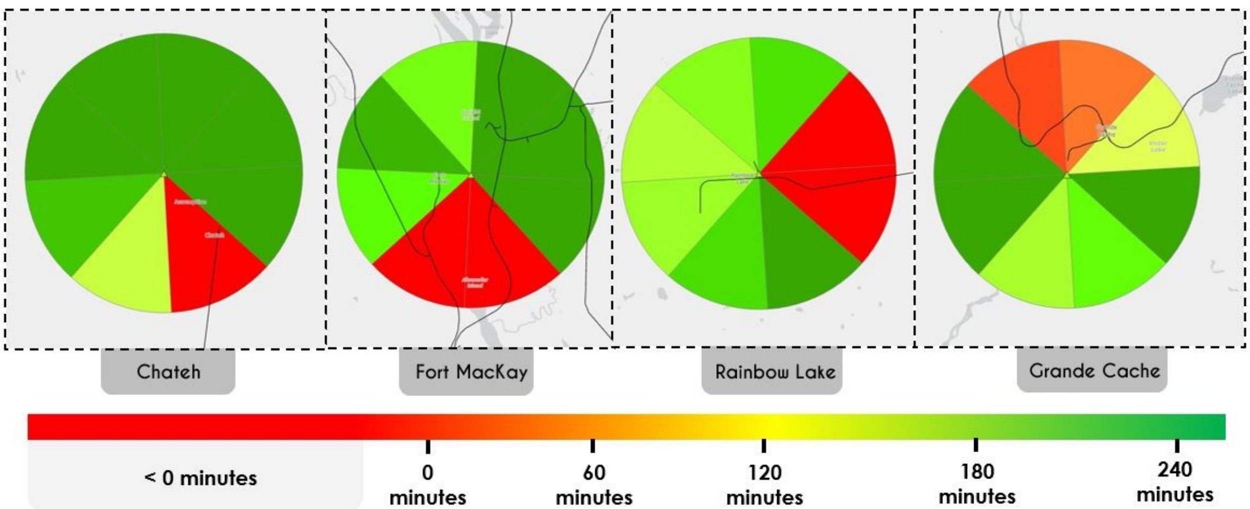

Figure 6.7: Results for smaller communities are showing red directions mainly due to road closures

The remaining 10 small communities may be adjacent to landscapes with critical fire exposure levels, but their roadway capacities are more than adequate to accommodate their small populations in an emergency evacuation.

6.4 The Storyline ArcGIS Online Map

The findings of all the analyses are also presented on an interactive online web page, created using the visual storyline tool from ArcGIS online. Access can also be requested via email from the author's thesis co-supervisors. The storyline shows the gradual steps of analysis from Chapters 4-6 in a single web page.

The storyline consists of the Introduction, Steps 1-3 (each representing the corresponding three chapters of the analyses presented in this thesis) and About Us section. Steps 1-3 sections contain interactive web maps hosted by ArcGIS online. Compared to the static visual maps presented in this thesis, these online maps provide more interactive features and details for readers. Maps can be zoomed in or out, communities can be searched for using the search icon, legends can be shown or minimized and most critically, detailed results for each community can be found in a pop-up window by clicking on the community centroid. Such an intuitive information and communication medium is important for communicating such results to experts and practitioners.

6.5 Summary and Conclusion

This chapter presented a dynamic method to assess directional wildfire evacuation vulnerability for communities, and addressed the third research question. To do so, we calculated Δt^s, the difference between fire travel time t_1^s and evacuation time t_2^s ($\Delta t^s = t_2^s - t_1^s$) for each of eight directional segments $s = 1 \dots 8$ for each community.

Our findings show that some communities, including Banff, Canmore, Hinton and Whitecourt, may face critical wildfire evacuation situations for some directions. The larger communities generally exhibit higher potential to face critical evacuation situations compared to the smaller communities. However, some smaller communities (e.g., Rainbow Lake) have only one or two access roads, potentially rendering them vulnerable in the case of a road closure. In general, directions with short estimated fire travel times compared with longer estimated evacuation times are deemed to be more vulnerable.

Our work provides insights into the vulnerability of communities under threat of wildfire and subsequent evacuation. The plots from Chapter 5 would indicate that directions with high fuel exposure with overlapping road networks would be the most vulnerable, but the analysis of this chapter shows this may not necessarily be the case due to small population or the directional setting of roads. A community with relatively less fuel exposure overall but a large population and relative limited road capacity may potentially be more vulnerable. Fuel exposure, road capacities and population interact to determine a community's vulnerability to wildfire, and our work assesses this interaction in a simple and easy-to-communicate approach. To the best of our knowledge, there are no existing approaches to illustrate the directional evacuation vulnerability of communities with respect transportation infrastructure and wildfire spread risk.

CHAPTER 7. CONCLUSION

We provide an overview of the goals and main tasks of this research (Section 7.1), summarize key findings (7.2), discuss research contributions (7.3), and limitations and scope for further research (7.4).

7.1 Overview of Research

This research combines simple transportation engineering and wildland fire science techniques to identify communities in fire-prone areas of Alberta, Canada, that have evacuation vulnerabilities. Community vulnerabilities are identified based on the attributes of the communities, the transportation network, and the surrounding landscape fire hazard, and addresses three research questions through three corresponding chapters. In Chapter 4, we used GIS-based analysis to identify vulnerable communities using readily available metrics applied to the data assembled for this thesis research. A total of 21 communities vulnerable to potential wildfire and evacuation were chosen using expert judgment. In Chapter 5, fire hazards and transportation capacities – simple, static quantities – were plotted together to understand the directional vulnerabilities of roadways on community egress capacity with respect to fire. In Chapter 6, the directional vulnerabilities for evacuation were assessed using more "dynamic" methods relying on fire travel times coupled with simulated community evacuation times, in a scenario-based analysis approach. The evacuation simulation was carried out using a constructed evacuation mobilization curve (transportation demand, informed by the fire travel time) input to a macroscopic traffic simulation model. Then, for each directional segment (eight in total for each community), the fire travel times were compared against estimated evacuation times, considering potential roadway closures based on scenarios of fire encroachment, and directional vulnerability was assessed. Overall, this thesis research sheds light on how communities' roadways, and in turn, evacuation capabilities, may be vulnerable depending on the direction in which fires encroach, thus providing insights for directions of concern with respect to community fire mitigation and evacuation planning (particularly rapid or time-limited responses).

7.2 Main Findings

In Chapter 4, we identified communities that have vulnerable road networks due to their geometric layout and the potential for wildfire-induced evacuations. We found that the five most vulnerable communities with respect to fire exposure are also among the 10 most vulnerable communities, based on both wildfire and transportation characteristics.

In Chapter 5, we identified fire trajectories around communities that will necessitate a rapid or time-limited response due to their impacts on road capacity. We identified the directions where a fire can cause road closures and induce evacuation situations of potential criticality. Rainbow Lake has limited fire exposure pathways to the east, but as it is the only route available for evacuation, any fire approaching from this direction can pose threats to public safety. Similar to Rainbow Lake, we showed that Chateh and Fort MacKay each have only one evacuating route through a fire exposure pathway. We also found Banff, Canmore, Swan Hills, Lake Louise, Jasper and Grand Cache could all face road closures during wildfire events, as all of their roads are situated in pathways of critical exposure. Although they have multiple evacuating routes, community size and evacuation demands remain in question (addressed in Chapter 6). We also found that Edson, Slave Lake, and Wabasca have limited surrounding lands with critical exposure levels, and thus are less vulnerable to wildfire evacuation.

In Chapter 6, we compare the estimated time required for a community to evacuate, in scenarios where fire travels into a community in a given direction of approach. Directional vulnerability results when a road with a high capacity aligns with a fire exposure pathway, or potential fire entry route into the built environment, and the potential road closure causes potentially problematic evacuation times compared with fire travel times. We found that the larger communities are showing comparatively higher potential to face critical evacuation situations. Communities with small populations are generally less vulnerable, given they require little road capacity to evacuate. However, some small communities have very limited evacuation routes, making them highly vulnerable in the case of road closure (sometimes the only road available). The seasonal analysis for spring and summer conditions shows relative vulnerability remains largely similar across these two seasons. Overall, we found that communities including Banff, Canmore, Hinton, Rainbow Lake, Grand Cache and Whitecourt may face critical evacuation situations in some directional scenarios of fire encroachment.

7.3 Contributions

7.3.1 Academic Contributions

This research contributes a simple and fast-to-apply tool to assess community directional vulnerabilities with respect to wildfire evacuation, bringing together wildland fire science with transportation operations within an integrated analysis framework showing multiple directional scenarios of fire encroachment within a single diagram. Our directional analysis approach – around which our key research contributions focus – reveals the directional context of vulnerability considering fire travel times, road closures, and resulting community evacuation capabilities. Although it might seem that communities having high fuel exposure would have the highest evacuation vulnerability, our directional analysis shows other variables such as road capacity, the directional layout of high capacity roads, and population play an important role in determining community transportation vulnerability for wildfire evacuation. A community with limited surrounding land areas classed as high exposure, but a large population and relatively limited road capacity, can potentially be as vulnerable during evacuation, if not more so, than a community with high fuel exposure but many egress routes and a small population. To the best our knowledge, directional community assessments of roadways combined with wildfire have not previously been seen in the literature, and our approach can be considered a starting point for further work within this directional, interdisciplinary line of inquiry.

7.3.2 Contributions for Practice

This research provides simple results to characterize community vulnerabilities during potential evacuation due to wildfire, from both the wildfire and transportation perspectives, and identifies how communities are vulnerable. This can, in turn, be used in strategic emergency management planning work – allocating resources to communities (by provincial and/or federal agencies) and by communities, particularly towards fire mitigation approaches (like FireSmart), early warning systems, and both community and provincial-level evacuation planning efforts. Agencies can use our results in their efforts towards allocating and prioritization often limited fire-fighting resources. In evacuation planning, the results may inform strategies for more efficient community egress. For example, staged evacuations may be planned, considering the spatial layouts of communities and neighborhoods with respect to the directional transportation vulnerabilities identified in the directional scenario analysis of Chapter 6.

7.4 Limitations and Future Work

This research has key limitations and directions for future improvements and extensions. Our work is a simple, relatively high-level analysis of community wildfire vulnerability, to be used for informing resource allocation and planning towards a more detailed study of individual communities (including agent-based simulation studies, for example), in developing fire mitigation and evacuation plans. There are also key limitations that should be noted and addressed in future work. First, the assumption of community boundaries pertaining to communities either designated “smaller” or “larger” may be revisited to include buffers more specific to each community assessed. Second, we assumed that demand is proportionally divided up between multiple egress routes, whereas demands for each would differ if we were to consider evacuation destinations. To address this, efforts should be made towards apportioning community egress demands to roadways more consistent with community land use patterns or the locations of reception centres towards which evacuees are directed; these efforts could also include consideration and the use of other traffic simulation methods. Third, our analysis is bounded by provincial boundaries and does not include local unpaved roads, which could impact potential evacuation routes and thus may be revisited in future analyses. Fourth, in the fire spread rate calculation, we simplified the calculation with several identified assumptions, considering that the spread rate varies due to the continuous presence of non-fuel patches. As mentioned before, other more complex approaches are also limited and do not necessarily improve our limitations. Also, the exposure assessment is a landscape level analysis and it uses simplifications about the hazard fuel classes. In addition, for small remote communities with highly limited road access, in future work air transport may be considered as a possible evacuation mode, or evacuees may be directed on roadways towards airstrips and other air transport facilities.

REFERENCES

Aguirre, B. E. (2005). Emergency evacuations, panic, and social psychology. *Psychiatry*, *68*(2), 121–129. https://doi.org/10.1521/psyc.2005.68.2.121

Barbero, R., Abatzoglou, J. T., Larkin, N. K., Kolden, C. A., & Stocks, B. (2015). Climate change presents increased potential for very large fires in the contiguous United States. *International Journal of Wildland Fire*, *24*(7), 892–899. https://doi.org/10.1071/WF15083

Bénichou, N., Adelzadeh, M., Singh, J., Gomaa, I., Elsagan, N., Kinateder M., Ma, C., Gaur, A., Bwalya, A., Sultan, M. (2021). National guide for wildland-urban-interface fires: guidance on hazard and exposure assessment, property protection, community resilience and emergency planning to minimize the impact of wildland-urban interface fires. *National Research Council of Canada.* https://doi.org/10.4224/40002647

Beverly, J. L., & Bothwell, P. (2011). Wildfire evacuations in Canada 1980-2007. *Natural Hazards*, *59*(1), 571–596. https://doi.org/10.1007/s11069-011-9777-9

Beverly, J. L., Bothwell, P., Conner, J. C. R., & Herd, E. P. K. (2010). Assessing the exposure of the built environment to potential ignition sources generated from vegetative fuel. *International Journal of Wildland Fire*, *19*(3), 299–313. https://doi.org/10.1071/WF09071

Beverly, J. L., McLoughlin, N., & Chapman, E. (2021). A simple metric of landscape fire exposure. *Landscape Ecology*, *36*(3), 785–801. https://doi.org/10.1007/s10980-020-01173-8

Beverly, J. L., Herd, E. P. K., & Conner, J. C. R. (2009). Modeling fire susceptibility in west central Alberta, Canada. *Forest Ecology and Management*, *258*(7), 1465–1478. https://doi.org/10.1016/j.foreco.2009.06.052

Beverly, J. L., & McLoughlin, N. (2019). Burn probability simulation and subsequent wildland fire activity in Alberta, Canada – Implications for risk assessment and strategic planning. *Forest Ecology and Management*, *451*(August), 117490. https://doi.org/10.1016/j.foreco.2019.117490

Beverly, J. L., & Forbes, A. M. (in review). Assessing directional exposure to wildfire. Submitted to *Natural Hazards*, October 2022.

Braun, W. J., Jones, B. L., Lee, J. S. W., Woolford, D. G., & Wotton, B. M. (2010). Forest fire risk assessment: An illustrative example from Ontario, Canada. *Journal of Probability and Statistics*, *2010*. https://doi.org/10.1155/2010/823018

Burghout, W. (2005). Mesoscopic simulation models for short-term prediction. *Centre for Traffic Research*, *September*, 10–20. http://www2.infra.kth.se/publications/ctr2005_03.pdf

Butler, C. (1974). The urban/wildland fire interface. *Proceedings of Western States Section/Combustion Institute Papers*, *74*(15), 1–17.

Calkin, D. E., Cohen, J. D., Finney, M. A., & Thompson, M. P. (2014). How risk management can prevent future wildfire disasters in the wildland-urban interface. *Proceedings of the National Academy of Sciences of the United States of America*, *111*(2), 746–751. https://doi.org/10.1073/pnas.1315088111

Chen, Y., Shafi, S. Y., & Chen, Y. fan. (2020). Simulation pipeline for traffic evacuation in urban areas and emergency traffic management policy improvements through case studies.

Transportation Research Interdisciplinary Perspectives, *7*. https://doi.org/10.1016/j.trip.2020.100210

Cova, T. J., Dennison, P. E., & Drews, F. A. (2011). Modeling evacuate versus shelter-in-place decisions in wildfires. *Sustainability*, *3*(10), 1662–1687. https://doi.org/10.3390/su3101662

Cova, T. J., Dennison, P. E., Kim, T. H., & Moritz, M. A. (2005). Setting wildfire evacuation trigger points using fire spread modeling and GIS. *Transactions in GIS, 9*(4). https://doi.org/10.1111/j.1467-9671.2005.00237.x

Cutter, S. L., Mitchell, J. T., & Scott, M. S. (2012). Revealing the vulnerability of people and places: A case study of Georgetown county, South Carolina. *Hazards, Vulnerability and Environmental Justice*, *90*(4), 83–114. https://doi.org/10.4324/9781849771542

Demange, M., Gabrel, V., Haddad, M. A., & Murat, C. (2020). A robust p-Center problem under pressure to locate shelters in wildfire context. *EURO Journal on Computational Optimization*, *8*(2), 103–139. https://doi.org/10.1007/s13675-020-00124-x

Dennison, P. E., Cova, T. J., & Mortiz, M. A. (2007). WUIVAC: A wildland-urban interface evacuation trigger model applied in strategic wildfire scenarios. *Natural Hazards*, *41*(1), 181–199. https://doi.org/10.1007/s11069-006-9032-y

Drews, F. A., Musters, A., Siebeneck, L. K., & Cova, T. J. (2014). Environmental factors that influence wildfire protective-action recommendations. *International Journal of Emergency Management*, *10*(2), 153–168. https://doi.org/10.1504/IJEM.2014.066187

Dye, A. W., Kim, J. B., McEvoy, A., Fang, F., & Riley, K. L. (2021). Evaluating rural Pacific Northwest towns for wildfire evacuation vulnerability. *Natural Hazards*, *107*(1), 911–935. https://doi.org/10.1007/s11069-021-04615-x

Erath, A., Birdsall, J., Axhausen, K. W., & Hajdin, R. (2009). Vulnerability assessment methodology for Swiss road network. *Transportation Research Record*, *2137*(2137), 118–126. https://doi.org/10.3141/2137-13

FEMA (2000). *HURREVAC and Inland Winds: Documentation and User's Manual Version 1.0.* Federal emergency management agency, Washington, D.C. http://hurrevac.com/wp-content/uploads/2022/08/HURREVAC_User_Guide_2022-08-01.pdf

Finney, M. A. (1998). FARSITE: Fire Area Simulator - Model development and evaluation. *Rocky Mountain Research Station*, *RMRS-RP-4*, 1–36. https://doi.org/10.2737/RMRS-RP-4

FireSmart: Protecting Your Community from Wildfire (2nd ed) (2003). *Northern Forestry Centre*.

https://www.firesmartcanada.ca/images/uploads/resources/FireSmart-Protecting-Your-Community.pdf

Forestry Canada Fire Danger Group. (1992). Development of the Canadian Forest Fire Behavior Prediction System. *Information Report ST-X-3* (Vol. 3, p. 66).

Forestry Canada Fire Danger Group. (1992). Development of the Canadian Forest Fire Behavior Prediction System. *Forestry Canada - Science and Sustainable Development Directorate* (Vol. 3, p. 66). https://cfs.nrcan.gc.ca/publications?id=10068%0Ahttps://www.frames.gov/documents/catalog/forestry_canada_fire_danger_group_1992.pdf

Fu, H. (2004). Development of Dynamic Travel Demand Models for Hurricane Evacuation. P*hD Thesis, Louisiana State University,* 2004. https://digitalcommons.lsu.edu/cgi/viewcontent.cgi?referer=&httpsredir=1&article=2582&context=gradschool_dissertations

Fu, H., Wilmot, C. G., Zhang, H., & Baker, E. J. (2007). Modeling the hurricane evacuation response curve. *Transportation Research Record*, *2022*, 94–102. https://doi.org/10.3141/2022-11

Furno, A., El Faouzi, N. E., Sharma, R., Cammarota, V., & Zimeo, E. (2018). A graph-based framework for real-time vulnerability assessment of road networks. *Proceedings - 2018 IEEE International Conference on Smart Computing, SMARTCOMP 2018*, 234–241. https://doi.org/10.1109/SMARTCOMP.2018.00096

Grajdura, S., & Niemeier, D. (2022). Inequities & injustices in large-Scale California wildfire evacuations & post-evacuations. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.4022006

Grajdura, S., Qian, X., & Niemeier, D. (2021). Awareness, departure, and preparation time in no-notice wildfire evacuations. *Safety Science*, *139*(September 2020), 105258. https://doi.org/10.1016/j.ssci.2021.105258

Greenshields, B., Bibbins, J., Channing, W., & Miller, H. (1935). A study of traffic capacity. *Highway Research Board Proceedings*, *Vol. 1935*. https://www.safetylit.org/citations/index.php?fuseaction=citations.viewdetails&citationIds[]=citjournalarticle_248667_38#

Gwynne, S., Ronchi, E., Bénichou, N., Kinateder, M., Kuligowski, E., Gomaa, I., & Adelzadeh, M. (2019). Modeling and mapping dynamic vulnerability to better assess WUI evacuation performance. *Fire and Materials*, *43*(6), 644–660. https://doi.org/10.1002/fam.2708

Hagelin, H., & Cluzel, M. (2016). *Applying FARSITE and Prometheus on the Västmanland Fire, Sweden (2014): fire growth simulation as a measure against forest fire spread: a model suitability study*. http://lup.lub.lu.se/student-papers/record/8881384

Hanes, C. C., Wang, X., Jain, P., Parisien, M. A., Little, J. M., & Flannigan, M. D. (2019). Fire-regime changes in Canada over the last half century. *Canadian Journal of Forest Research*, *49*(3), 256–269. https://doi.org/10.1139/cjfr-2018-0293

Hély, C., Flannigan, M., Bergeron, Y., & McRae, D. (2001). Role of vegetation and weather on fire behavior in the Canadian mixedwood boreal forest using two fire behavior prediction systems. *Canadian Journal of Forest Research*, *31*(3), 430–441. https://doi.org/10.1139/cjfr-31-3-430

Institute for catastrophic loss and Reduction (2019) *Issue Fort McMurray Wildfire: Learning from Canada's costliest disaster.* https://www.zurichcanada.com/-/media/project/zwp/canada/docs/english/weather/fort-mcmurray-report_canada.pdf

Intini, P., Ronchi, E., Gwynne, S., & Bénichou, N. (2020). Guidance on design and construction of the built environment against wildland urban interface fire hazard: A review. *Fire Technology, 56*(5). https://doi.org/10.1007/s10694-019-00902-z

Intini, P., Ronchi, E., Gwynne, S., & Pel, A. (2019). Traffic modeling for Wildland–Urban Interface fire evacuation. *Journal of Transportation Engineering, Part A: Systems*, *145*(3), 04019002. https://doi.org/10.1061/jtepbs.0000221

Johnston, L. M., Wang, X., Erni, S., Taylor, S. W., McFayden, C. B., Oliver, J. A., Stockdale, C., Christianson, A., Boulanger, Y., Gauthier, S., Arseneault, D., Wotton, B. M., Parisien, M. A., & Flannigan, M. D. (2020). Wildland fire risk research in Canada. *Environmental Reviews*, *28*(2), 164–186. https://doi.org/10.1139/er-2019-0046

Jolly, W. M., Cochrane, M. A., Freeborn, P. H., Holden, Z. A., Brown, T. J., Williamson, G. J., & Bowman, D. M. J. S. (2015). Climate-induced variations in global wildfire danger from 1979 to 2013. *Nature Communications*, *6*(May), 1–11. https://doi.org/10.1038/ncomms8537

Larsen, J. C., Dennison, P. E., Cova, T. J., & Jones, C. (2011). Evaluating dynamic wildfire evacuation trigger buffers using the 2003 Cedar Fire. *Applied Geography*, *31*(1), 12–19. https://doi.org/10.1016/j.apgeog.2010.05.003

Li, D., Cova, T. J., & Dennison, P. E. (2019). Setting wildfire evacuation triggers by coupling fire and traffic simulation models: A spatiotemporal GIS approach. *Fire Technology*, *55*(2), 617–642. https://doi.org/10.1007/s10694-018-0771-6

Li, J., Ozbay, K., Bartin, B., Iyer, S., & Carnegie, J. (2013). Empirical evacuation response curve during hurricane Irene in Cape May County, New Jersey. *Transportation Research Record*, *2376*, 1–10. https://doi.org/10.3141/2376-01

Lighthill, M. J., & Whitham, G. B. (1955). On kinematic waves II. A theory of traffic flow on long crowded roads. *Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences*, *229*(1178), 317–345. https://doi.org/10.1098/rspa.1955.0089

Lovreglio, R., Kuligowski, E., Gwynne, S., & Strahan, K. (2019). A modelling framework for householder decision-making for wildfire emergencies. *International Journal of Disaster Risk Reduction*, *41*, 101274. https://doi.org/10.1016/j.ijdrr.2019.101274

McCaffrey, S., Wilson, R., & Konar, A. (2017). Should I stay or should I go now? Or should I wait and see? Influences on wildfire evacuation decisions. *Society for Risk Analysis*, *38*(7), 1390–1404. https://doi.org/10.1111/risa.12944

McNeill, I. M., Dunlop, P. D., Skinner, T. C., & Morrison, D. L. (2015). Predicting delay in residents' decisions on defending v. evacuating through antecedents of decision avoidance. *International Journal of Wildland Fire*, *24*(2), 153–161. https://doi.org/10.1071/WF12213

Mozumder, P., Raheem, N., Talberth, J., & Berrens, R. P. (2008). Investigating intended evacuation from wildfires in the wildland-urban interface: Application of a bivariate probit model. *Forest Policy and Economics*, *10*(6), 415–423. https://doi.org/10.1016/j.forpol.2008.02.002

Ozbay, K., & Yazici, M. A. (2006). Analysis of network-wide impacts of behavioral response curves for evacuation conditions. *2006 IEEE Intelligent Transportation Systems Conference Toronto, Canada, September 17-20, 2006 MA6.3*. https://doi.org/10.1109/ITSC.2006.1706735

Parisien, M. A., Junor, D. R., & Kafka, V. G. (2006). Using landscape-based decision rules to prioritize locations for placement of fuel treatments in the Boreal Mixedwood of Western Canada. *USDA Forest Service Proceedings RMRS-P-41. 2006. March, 1–29.*

Parisien, M. A., Kafka, V. G., Hirsch, K. G., Todd, J. B., Lavoie, S. G., Maczek, P. D., Service,

C. F., & Centre, N. F. (2005). Mapping wildfire susceptibility with the Burn-P3 simulation model. *Canadian Forest Service: Northern Forestry Centre*, *information report nor-x-405*

Pel, A. J., Bliemer, M. C. J., & Hoogendoorn, S. P. (2012). A review on travel behaviour modelling in dynamic traffic simulation models for evacuations. *Transportation*, *39*(1), 97–123. https://doi.org/10.1007/s11116-011-9320-6

Radeloff, V. C., Hammer, R. B., Stewart, S. I., Fried, J. S., Holcomb, S. S., & McKeefry, J. F. (2005). The wildland-urban interface in the United States. *Ecological Applications*, *15*(3), 799–805. https://doi.org/10.1890/04-1413

Radeloff, Volker C., Helmers, D. P., Anu Kramer, H., Mockrin, M. H., Alexandre, P. M., Bar-Massada, A., Butsic, V., Hawbaker, T. J., Martinuzzi, S., Syphard, A. D., & Stewart, S. I. (2018). Rapid growth of the US wildland-urban interface raises wildfire risk. *Proceedings of the National Academy of Sciences of the United States of America*, *115*(13), 3314–3319. https://doi.org/10.1073/pnas.1718850115

Radwan, A. E., G. Hobeika, A., & Sivasailam, D. (1985). Computer simulation model for rural network evacuation under natural disasters. *ITE Journal*, *55(9)*, pp.25-30. https://www.safetylit.org/citations/index.php?fuseaction=citations.viewdetails&citationIds[]=citjournalarticle_241152_38

Radwan, A., Hobeika, A., & Sivasailam, D. (1985). Computer simulation model for rural network evacuation under natural disasters. *ITE Journal*, *55(9)*, 25–30. https://www.safetylit.org/citations/index.php?fuseaction=citations.viewdetails&citationIds[]=citjournalarticle_241152_38

Ramsey, M. L., Murphy, M., & Diaz, J. (2020). The camp fire public report : A summary of the Camp Fire investigation. In *Butte County District Attorney*. https://www.buttecounty.net/Portals/30/CFReport/PGE-THE-CAMP-FIRE-PUBLIC-REPORT.pdf?ver=2020-06-15-190515-977

Rasid, H., Haider, W., & Hunt, L. (2000). Post-flood assessment of emergency/evacuation policies in the Red River basin, Southern Manitoba. *Canadian Geographer*, *44*(4), 369–386. https://doi.org/10.1111/j.1541-0064.2000.tb00719.x

Ronchi, E., Wahlqvist, J., Gwynne, S., Kinateder, M., Rein, G., Mitchell, H., Benichou, N., Ma, C., & Kimball, A. (2020). WUI-NITY: a platform for the simulation of wildland-urban interface fire evacuation. *Fire Protection Research Foundation*, *April*, 80. https://doi.org/10.1016/j.ssci.2020.105145

Sandink, D. (2009). The resilience of the City of Kelowna : Exploring mitigation before , during and after the Okanagan Mountain Park Fire. *Institute for Catastrophic Loss Reduction (Issue January).*

https://www.iclr.org/wp-content/uploads/PDFS/the-resilience-of-the-city-of-kelowna.pdf

Stantec Consulting Ltd. (2007). *Provincial Highway Service Classification*. *12*(235), 245. http://www.transportation.alberta.ca/Content/docType181/Production/HwyServiceClass.pdf

Statistics Canada. (2017). *Census Profile, 2016 Census.* https://doi.org/https://doi.org/10.1016/0362-3319(86)90035-2

Stocks, B. J., Lawson, B. D., Alexander, M. E., Van Wagner, C. E., McAlpine, R. S., Lynham, T.

J., & Dube, D. E. (1989). Candian forest fire danger rating system: An Overview. *The Forestry Chronicle*.

Tibbits, A., & Whittaker, J. (2007). Stay and defend or leave early: Policy problems and experiences during the 2003 Victorian bushfires. *Environmental Hazards*, *7*(4), 283–290. https://doi.org/10.1016/j.envhaz.2007.08.001

Tweedie, S. W., Rowland, J. R., Walsh, S. J., & Rhoten, R. P. (1986). A methodology for estimating emergency evacuationy times. In *The Social Science Journal* (Vol. 23, Issue 2). https://doi.org/10.1016/0362-3319(86)90035-2

Tymstra, C., Bryce, R. W., Wotton, B. M., Taylor, S. W., & Armitage, O. B. (2010). *Development and structure of Prometheus: the Canadian wildland fire growth simulation model.* (Vol. 417). https://d1ied5g1xfgpx8.cloudfront.net/pdfs/31775.pdf

Van Wagner, C. E. (1987). Development and structure of the Canadian forest fire weather index system. In *Forestry Technical Report*. http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Development+and+Structure+of+the+Canadian+Forest+Fire+Weather+Index+System#0

Wahlqvist, J., Ronchi, E., Gwynne, S. M. V., Kinateder, M., Rein, G., Mitchell, H., Bénichou, N., Ma, C., Kimball, A., & Kuligowski, E. (2021). The simulation of wildland-urban interface fire evacuation: The WUI-NITY platform. *Safety Science*, *136*. https://doi.org/10.1016/j.ssci.2020.105145

Wildland fire evacuations: Why wildland fire evacuations are important. (2021). *Government of Canada*. https://www.nrcan.gc.ca/climate-change/impacts-adaptations/climate-change-impacts-forests/forest-change-indicators/wildland-fire-evacuations/17787

Wong, S. D., Broader, J. C., Shaheen, S. A., & Org, E. (2020). Review of California Wildfire evacuations from 2017 to 2019. *UC Office of the President, ITS reports. https://escholarship.org/uc/item/5w85z07g*. https://doi.org/10.7922/G29G5K2R

Wong, S. D., Pel, A. J., Shaheen, S. A., & Chorus, C. G. (2020). Fleeing from hurricane Irma: Empirical analysis of evacuation behavior using discrete choice theory. *Transportation Research Part D: Transport and Environment*, *79*(January), 102227. https://doi.org/10.1016/j.trd.2020.102227

Woo, M., Hui, K. T. Y., Ren, K., Gan, K. E., & Kim, A. (2017). Reconstructing an emergency evacuation by ground and air: The wildfire in fort McMurray, Alberta, Canada. *Transportation Research Record*, *2604*(1), 63–70. https://doi.org/10.3141/2604-08

Wotton, B. M., Flannigan, M. D., & Marshall, G. A. (2017). Potential climate change impacts on fire intensity and key wildfire suppression thresholds in Canada. *Environmental Research Letters*, *12*(9). https://doi.org/10.1088/1748-9326/aa7e6e

Wotton, B. M., Nock, C. A., & Flannigan, M. D. (2010). Forest fire occurrence and climate change in Canada. *International Journal of Wildland Fire*, *19*(3), 253–271. https://doi.org/10.1071/WF09002

Yazici, M. A., & Ozbay, K. (2008). Evacuation modelling in the United States: Does the demand model choice matter? *Transport Reviews*, *28*(6), 757–779. https://doi.org/10.1080/01441640802041812

Zhao, B., & Wong, S. D. (2021). Developing transportation response strategies for wildfire evacuations via an empirically supported traffic simulation of Berkeley, California. *Transportation Research Record*, *2675*(12), 557–582. https://doi.org/10.1177/03611981211030271

Zimmerman, C., Brodesky, R., & Karp, J. (2007). Using Highways for no-notice evacuations: Routes to effective evacuation planning primer series. *U.S. Department of Transportation, Federal Highway Administration.* https://ops.fhwa.dot.gov/publications/evac_primer/00_evac_primer.htm

APPENDIX A - Plots of all communities

Following the method described in Section 5.2, individual plots for each of the selected 21 communities are presented in this Appendix A. All the populations mentioned in this section are collected from the latest population Census (2016) conducted by Statistics Canada (*Statistics Canada*, 2016).

Banff:

Community facts: Banff is a community located within Banff National Park and situated close to the western border of Alberta with British Columbia. It is a highly popular tourist attraction. Highway 1 passes through Banff, providing most of its roadway egress capacity. It has a population of about 8,875 residents.

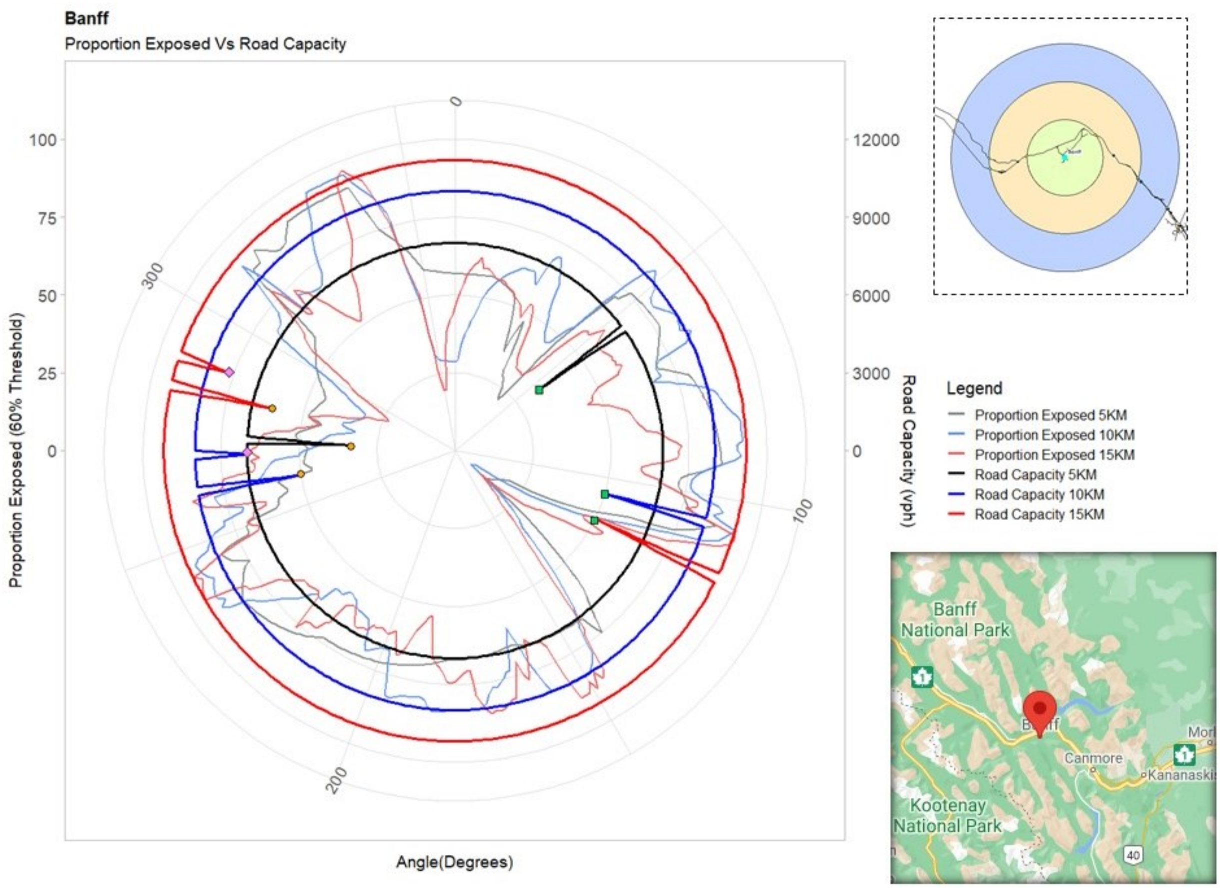

Figure: Plot of Proportion Exposed and Road Capacity for Banff

Blairmore:

Community facts: Blairmore is a community located in the Rocky Mountains, very close to the southwest border of Alberta with British Columbia. It is the principal commercial center of the Municipality of Crowsnest Pass. Highway 3 passes through Blairmore and contributes all its roadway egress capacity.

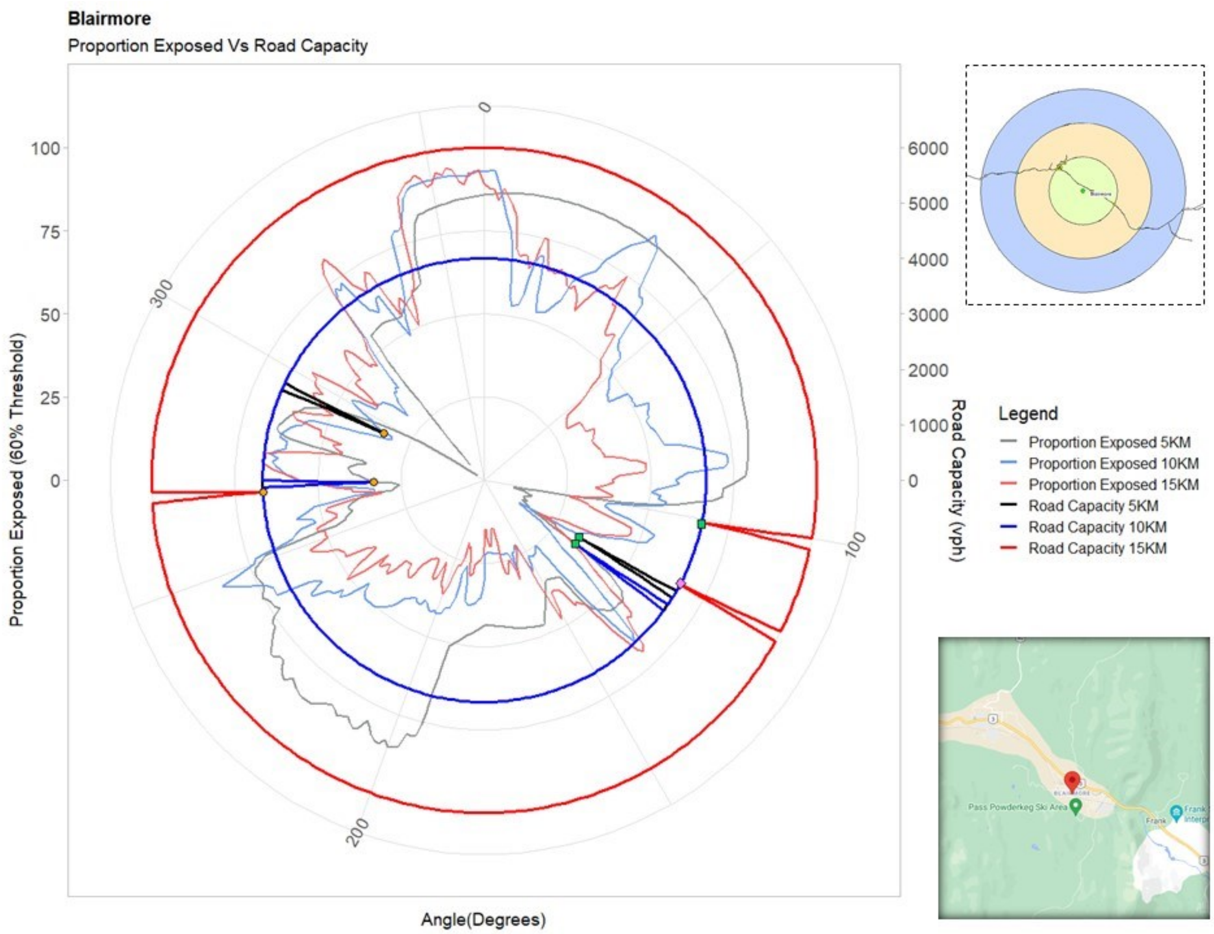

Figure: Plot of Proportion Exposed and Road Capacity for Blairmore

Bragg Creek:

Community facts: Bragg Creek is located in southern Alberta, 30 kilometers west of Calgary, situated on the southeast side of the Elbow River. Highway 66 and 22 intersected just south of the community. It is a popular recreational spot.

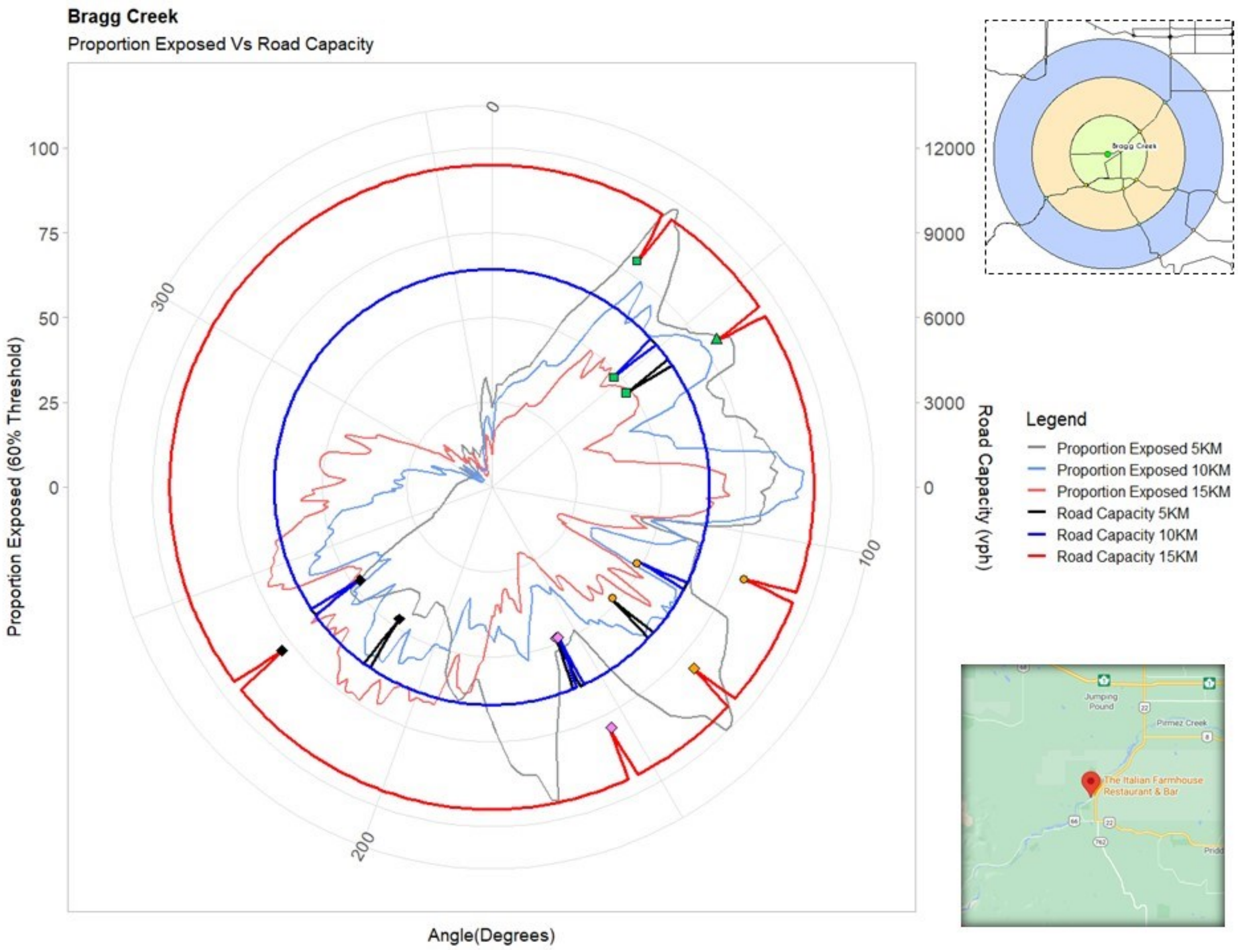

Figure: Plot of Proportion Exposed and Road Capacity for Bragg Creek

Calling Lake:

Community facts: Calling Lake is located in northern Alberta, situated on the southeast side of Calling Lake and along Highway 813. Its population is about 299 people.

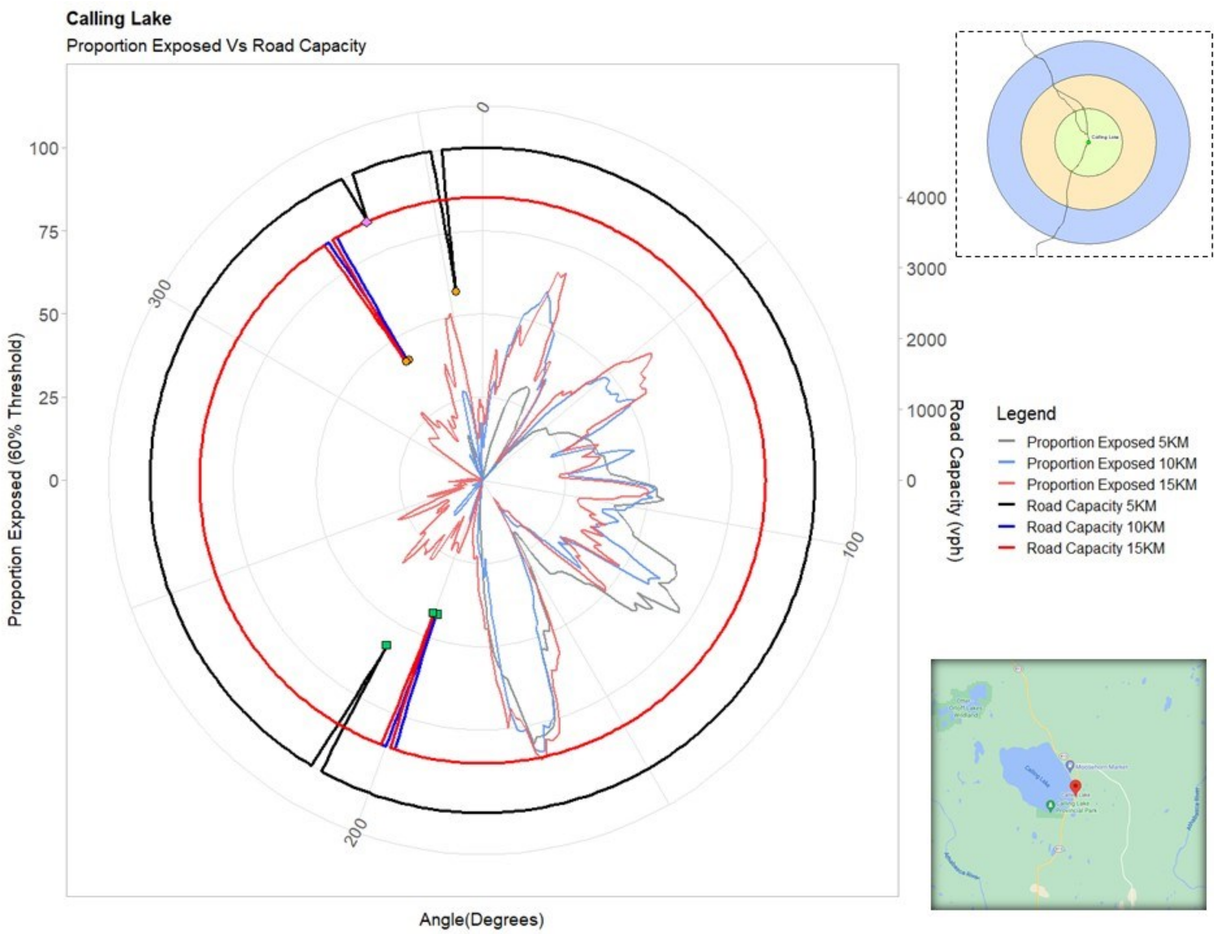

Figure: Plot of Proportion Exposed and Road Capacity for Calling Lake

Canmore:

Community facts: Canmore is located in the Alberta Rockies, west of Calgary. It is a tourist attraction, well-known for recreational activities like skiing and mountain biking. Its population is about 13,992.

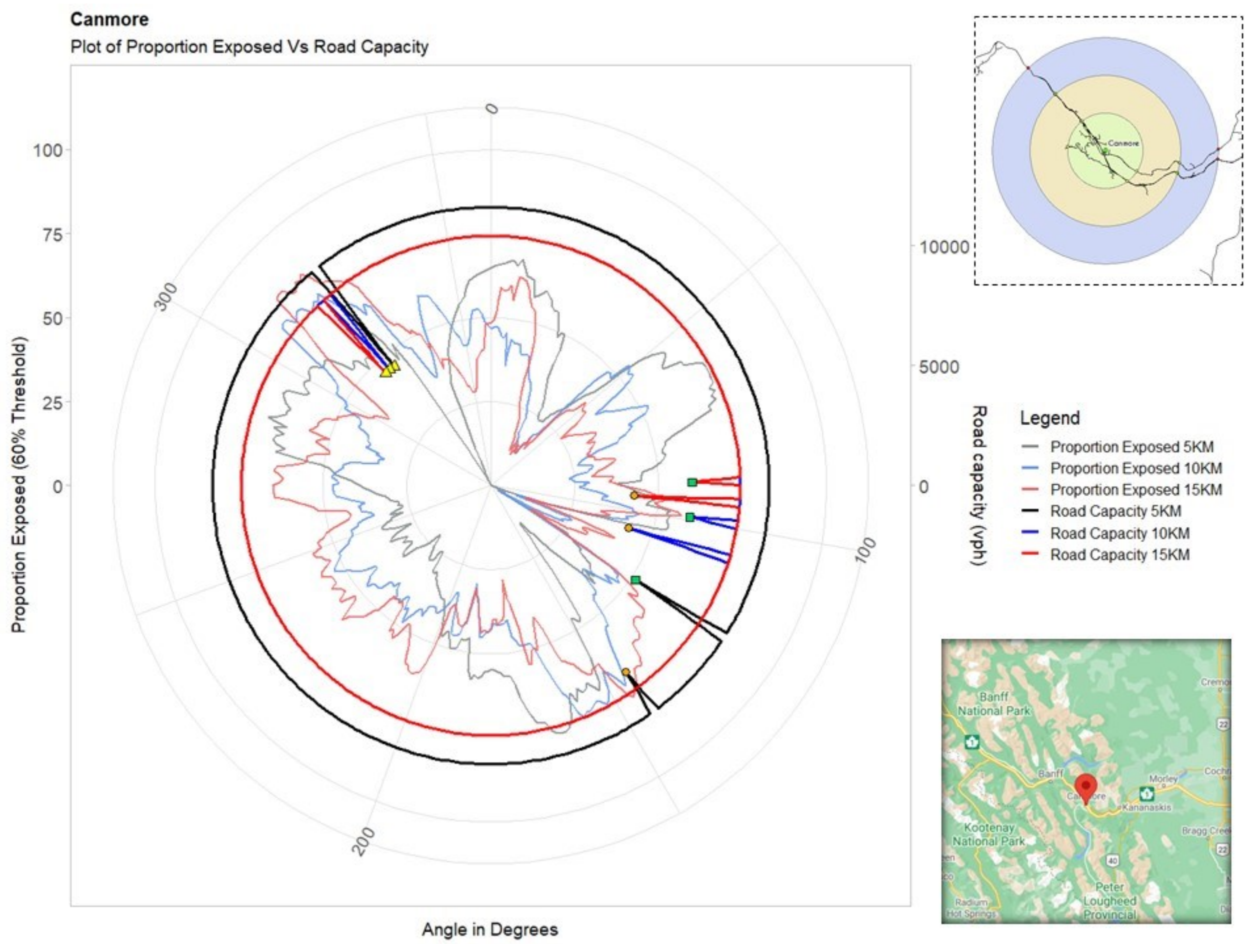

Figure: Plot of Proportion Exposed and Road Capacity for Canmore

Chateh:

Community facts: Chateh, also known as Assumption, is an unincorporated community located in northern Alberta. It is connected to the rest of Alberta only by Highway 58, and has a population of around 883 people.

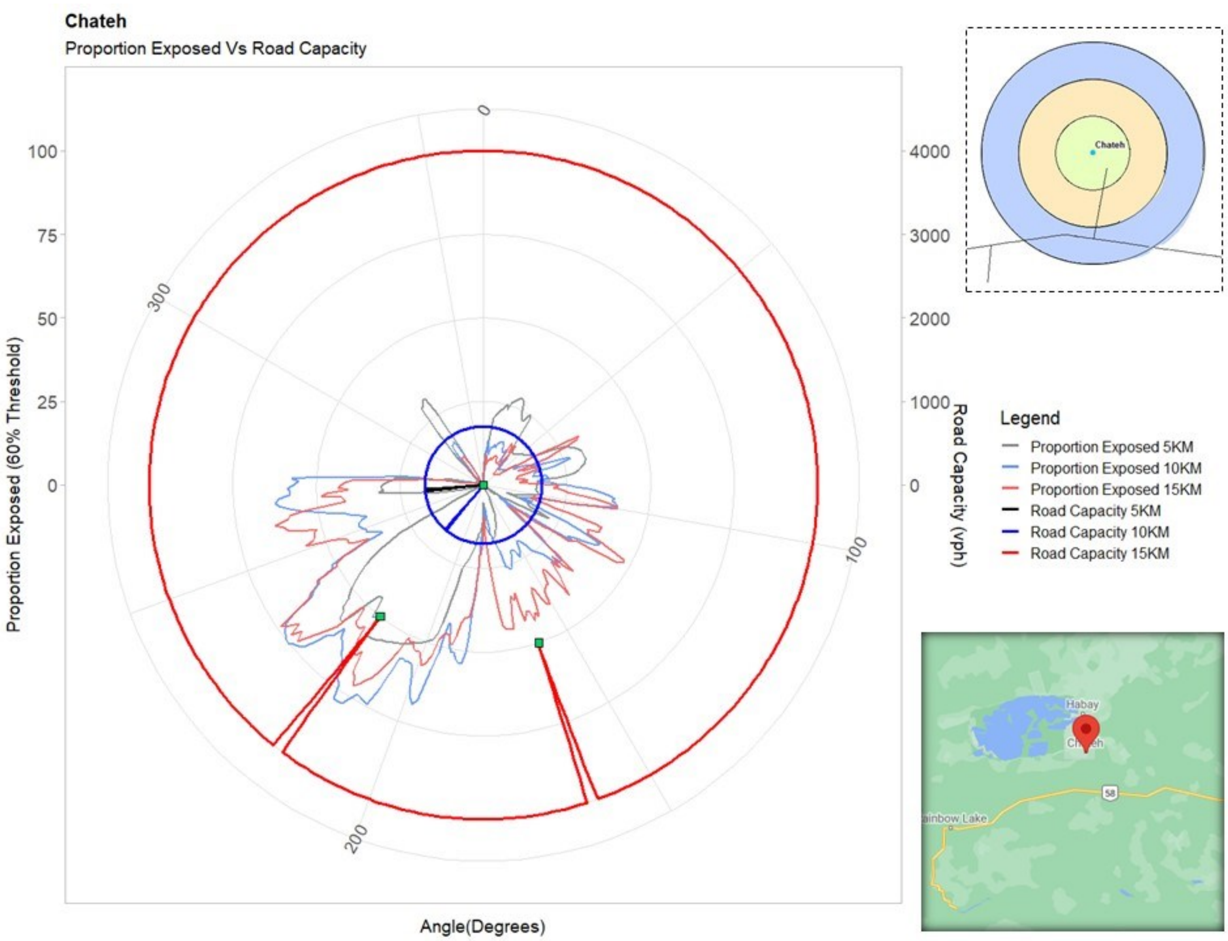

Figure: Plot of Proportion Exposed and Road Capacity for Chateh

Coleman:

Community facts: Coleman is a community located in the Rocky Mountains with a population of around 1,475. It is situated very close to Blairmore along the border of Alberta and British Columbia. Highway 3 is the only route through the community.

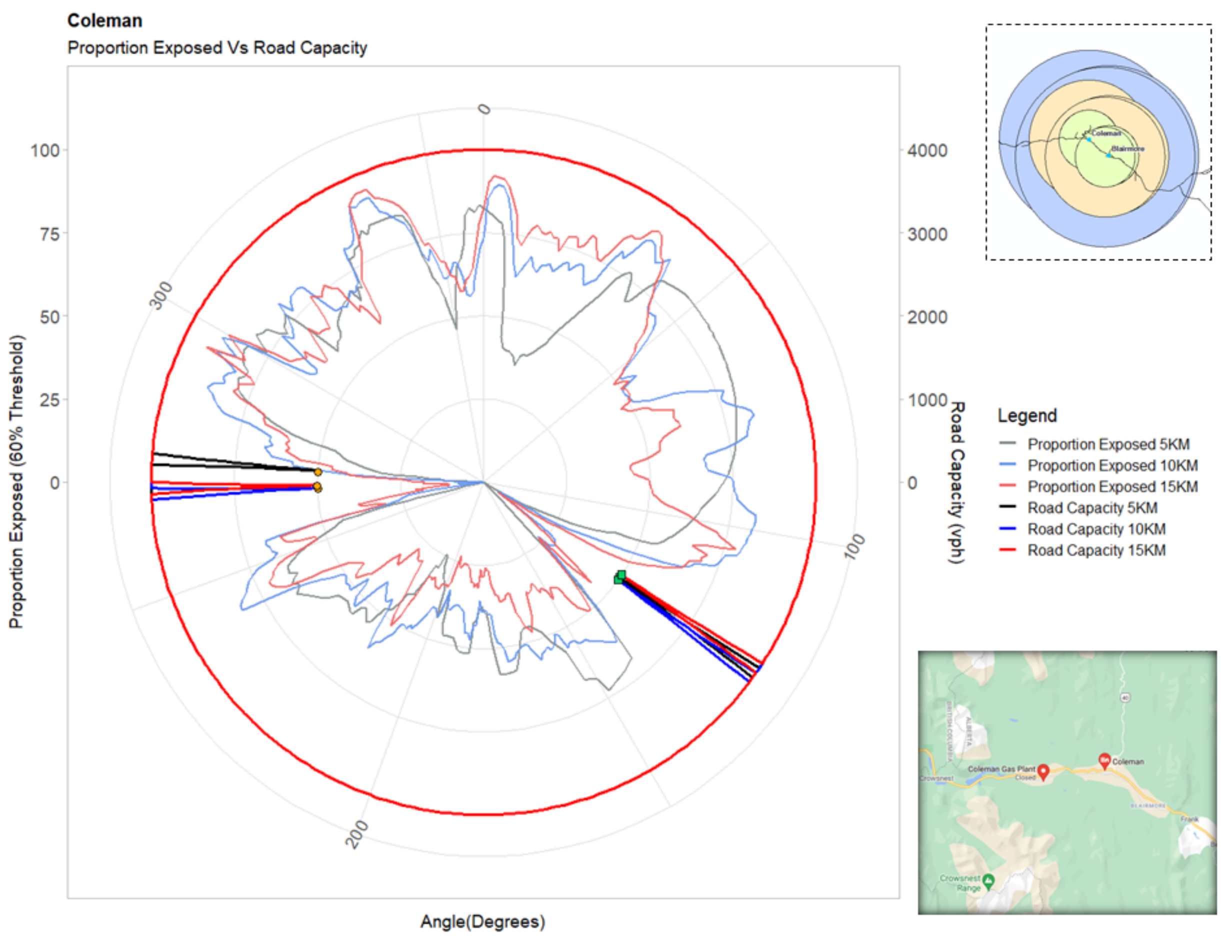

Figure: Plot of Proportion Exposed and Road Capacity for Bragg Creek

Edson:

Community facts: Edson is located in Yellowhead County along Highway 16, and its population is about 8,414.

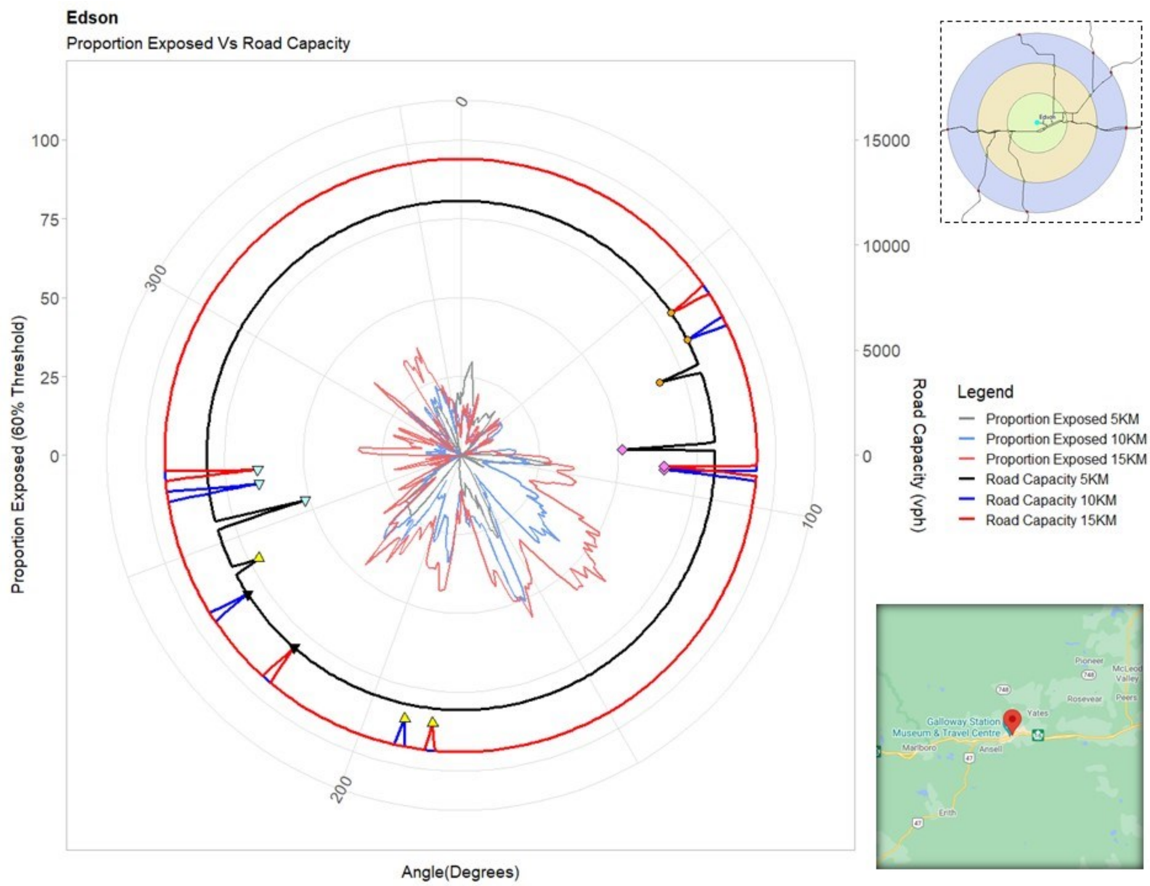

Figure: Plot of Proportion Exposed and Road Capacity for Edson

Exshaw:

Community facts: Exshaw is a community located very close to Canmore along Highway 1 and the Bow River. it is a very small community with population about 412.

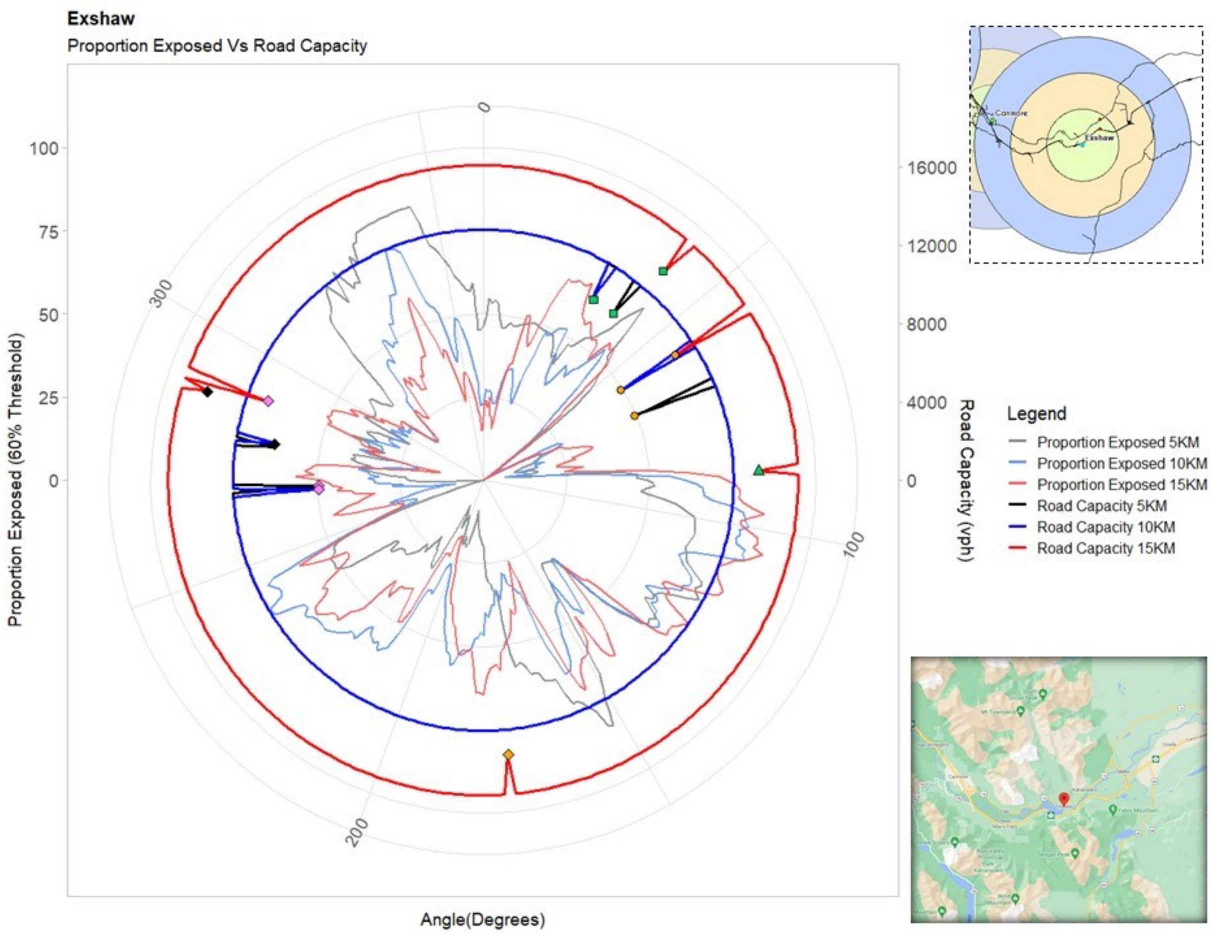

Figure: Plot of Proportion Exposed and Road Capacity for Exshaw

Fort MacKay:

Community facts: Fort MacKay is located in northwestern Alberta, just north of Fort McMurray along Highway 63 and Athabasca River. Its population is about 742.

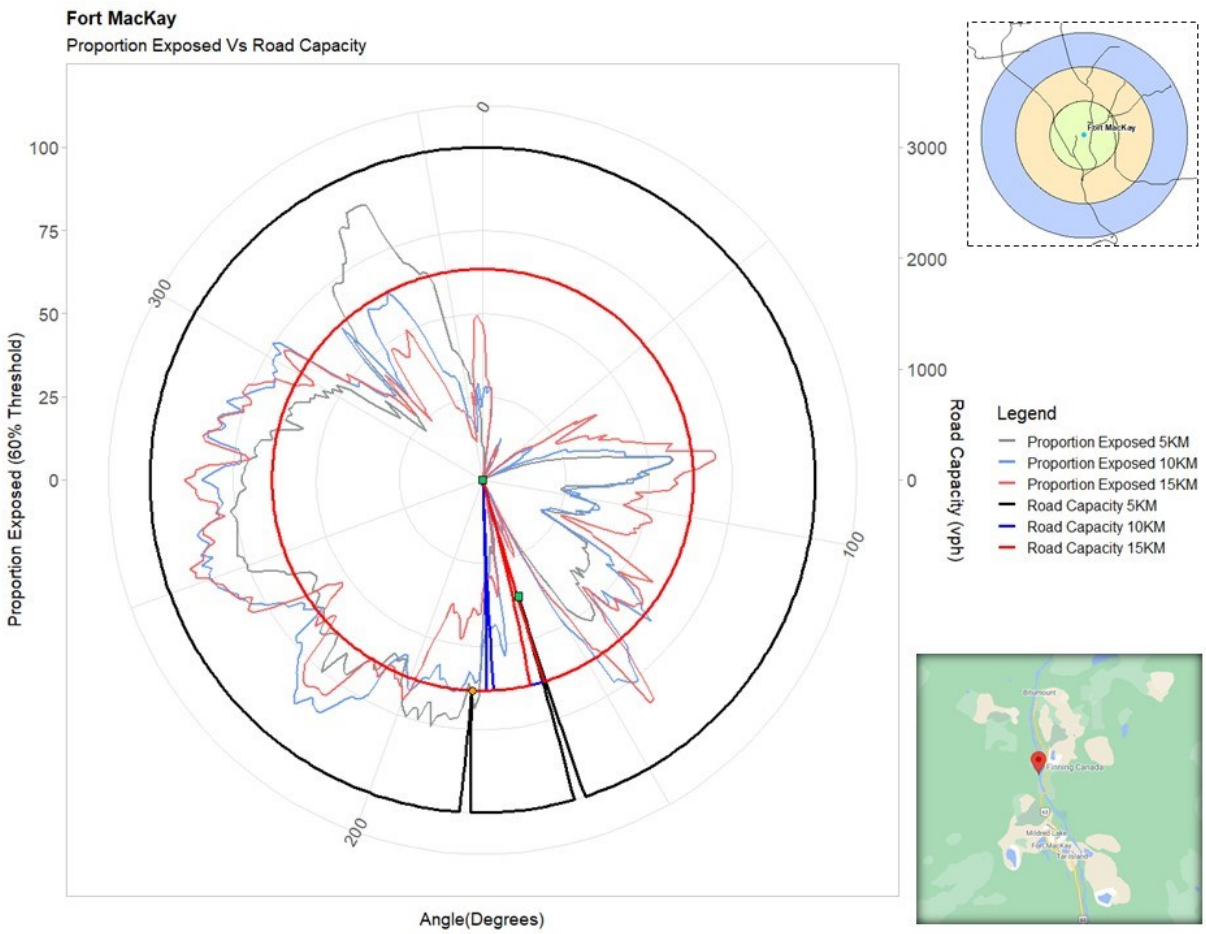

Figure: Plot of Proportion Exposed and Road Capacity for Fort MacKay

Fort McMurray:

Community facts: Fort McMurray is located in northwestern Alberta, along Highway 63 and the Athabasca River. Its population is about 66,573, its size due to the proximity of the oilsands operations.

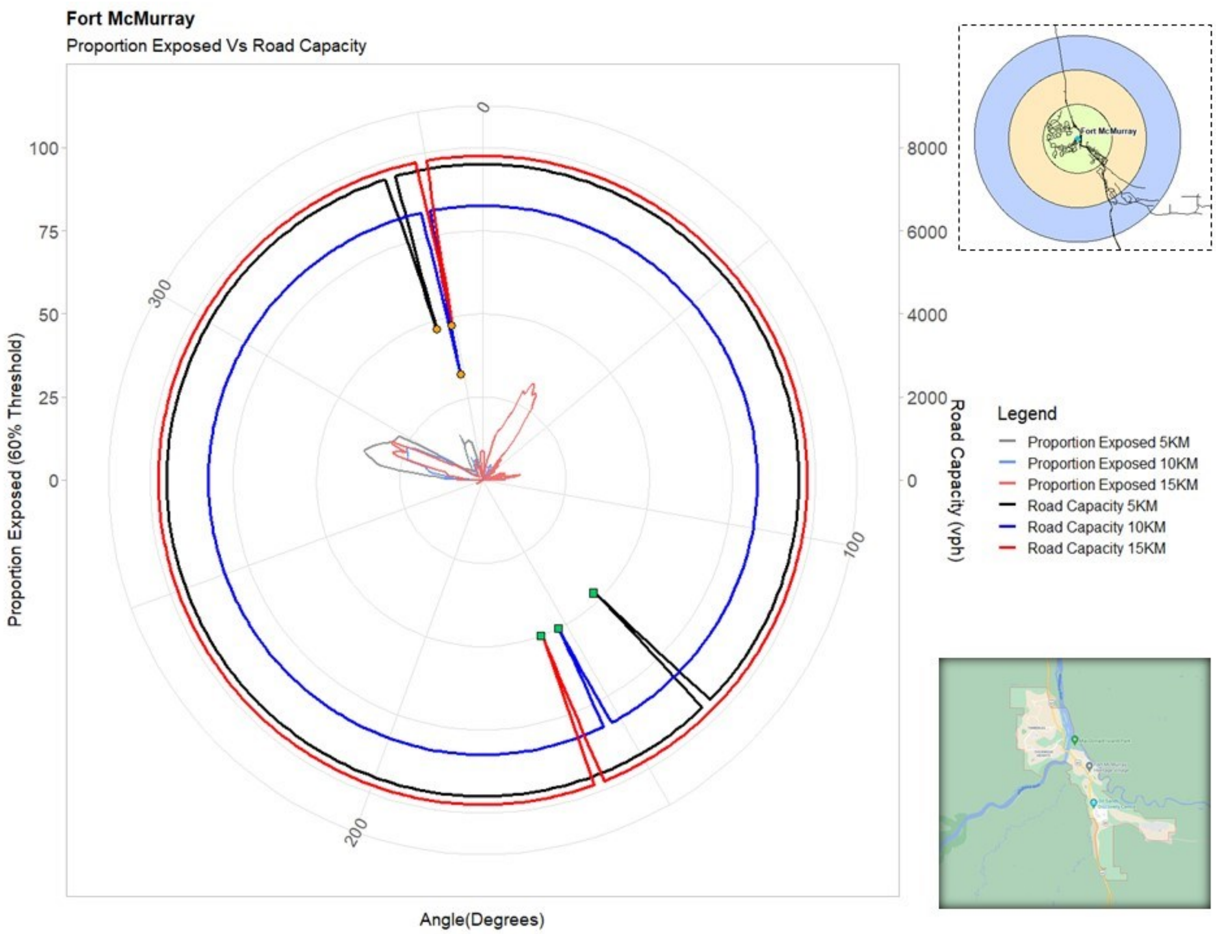

Figure: Plot of Proportion Exposed and Road Capacity for Fort McMurray

Fox Creek:

Community facts: Fox Creek is a community located in northwestern Alberta, along Highway 43, with a population of about 2,589.

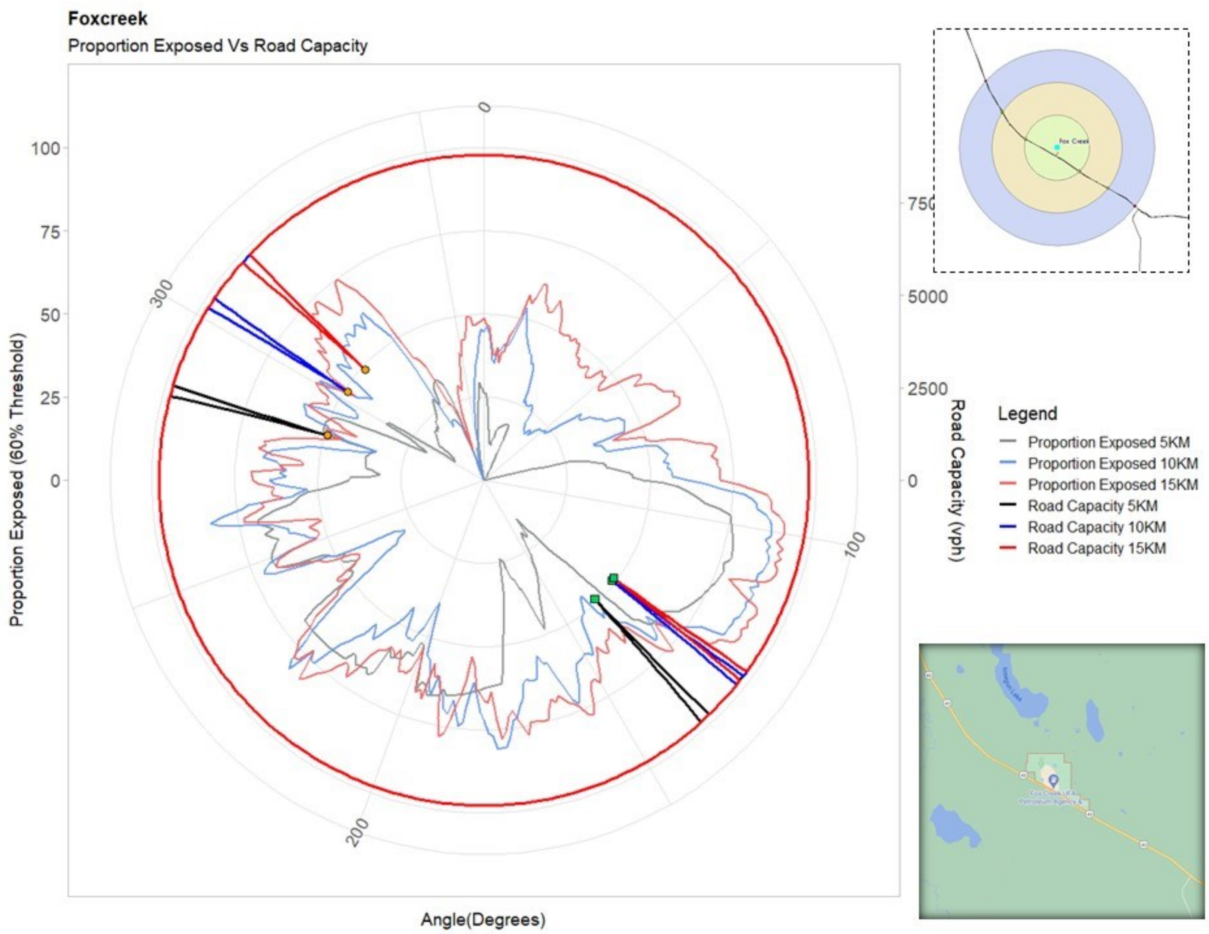

Figure: Plot of Proportion Exposed and Road Capacity for Fox Creek

Grande Cache:

Community facts: Grande Cache is a community located in West-Central Alberta, with a population of about 3,571. It is connected to Hinton and Grande Prairie via Highway 40.

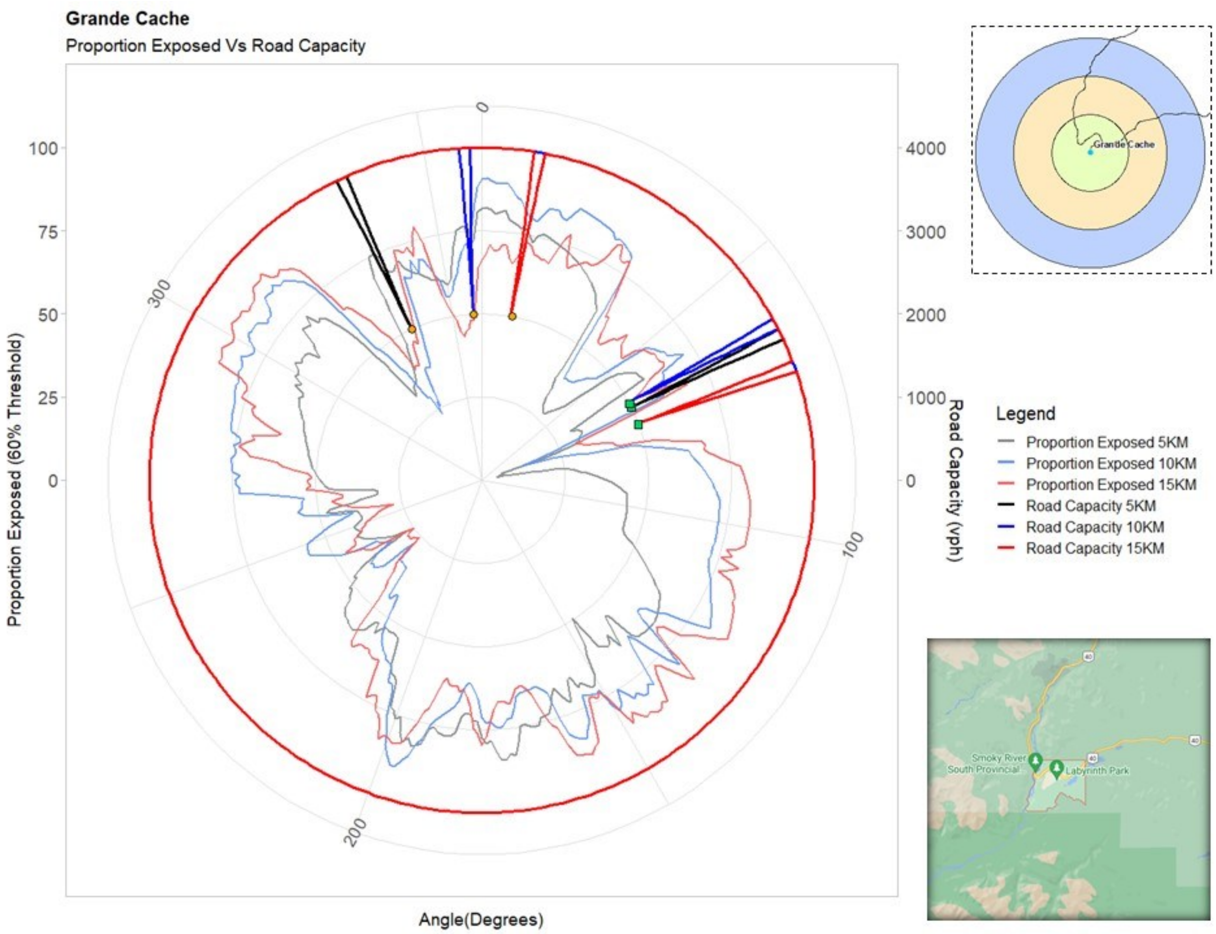

Figure: Plot of Proportion Exposed and Road Capacity for Grande Cache

Hinton:

Community facts: Hinton is a community located in West-Central Alberta, with a population of about 9,882. It is connected to Jasper to the west and Edmonton to the east via Highway 16.

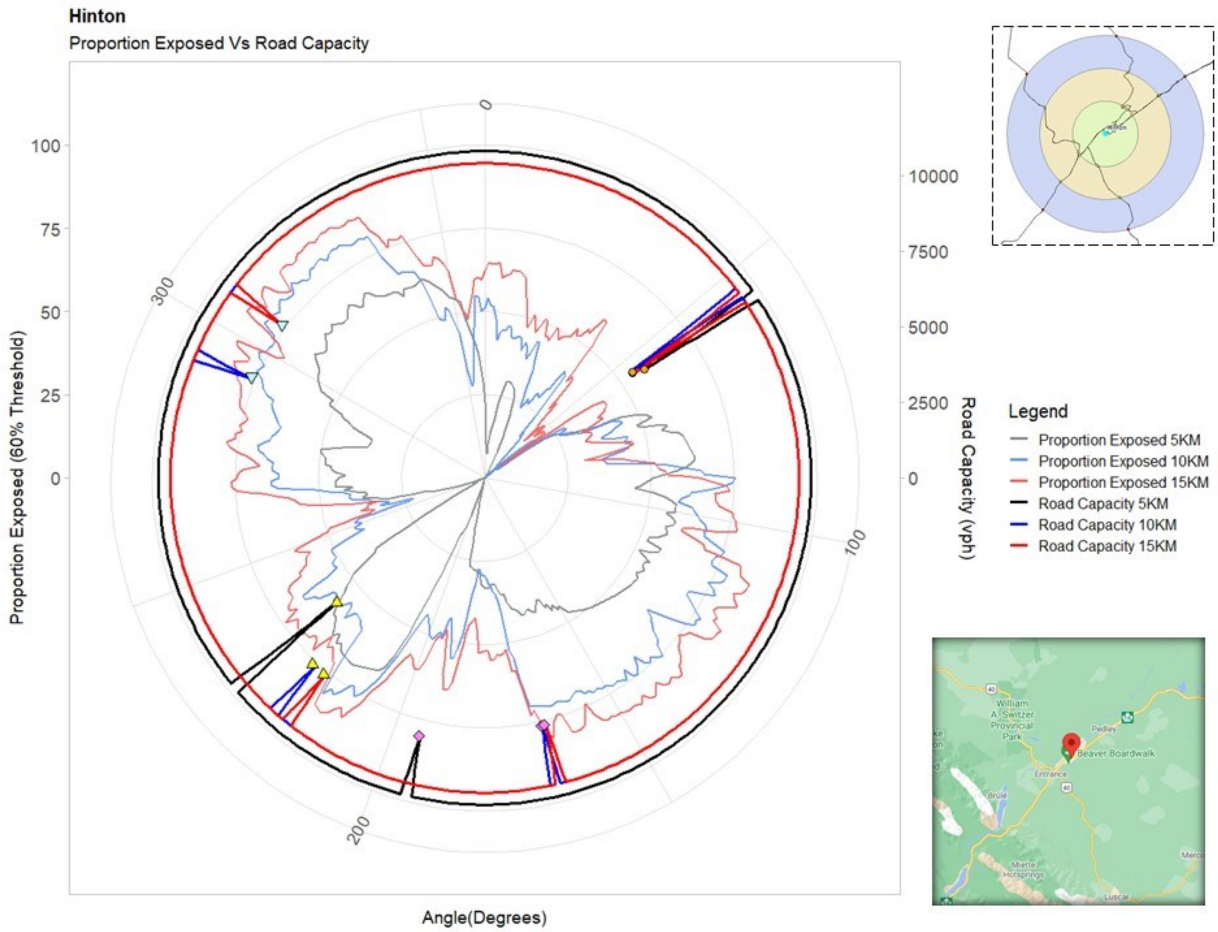

Figure: Plot of Proportion Exposed and Road Capacity for Hinton

Jasper:

Community facts: Jasper is a community located in the Rocky Mountains on the border between Alberta and British Columbia, with a population about 4,590. It is the commercial center of Jasper National Park. Jasper is a popular tourist destination.

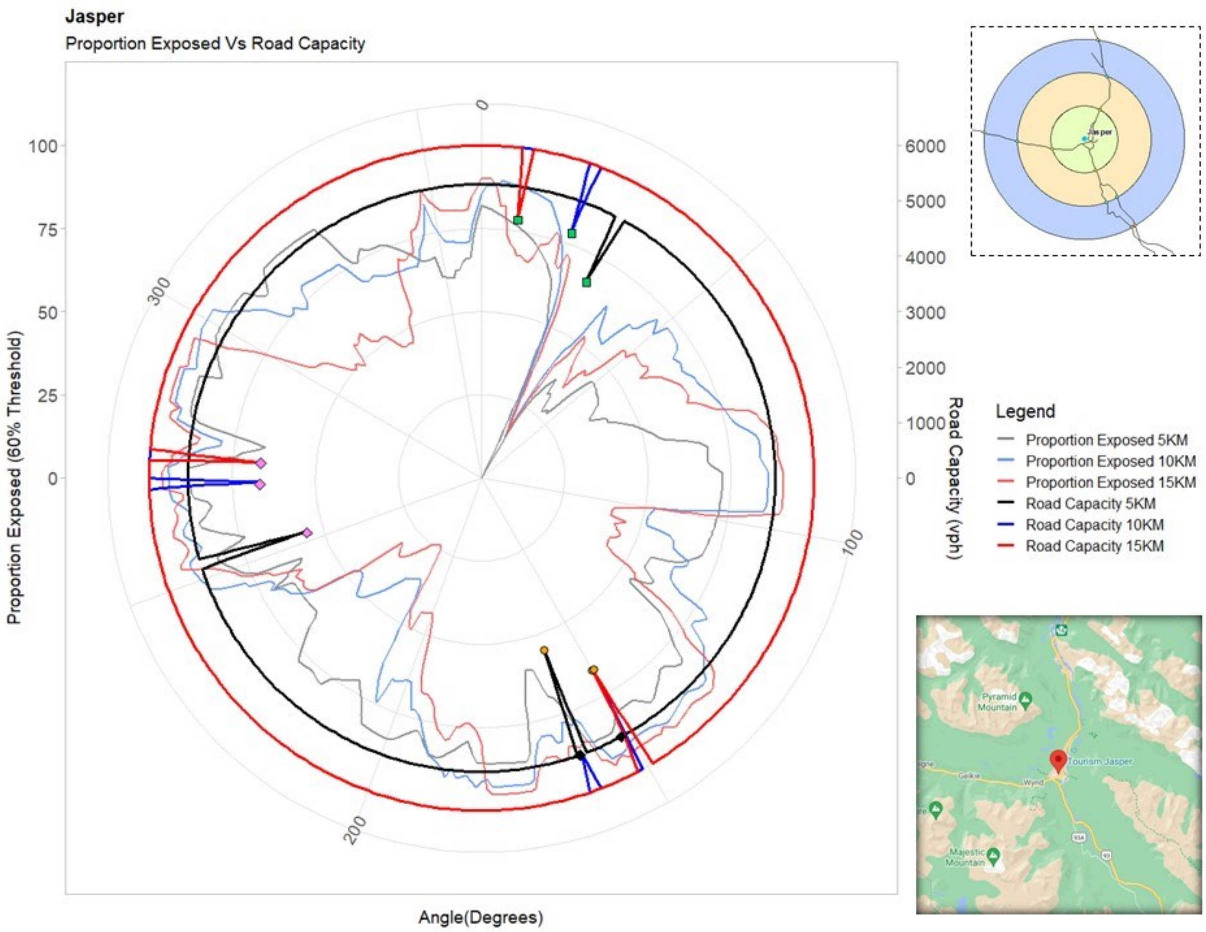

Figure: Plot of Proportion Exposed and Road Capacity for Jasper

Lake Louise:

Community facts: Lake Louise is in the Rocky Mountains near the border of Alberta and British Columbia, with a population of about 1,028. It is at the junction of Highway 1 and Highway 93. Lake Louise is a very popular tourist attraction, and a hamlet of Banff National Park.

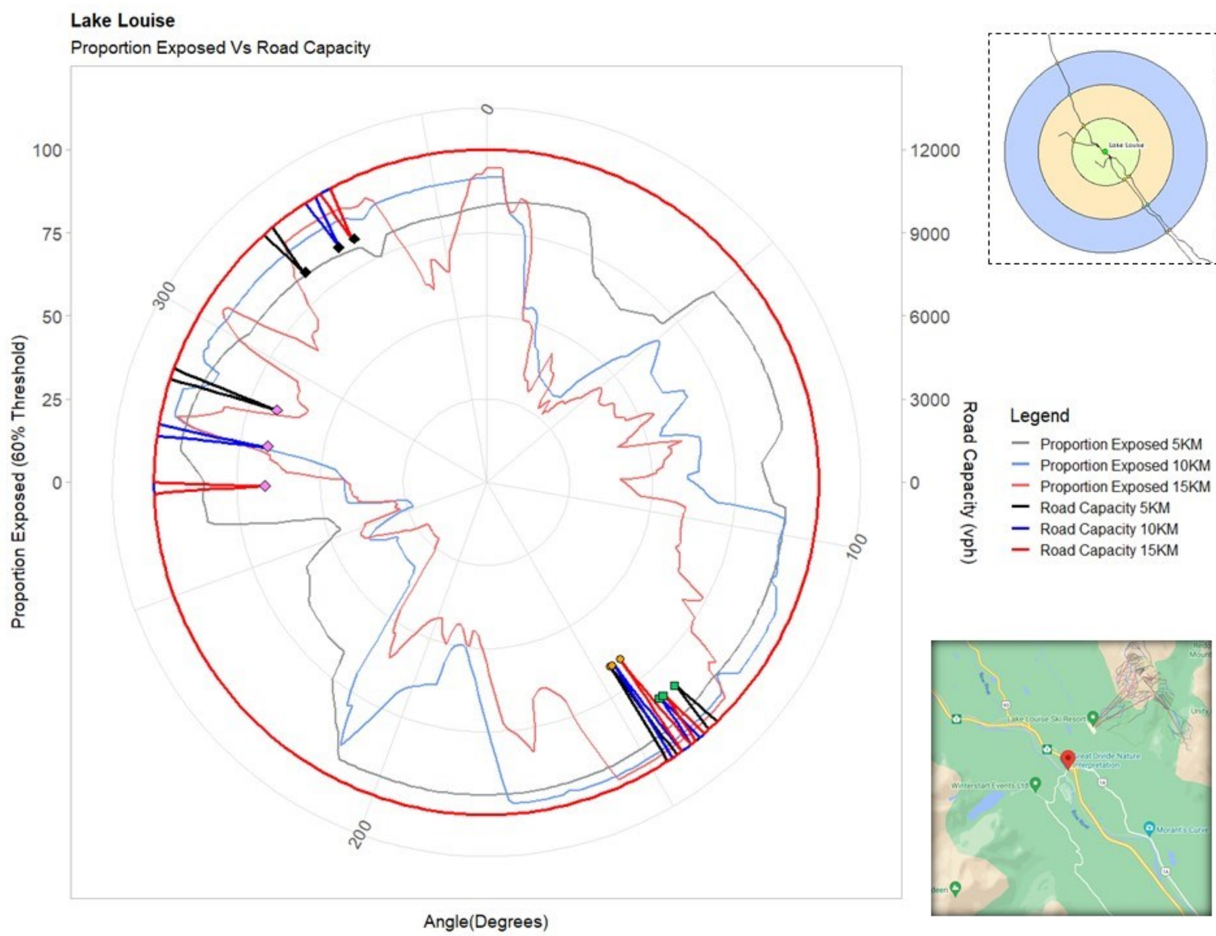

Figure: Plot of Proportion Exposed and Road Capacity for Lake Louise

Rainbow Lake:

Community facts: Rainbow Lake is a community located in north-west Alberta, near the end of Highway 58. It has a population of about 795.

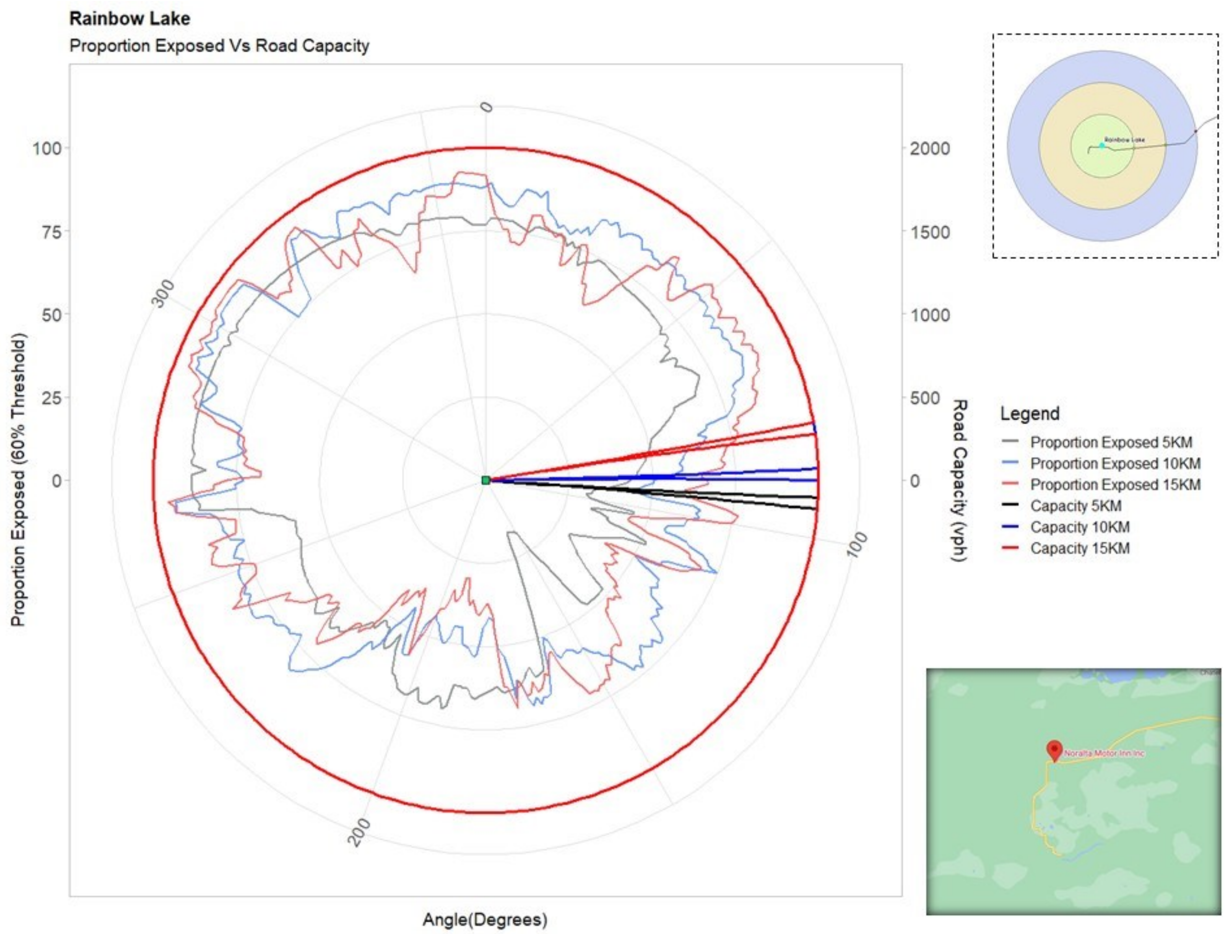

Figure: Plot of Proportion Exposed and Road Capacity for Rainbow Lake

Slave Lake:

Community facts: Slave Lake is a community located on the southeast shore of Lesser Slave Lake, at the junction of Highway 88 and Highway 2. It has a population of about 6,651.

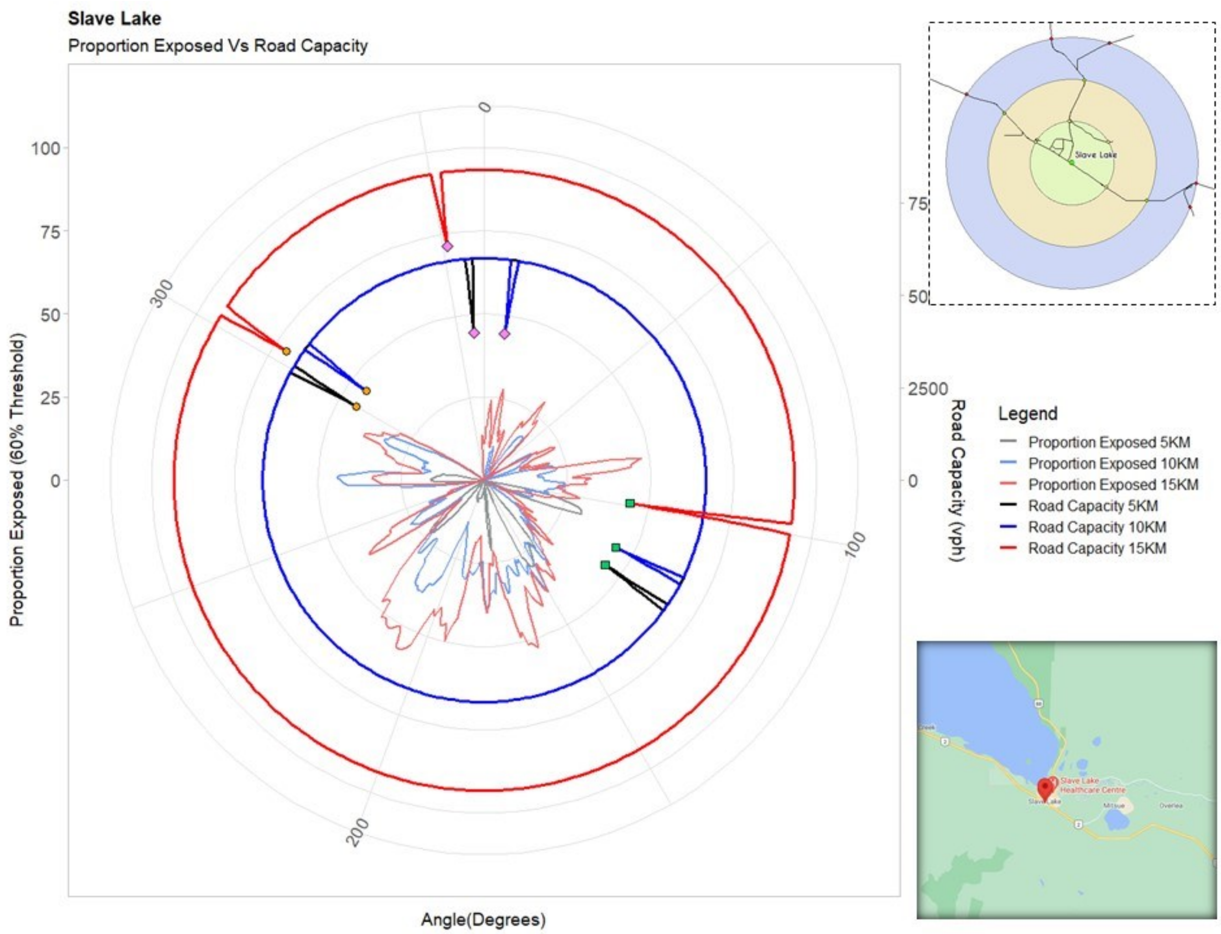

Figure: Plot of Proportion Exposed and Road Capacity for Slave Lake

Swan Hills:

Community facts: Swan Hills is a community located in Northern Alberta, at the junction of Highway 33 and Highway 32 with a population about 1,301.

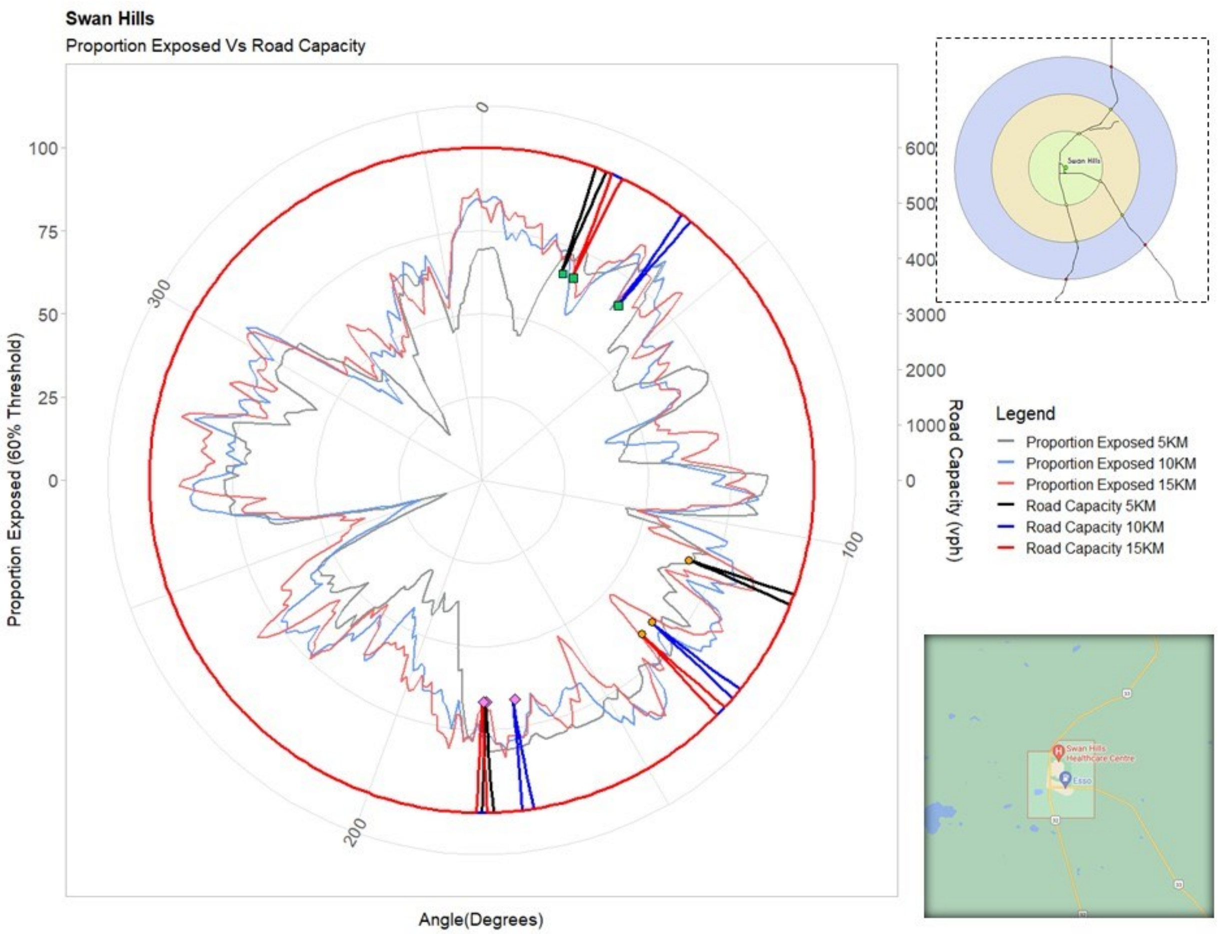

Figure: Plot of Proportion Exposed and Road Capacity for Swan Hills

Wabasca:

Community facts: Wabasca is a small community situated at the intersections of Highway 754 and Highway 813, with a population of about 1,585. It is located in between the North and South Wabasca Lakes. The forestry and oil-gas industry primarily drive the economy of the community.

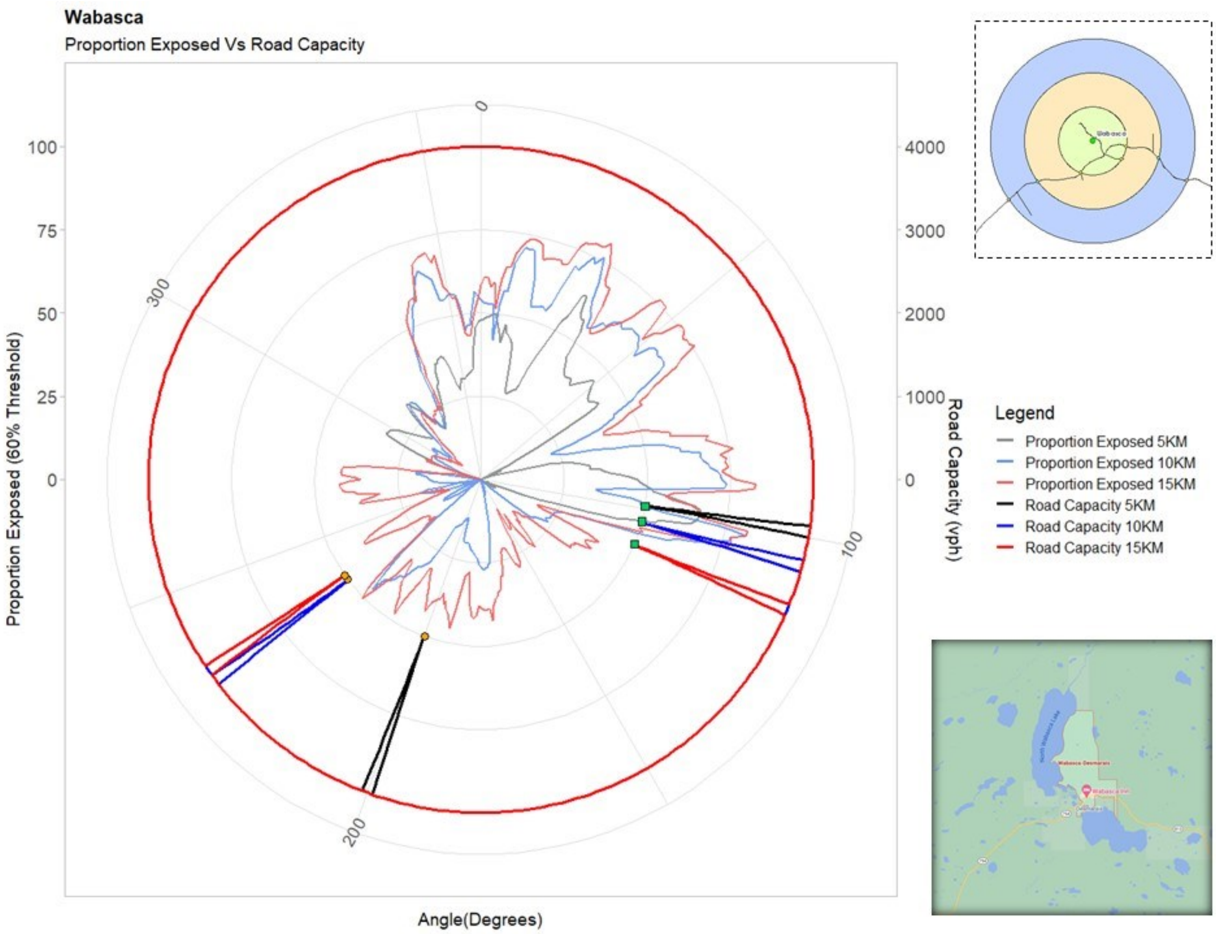

Figure: Plot of Proportion Exposed and Road Capacity for Wabasca

Whitecourt:

Community facts: Whitecourt is located in central Alberta with a population of 10,204. It is at the junction of Highway 43 and Highway 32, at the confluence of the Athabasca River, McLeod River, Sakwatamau River and Beaver Creek.

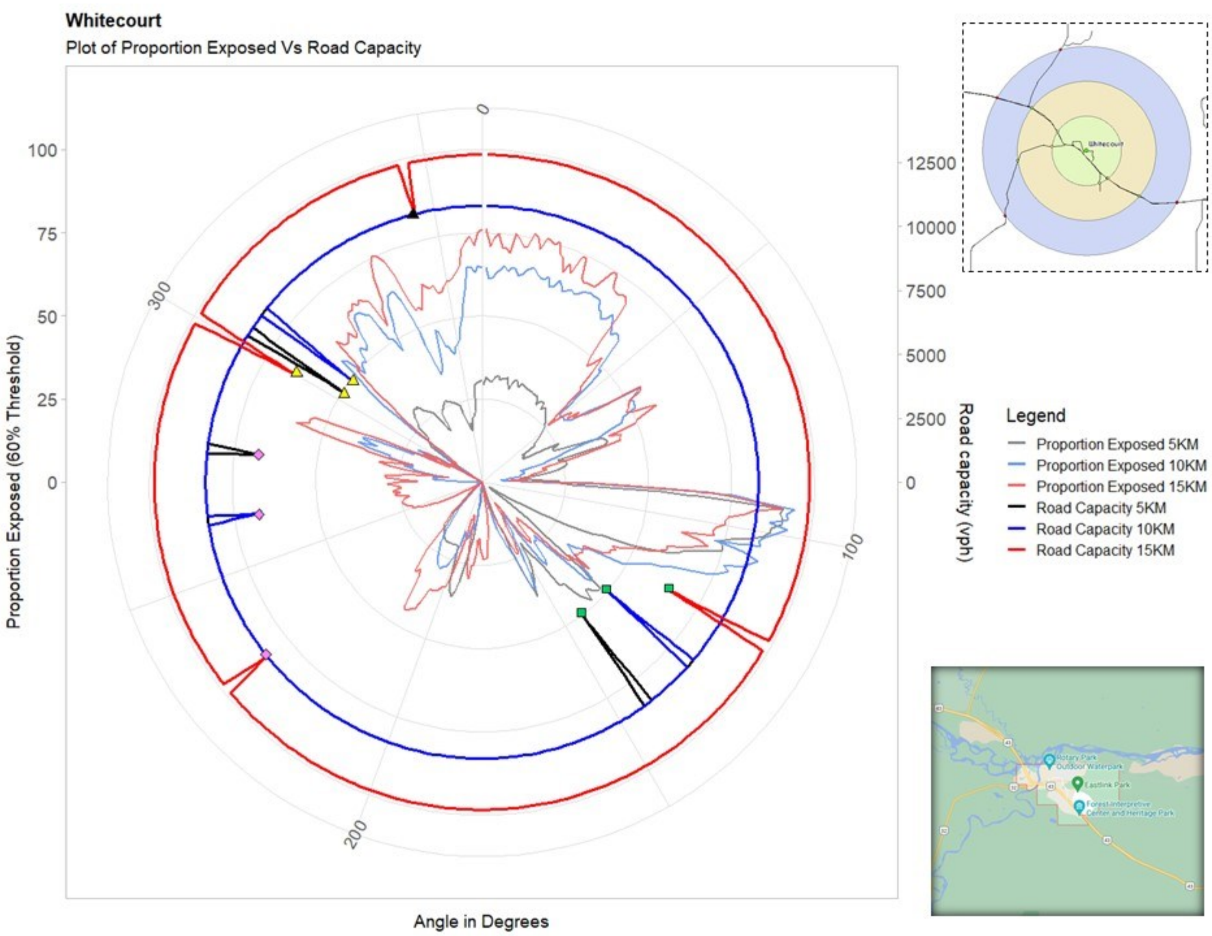

Figure: Plot of Proportion Exposed and Road Capacity for Whitecourt

Appendix B – Relative Direction Rankings for the Smaller Communities, Summer and Spring Conditions

Community Name	*Directional Segment (Degrees from north, clockwise)*	*Rank in Spring Condition*	*Rank in Summer Condition*
Rainbow Lake	1-45 (segment s =1)	6	7
	46-90 (segment 2)	1	1
	91-135 (segment 3)	2	2
	136-180 (segment 4)	8	8
	181-225 (segment 5)	7	6
	226-270 (segment 6)	4	4
	271-315 (segment 7)	3	3
	316-360 (segment 8)	5	5
Swan Hills	1-45 (segment 1)	5	5
	46-90 (segment 2)	1	1
	91-135 (segment 3)	3	3
	136-180 (segment 4)	6	6
	181-225 (segment 5)	8	8
	226-270 (segment 6)	2	2
	271-315 (segment 7)	4	4
	316-360 (segment 8)	7	7
Fox Creek	1-45 (segment 1)	8	8
	46-90 (segment 2)	7	7
	91-135 (segment 3)	1	4
	136-180 (segment 4)	4	1
	181-225 (segment 5)	3	3
	226-270 (segment 6)	2	2
	271-315 (segment 7)	6	6
	316-360 (segment 8)	5	5
Jasper	1-45 (segment 1)	6	5
	46-90 (segment 2)	4	8
	91-135 (segment 3)	7	6
	136-180 (segment 4)	3	3
	181-225 (segment 5)	8	7
	226-270 (segment 6)	2	2
	271-315 (segment 7)	1	1
	316-360 (segment 8)	5	4
Lake Louise	1-45 (segment 1)	5	5
	46-90 (segment 2)	7	7
	91-135 (segment 3)	8	8

	136-180 (segment 4)	2	2
	181-225 (segment 5)	3	3
	226-270 (segment 6)	6	6
	271-315 (segment 7)	1	1
	316-360 (segment 8)	4	4
Grande Cache	1-45 (segment 1)	2	2
	46-90 (segment 2)	3	3
	91-135 (segment 3)	8	7
	136-180 (segment 4)	5	5
	181-225 (segment 5)	4	4
	226-270 (segment 6)	7	8
	271-315 (segment 7)	6	6
	316-360 (segment 8)	1	1
Coleman	1-45 (segment 1)	2	2
	46-90 (segment 2)	3	3
	91-135 (segment 3)	7	7
	136-180 (segment 4)	8	8
	181-225 (segment 5)	5	5
	226-270 (segment 6)	6	6
	271-315 (segment 7)	4	4
	316-360 (segment 8)	1	1
Blairmore	1-45 (segment 1)	1	1
	46-90 (segment 2)	6	6
	91-135 (segment 3)	7	7
	136-180 (segment 4)	4	4
	181-225 (segment 5)	3	3
	226-270 (segment 6)	2	2
	271-315 (segment 7)	8	8
	316-360 (segment 8)	5	5
Fort MacKay	1-45 (segment 1)	8	8
	46-90 (segment 2)	6	6
	91-135 (segment 3)	7	7
	136-180 (segment 4)	1	1
	181-225 (segment 5)	2	2
	226-270 (segment 6)	4	4
	271-315 (segment 7)	5	5
	316-360 (segment 8)	3	3
Exshaw	1-45 (segment 1)	5	5
	46-90 (segment 2)	6	6
	91-135 (segment 3)	1	1
	136-180 (segment 4)	3	3

	181-225 (segment 5)	7	7
	226-270 (segment 6)	4	4
	271-315 (segment 7)	8	8
	316-360 (segment 8)	2	2
Bragg Creek	1-45 (segment 1)	1	1
	46-90 (segment 2)	2	2
	91-135 (segment 3)	4	4
	136-180 (segment 4)	3	3
	181-225 (segment 5)	6	5
	226-270 (segment 6)	5	6
	271-315 (segment 7)	8	8
	316-360 (segment 8)	7	7
Wabasca	1-45 (segment 1)	1	1
	46-90 (segment 2)	4	4
	91-135 (segment 3)	2	2
	136-180 (segment 4)	8	8
	181-225 (segment 5)	7	7
	226-270 (segment 6)	6	6
	271-315 (segment 7)	5	5
	316-360 (segment 8)	3	3
Chateh	1-45 (segment 1)	5	5
	46-90 (segment 2)	8	8
	91-135 (segment 3)	6	6
	136-180 (segment 4)	1	1
	181-225 (segment 5)	2	2
	226-270 (segment 6)	3	3
	271-315 (segment 7)	4	4
	316-360 (segment 8)	7	7
Calling Lake	1-45 (segment 1)	4	4
	46-90 (segment 2)	3	3
	91-135 (segment 3)	2	2
	136-180 (segment 4)	1	1
	181-225 (segment 5)	5	5
	226-270 (segment 6)	7	7
	271-315 (segment 7)	8	8
	316-360 (segment 8)	6	6

Appendix B – Relative Direction Rankings for the Larger Communities, Summer and Spring Conditions

Community Name	*Directional Segment (Degrees from north, clockwise)*	*Rank in Spring Condition*	*Rank in Summer Condition*
Banff	1-45 (segment 1)	8	8
	46-90 (segment 2)	3	3
	91-135 (segment 3)	2	2
	136-180 (segment 4)	6	6
	181-225 (segment 5)	5	5
	226-270 (segment 6)	4	4
	271-315 (segment 7)	1	1
	316-360 (segment 8)	7	7
Canmore	1-45 (segment 1)	7	7
	46-90 (segment 2)	5	5
	91-135 (segment 3)	1	1
	136-180 (segment 4)	2	2
	181-225 (segment 5)	8	8
	226-270 (segment 6)	6	6
	271-315 (segment 7)	4	4
	316-360 (segment 8)	3	3
Edson	1-45 (segment 1)	7	7
	46-90 (segment 2)	2	2
	91-135 (segment 3)	3	1
	136-180 (segment 4)	4	4
	181-225 (segment 5)	5	5
	226-270 (segment 6)	1	3
	271-315 (segment 7)	6	6
	316-360 (segment 8)	8	8
Fort McMurray	1-45 (segment 1)	4	4
	46-90 (segment 2)	7	6
	91-135 (segment 3)	6	7
	136-180 (segment 4)	2	2
	181-225 (segment 5)	8	8
	226-270 (segment 6)	5	5
	271-315 (segment 7)	3	3
	316-360 (segment 8)	1	1
Hinton	1-45 (segment 1)	6	6
	46-90 (segment 2)	5	5
	91-135 (segment 3)	8	8
	136-180 (segment 4)	3	1

	181-225 (segment 5)	4	4
	226-270 (segment 6)	1	3
	271-315 (segment 7)	2	2
	316-360 (segment 8)	7	7
Slave Lake	1-45 (segment 1)	5	4
	46-90 (segment 2)	4	5
	91-135 (segment 3)	2	1
	136-180 (segment 4)	3	3
	181-225 (segment 5)	6	6
	226-270 (segment 6)	7	7
	271-315 (segment 7)	1	2
	316-360 (segment 8)	8	8
Whitecourt	1-45 (segment 1)	4	4
	46-90 (segment 2)	6	6
	91-135 (segment 3)	2	2
	136-180 (segment 4)	3	5
	181-225 (segment 5)	8	8
	226-270 (segment 6)	7	7
	271-315 (segment 7)	1	1
	316-360 (segment 8)	5	3