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Vulnerability assessment of Alberta's provincial highway network

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ABSTRACT

Within their emergency planning and management roles, it is critical for transportation authorities to understand the characteristics of the transportation network and the communities it serves. The northeastern section of the province of Alberta, Canada has a very limited roadway network and is remote from major population centers, yet also has a relatively large population concentration due to the oil and gas industry. It is also prone to wildfires, with subsequent community evacuations every year in the summer months. This paper is a case study of the application of several network analysis measures (related to network topology, community accessibility, and transportation facility characteristics) to this wildfire-prone region, to better understand the region's vulnerability in the face of emergency evacuation and facility disruption. Our results show communities in the Regional Municipality of Wood Buffalo are highly vulnerable to facility disruptions while accessibility to major centers during evacuation is relatively low. Our results also determine critical communities with respect to network vulnerability, and locations for interim emergency supplies. Despite the concentrated populations supporting oil and gas extraction, historical indigenous communities, and the growing prevalence of wildfires and evacuations, justification of transportation infrastructure investments is difficult in this remote area. The findings demonstrate the need for provincial and federal emergency management plans that incorporate the use of existing intermodal infrastructures (i.e. aerodromes) as an alternate means of transport connecting impacted communities. The findings also provide guidance for traffic management planning, strategic placement of emergency services, and identifying where infrastructure investments are most critical.

1. Introduction

In the province of Alberta, Canada – particularly the northern region – wildfires (and floods) have caused significant damage to property, infrastructure, and the environment, and prompted large-scale evacuation demands on a limited highway system. The 2016 Fort McMurray Wildfire was the largest wildfire evacuation and costliest disaster in Canadian history, with 88,000 people evacuated (Alberta Government, 2016) and total costs estimated to be at least 8.86B Canadian dollars (Snowdon, 2016). Understanding the transportation network – particularly by quantifying important features that can inform emergency preparedness decisions – is important for transportation engineers, planners, and emergency management specialists. With increasing frequency of extreme natural events throughout the world, the literature on this subject has grown rapidly over the past decade. Alberta, although relatively sparsely populated, has isolated pockets of large populations in boreal forest due to its natural resource-based economy, and two major Canadian cities (Edmonton and Calgary). The heightened risk of wildfires makes emergency preparedness critical. However, measures to assess the characteristics of the Alberta transportation network have not been applied.

In this paper, we apply a set of simple measures that address key definitions of community and transportation network vulnerability in Alberta's northeastern quadrant, in the face of disruptions and emergency evacuations due to wildfire. We aim to describe community vulnerability (in terms of their accessibility to service centers), network vulnerability (with respect to total transportation capacity available to communities), and how to reduce community vulnerability (by identifying important locations on the network for emergency services). We constructed a representation of the network and communities, as well as a grid-based network scanning method to implement our measures. The purpose of our work is to present a simple but comprehensive set of information about a remote and sparsely populated (and wildfire prone) region, that can be easily understood by emergency planners (whether they have a transportation background or not) at agencies such as Wildfire Alberta, Alberta Emergency Management Agency, and Alberta Transportation. The results may be useful in guiding strategic placement of emergency and alternate transportation services, develop evacuation policies, and consider future infrastructure investments.

2. Literature review

This review focuses on transportation network performance assessment in emergencies and evacuations. In the context of emergency preparedness, transportation systems are assessed with respect to both vulnerability and robustness to disruptive events, and flexibility and resilience in response

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to those events. There are many definitions of these terms within the literature; we will briefly summarize those most prevalently used.

Vulnerability can be defined as a system's susceptibility to disruptive events, measured by its ability (or inability) to satisfactorily perform intended functions when impacted by such events (Berdica, 2002). Because vulnerability measures rely on estimations of the severity of an event's consequences, without considering the event occurrence probability (i.e., risk), they help evaluate the potential performance of networks in a disruptive event whose occurrence likelihood is often unknown (Jenelius et al., 2006). Various measures have been developed to quantify vulnerability for large-scale, sparse, and remote transportation networks (Taylor and Susilawati, 2012). Specific to transportation systems, we can define vulnerability as inability of the transportation network to perform its intended function of transporting individuals to a safe location in emergencies, where basic services are available.

Flexibility is the ability of a system to recover from, or absorb, the effects of a disruptive event, regardless of how much its performance degrades during the event (Faturechi and Miller-Hooks, 2014a, 2014b). Conversely, ***robustness*** measures how well (at some predetermined level of functionality considered acceptable) a system continues to operate during the disruption (Faturechi and Miller-Hooks, 2014b). Robustness focuses on measuring a system's remaining functionality during disruption, rather than the loss due to, or recovery from disruption (Jenelius et al., 2006). ***Resilience*** is defined in such a way that it includes both flexibility and robustness – defined as a system's ability to resist and absorb the impact of disruptions (Bruneau et al., 2003), covering a system's operational performance during disruption, as well as the system's ability to restore itself back to (near) normal operations. Because we are primarily interested in better understanding how our infrastructure would accommodate the effects of emergency evacuations during disruptions, we focus on ***vulnerability*** within the following performance measures.

2.1. Performance measures

2.1.1. Topological measures

Topological measures are used to describe networks based on the relative locations and configurations of nodes and links. These measures do not consider how the network is used (Faturechi and Miller-Hooks, 2014b), and are therefore basic network descriptors. Topological measures have been applied to assess the vulnerability of public transit networks (Cats and Jenelius, 2018; Gai et al., 2018; Zhang et al., 2018). Sun et al. (2018) studied the impact of an intentional attack on nodes with high degree and betweenness in an urban rail network, demonstrating that targeted removal of high degree and high betweenness nodes is more impactful than random node removal. However, because topological measures account only for node-link configuration and do not consider traffic flows between origin-destination pairs, measures that focus more on functional characteristics of the network have also been developed (Lu, 2018).

2.1.2. Operational measures

Operational (or system-based) measures assess a transportation system's performance with respect to travel time, travel distance, flow, capacity, and others. Some of these measures are based on the results of demand-supply interactions (output from travel demand models), allowing for a more comprehensive assessment of the consequences of disruption on network users. Most operational measures focus on measuring remaining functionality after a disruptive event, such as estimating the change in travel cost resulting from traffic flow when a specific link(s) are disrupted in a network, using traffic assignment (Jenelius and Mattsson, 2012; Sullivan et al., 2010). Jenelius et al. (2006) calculate travel time increases for trips between different origin-destination zones using user equilibrium traffic assignment after a link disruption. They define link importance and regional vulnerability to network failures based on travel time increases after a link disruption. Scott et al. (2006) identify and rank critical network links based on user equilibrium travel time increases caused by link closures. Another class of operational measures (apart from those that use traffic assignment) is probability based. Researchers have developed probability-based reliability measures such as connectivity reliability (probability that nodes remain connected), travel time reliability (probability of trip completion within a specific period of time) and capacity reliability (probability that a network can accommodate demands) (Bell and Lida, 1997; Chen et al., 2002).

2.1.3. Accessibility-based measures

Researchers have also proposed measures to characterize accessibility reductions to services, communities, etc. in emergencies and disruptions. Taylor and Susilawati (2012) developed a vulnerability scanning method and a remoteness index for rural areas quantifying the extent of community isolation and the transportation network's contribution to this isolation. Lu and Peng (2011) developed a framework to identify vulnerable regions in South Miami, Florida under scenarios of sea level rise, while Lu et al. (2015) developed a method to identify critical roadway segments and prioritize them with respect to the accessibility they provide, under coastal flooding. Alasia et al. (2017) developed a remoteness index for Canadian communities based how many cities and towns with basic services are within a given radius of a community, and the sizes of these proximate service centers. Performance measures are also obtained through mathematical modeling, which can be used to identify worst-case scenarios of network performance under various disruptions (Matisziw and Murray, 2009).

2.2. Simulating and measuring network disruptions

Previous research on the impacts of transportation facility disruptions have largely focused on a single link or a pre-determined link group failure and removal (Erath et al., 2009; Sohn, 2006). Alternately, random area disruptions causing failures on links within the area disrupted (rather than pre-specified scenarios involving certain link groups) have also been modeled (Jenelius and Mattsson, 2012; Jenelius et al., 2006). The authors proposed an approach where disrupted areas are identified by grid cells. The grid-based approach allows for a complete, uniform assessment of disruptions over an entire network. All roadway links located within a disrupted grid are assumed to be closed for some (pre-specified) period. Grid cells are determined to be most critical when their closures result in a significant increase in total travel time through the network (Jenelius and Mattsson, 2012). In this work, we use a similar grid-based approach to Jenelius and Mattsson (2012) and Jenelius et al. (2006) to analyse capacity changes due to disruption events covering extended areas. These authors also calculate the impact of disruptions using different closure durations, with a focus on relatively short-term disruptions assuming the network users may choose to travel along the new shortest route or to wait until the disrupted (closed) links are reopened. The authors assume that users are aware of the duration of the closure and thus behave optimally; this may not be true in case of random emergency events such as wildfires, floods, or intentional attacks. In this work we focus on high-level planning for evacuation scenarios and thus, do not assume that the users wait until the link is reopened; in fact, we consider this as the most critical case where a link disruption results in inability of the road users to travel.

An important consideration in network performance studies of disruption, specifically when considering re-routing and alternate routes, are isolating links. An isolating link is defined as the sole connection between one subset of a network to the rest, where its disruption leads to isolation of the subset (Erath et al., 2009; Jenelius et al., 2006; Sullivan et al., 2010). It can be challenging to measure the impacts of an isolating link failure on network performance, because this failure leads to two independently functioning sub-networks with “stranded” travelers. In actual cases of such events, other transportation modes such as air or marine have been used (Boone, 2018; Woo et al., 2017); these are overlapping transportation networks not considered part of the original network.

2.3. Summary

This literature review affirms the importance of defining the emergency policy and planning objectives in evaluating a network, because there are many ways to define and measure community and network vulnerability during disruptions. In this paper, we are interested in provides some relevant measures of the transportation network that would specifically help prepare for wildfire emergencies. Thus, we adjust and apply existing measures proposed by Taylor and Susilawati (2012) and Alasia et al. (2017) to quantify community isolation in emergency events, based on their transportation network accessibility to major cities, for northeastern Alberta. In addition, using a grid-based approach similar to Jenelius and Mattsson (2012) and Jenelius et al. (2006), we calculated network capacity changes during disruptions. These authors applied their method to the sparse network of northern Sweden, similar to northeastern Alberta in that congestion is unlikely at a regional scale.

We first present the Alberta geography and data in Section 3. Section 4.1 focuses on identifying vulnerable communities with respect to network topology. Section 4.2 focuses on network scans to identify capacity deficiencies. This capacity scanning framework identifies network facilities that, if disrupted, isolate entire communities or potentially cause serious capacity shortfalls with respect to community populations.

3. Case study and data

3.1. Geography

The province of Alberta, Canada covers 640,330 km^2, with a population of just over 4 million largely concentrated in Edmonton and Calgary, its two largest cities (Statistics Canada, 2016a). The northeastern quadrant of the province is remote, with a sparse transportation network serving a very low population. The one notable exception is Fort McMurray, a city in the Regional Municipality of Wood Buffalo (RMWB), with a permanent population of 66,573 as of 2016 (Statistics Canada, 2016b). This population, based largely due to the oil and gas industry, decreased from a peak of 72,400 in 2014 (Municipal Services Branch, 2015). Within the RMWB is also a "shadow population" of fly-in, fly-out workers that typically number in the low tens of thousands. A sparse transportation system serving the highly concentrated Fort McMurray population, particularly in an area covered largely by boreal forest, was heavily taxed during a 2016 wildfire that caused one of the largest evacuations in Canadian history. Wildfires have historically occurred every summer, and have been growing in frequency and size in western Canada due to climate change (Westerling, 2016). Fig. 1 shows a map of northeastern Alberta and the RMWB, the geographic focus of our study.

3.2. Data sources

We constructed a model of the provincial highway network and communities of northeastern Alberta. We obtained geographic locations of 188 communities and their municipal boundaries in the form of shapefiles from *AltaLIS* (AltaLIS, 2017). Each community's 2016 population data was obtained from *Geosuite*, a Statistics Canada tool (Statistics Canada, 2016c).

We limited the network model representation to provincial highway facilities only, because the local road network is highly limited in this region, and it is unlikely that evacuees will not use the provincial highway system to travel an adequate distance away from wildfire. Communities connected by winter roads (temporary roads "paved" on frozen water or ground/snow in winter) were deemed completely isolated from the provincial highway network. We obtained data on the provincial highway system (with highway lengths) from Alberta Transportation's GIS section. Highway capacities were calculated based on information from Alberta Transportation, using the uninterrupted flows analysis (Volume 2) from the 5th Edition of the Highway Capacity Manual 2010 (Transportation Research Board, 2010). This information was used to create an undirected graph (nodes and links) in MATLAB. We chose an undirected (versus directed) graph for three reasons. First, all Alberta facilities are two-way. Second, the

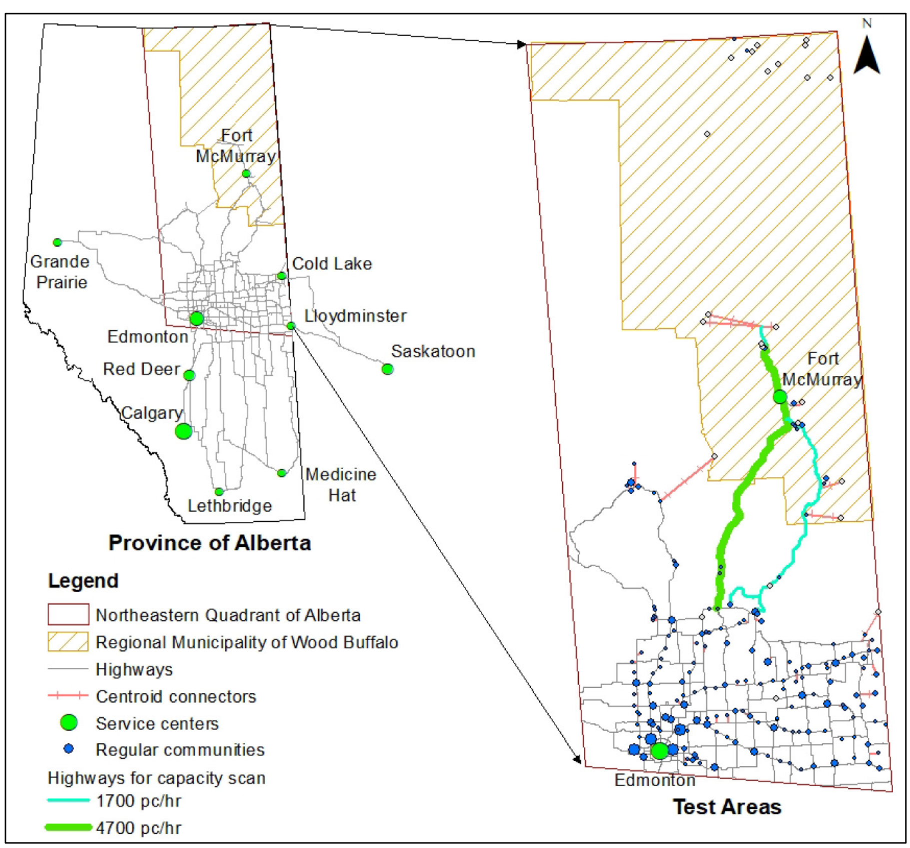

Fig. 1. Study area.

probability of evacuation counterflow operations (and thus, the need to represent it) is relatively low given the sparseness of the transportation network, leaving few alternate routes and thus, right-of-way options for emergency services heading towards the impacted area. Counterflow operations were not used even in the Fort McMurray wildfire of 2016, one of the largest evacuations in Canadian history, due to the need for emergency vehicle ingress and lack of traffic control capabilities. Third, this work's focus on community connectivity to service centers is not impacted by whether links are coded as directed or undirected graphs.

Communities are represented using centroids, connected by centroid connectors (meant to represent local roads) to nodes on the provincial highways network (Fig. 1). We apply our performance measures and highway network scanning on the network models constructed of northeastern Alberta and a subnetwork of the RMWB, respectively.

4. Network performance measures

We applied a set of performance measures (some modified) from the literature addressing vulnerability (Alasia et al., 2017; López et al., 2017; Taylor and Susilawati, 2012), to our study network introduced in Section 3. We introduce a set of measures that focus on topology, community accessibility to service centers, and capacity reduction based on network scans.

4.1. Topological and community measures

We describe basic highway network topology and identify vulnerable communities by modifying and implementing three measures to our study network (Alberta's northeastern quadrant): ***betweenness***, ***remoteness index*** (***RI***) (Taylor and Susilawati, 2012), and ***accessibility index*** (***AI***) (Alasia et al., 2017). Betweenness is a basic topological measure as described in Section 2.1.1, while *RI* and *AI* are accessibility-based measures as per Section 2.1.3.

Betweenness is a commonly used measure in graph theory to identify critical areas that, if removed, would significantly degrade the network. However, in our work, we use this definition from the opposite angle – i.e., to identify communities that are critically located, and thus, key locations for emergency services (reducing community vulnerability). To quantify the extent of community isolation, measures that characterize a community's accessibility to services have also been applied. Most existing accessibility-based measures evaluate the regular day-to-day accessibility of vulnerable communities to the nearest and most populated cities. However, we applied *RI* and *AI* measures to evaluate the accessibility of vulnerable communities in Alberta to all major cities in the province, irrespective of distance, due to the critical nature of wildfire evacuations. *RI* considers accessibility to all major cities in the province irrespective of distance and population, while *AI* considers accessibility to all cities irrespective of distance alone. These measures are described further in the following Sections 4.1.1–4.1.3.

We first provide some definitions and assumptions. Communities that could be at risk from disruptive events and are considered travel origins (i). Service centers are larger cities within Alberta where emergency services may be obtained and, hence, are treated as destinations (j). Both remoteness measures consider the shortest distance between a community and service centers, which we calculated using Dijkstra's shortest path algorithm. For our three measures, we assume that residents of a community would travel to their nearest service centers in an emergency evacuation situation. We use the following variables:

i	origin community
k	community other than i
j	service center
n_{ij}^{k}	1 if shortest path between i and j passes through k; otherwise zero
n_{ij}	1 if community i and service center j are connected
d_{ij}	length of shortest path between community i and service center j
$\overline{d_{j\forall i}}$	average of shortest path lengths to j from all i
p_j	population of service center j
P	set of communities in the network, $i, k \in P$
M	total number of service centers j in network; $M = 10$.

4.1.1. Betweenness

Betweenness (B_k) provides a count of how often a given community node (k) lies between other communities (i) and service centers (j) (Li et al., 2017; Sun and Guan, 2016). Betweenness is a commonly used measure in graph theory, typically used to identify critical nodes that, if removed, would significantly degrade the network. In our work, we adapt the concept of betweenness by "flipping" this perspective – using it to identify communities that are critically located, and are thus key locations for emergency services. We calculate betweenness for community k as:

$$B_k = \sum_{i}^{P}\sum_{j}^{M} n_{ij}^{k} \Big/ \sum_{i}^{P}\sum_{j}^{M} n_{ij}, \quad k \neq i; i, k \in P \tag{1}$$

4.1.2. Remoteness index

The remoteness index (*RI*) is a modification of the Accessibility and Remoteness Index of Australia (*ARIA*) adopted by the Australian government. *ARIA* was developed by first categorizing service centers by population and then calculating the network distance from a community to service centers (Taylor and Susilawati, 2012). For our measure, we consider the shortest path distance from a community i to all service centers j in the province, rather than just the closest as does *ARIA*. Our rationale is that during a major emergency, such as the Fort McMurray wildfire, evacuees traveled to, and accessed services in, cities throughout the province, although they did concentrate in Edmonton and Calgary. Also, evacuating residents would access multiple service centers irrespective of their population. Thus, we define remoteness index (*RI*) as the ratio of the shortest path distance between community i and service center j (d_{ij}) to the average distance of all communities to that service center ($\overline{d_{j\forall i}}$), summed for all service centers:

$$RI_i = \sum_{j} {d_{ij}} \Big/ {\overline{d_{j\forall i}}} \tag{2}$$

A higher *RI* value for a community i implies that it is farther from all service centers, compared to the average distance of all communities to service centers.

4.1.3. Accessibility index

The accessibility index (*AI*) considers basic topology as well as community populations. We developed *AI* by modifying the index proposed by Alasia et al. (2017) because the latter only considered travel times from the at-risk community to service centers within a predefined radius. In a sparsely populated and serviced area like northeastern Alberta, people are likely to drive the longer distances to Edmonton and Calgary (between 4 and 9 h). Therefore, we considered travel distance to all service centers in the province. A community's *AI* is defined as the ratio of a service center's population to the shortest distance from the community to that service center, summed for all the service centers in the study area.

$$AI_i = \ln\left(\sum_{j=1}^{M} \frac{p_j}{d_{ij}}\right) \tag{3}$$

A community located farther from larger service centers will have a lower value of *AI*.

4.2. Network scan: capacity reduction

We implemented network scans that identify capacity deficiencies during facility disruptions, which we modeled by systematic link disruption.

We define acceptable functionality, after link disruption, by total capacity reduction (*TC*) from affected communities in the Regional Municipality of Wood Buffalo (RMWB) to Edmonton (the closest major service center). Note that for our network scans we do not include Fort McMurray as a service center even for points further north. This is due to the fact that if people are evacuating from the RMWB due to wildfire (the predominant concern in northern Alberta), it is unlikely they would evacuate to Fort McMurray over Edmonton or Calgary, given Fort McMurray's location within the boreal forest.

We first calculated the capacities of all paths from communities to Edmonton under the base case: normal (full capacity) highway operations. We calculated base case capacities by summing the capacities of all available paths (at their smallest capacity points) (Fig. 1). We focus our scans to the sparse highway network within the RMWB, because the network closer to Edmonton is quite dense and thus can easily accommodate the potential evacuation demands from the northern region. Next, we overlaid the study area with a 12 km × 12 km grid. Each cell of the grid represents a possible location of a disrupting event, with highway links in a disrupted cell impacted. Each cell was "disrupted" individually (although, in the future, groups of cells might be "disrupted" to model a wildfire or other emergency) such that the highway network within the disrupted cells is assumed unusable. Using this gridding approach, we can ensure a uniform consideration of disruptions over the study area. The reasoning behind this approach is that without data on wildfire risk, we cannot say where in the study area problems will arise, and hence, a uniform coverage approach allows for emergency planners to find relevant information for wildfires arising anywhere across the region.

For each grid g disruption, we recalculated the capacities of all paths from all communities to Edmonton. We calculated the total capacity reduction (*TC*) from affected communities to Edmonton due to disruption of grid (TC^g).

$$C_i^g = \frac{BC_i - DC_i^g}{BC_i} \tag{4}$$

$$TC^g = \begin{cases} \dfrac{\sum_{i=1}^{N} (C_i^g \cdot p_i)}{\sum_{i=1}^{N} p_i}, C_i^g \forall i < 1 \\ 1, otherwise \end{cases} \tag{5}$$

where:

C_i^g	community i capacity reduction (to service center) due to grid g disruption
BC_i	total capacity of all paths from i to service center (Edmonton) in the base case
DC_i^g	total capacity of all paths from i to service center (Edmonton) after disruption of g
p_i	population of community i, $i = 1 \ldots N$
N	total number of communities in the study area, excluding communities in grid g.

If the capacity reduction $C_i^g = 1$ for any community i, meaning that disruption of g leads to a total disconnection of i from Edmonton service center, then $TC^g = 1$. We adopted this approach such that the measure clearly indicates when a grid (containing isolating links) disruption leads to the complete (or partial) inability for any community (irrespective of its population) to reach a service center.

5. Results

5.1. Topological and community measures

We calculated the measures introduced in Section 4.1 for each community in the study area, and compared them to one another to identify those that are relatively vulnerable.

5.1.1. Betweenness

A community with a relatively high betweenness score is one that is located on routes between communities and service centers at a greater frequency, and therefore more likely to be traversed. In our study area (Fig. 2), 23 (of 188) communities have a betweenness score of zero, indicating they are not located between any communities and service centers and therefore comprise the boundaries of the studied network. Communities with betweenness values from 0.06 to 0.10 are in the intermediate group (these comprise 23% of all communities). Communities with the highest betweenness scores (0.16–0.20) are mainly located along Highways 63, 28 and 16. Shortest paths from communities in the study area to service centers often fall on one of these three highways. The Town of Redwater and Hamlet of Opal each have the highest betweenness score of 0.20 among all communities in the study area, indicating they have the maximum number of shortest paths passing through them.

Disruption of highway links to communities with high betweenness scores would have a disproportionate impact on the network, as this would interrupt a larger number of shortest paths between communities and service centers. Communities on Highway 28 between Radway and Edmonton have relatively high betweenness scores, as all shortest paths from communities in northeastern Alberta are along Highway 28 (Fig. 2). Therefore, disruption of Highway 28 can significantly degrade network connectivity.

A map of betweenness scores, such as Fig. 2, can be overlaid on those of natural disaster risk (i.e., wildfire and flood maps), such that emergency management planners can understand where disruptions would result in greater risks to populations, and the highways they would utilize.

Betweenness results can offer guidance to emergency management planners regarding where services and supplies ought to be placed, and where multimodal transfers may be developed or existing ones utilized. Communities with high betweenness may be good locations to store supplies (gas, water, first aid, firefighting equipment, etc.); evacuees may access supplies on their way out, and emergency crews can access on their way towards the event. Use of these key locations can help to ease both evacuation stress and event impact. For the three highways identified above, candidate communities for emergency service and supply locations (due to high betweenness scores) are the Village of Boyle on Highway 63, Ashmont on Highway 28, and the Town of Vegreville on Highway 16. In addition, certain types of emergencies may require airlift for some evacuees (or even provide additional transport capacity); therefore, we can also identify existing aviation infrastructure near these communities to further accommodate emergency air services.

Betweenness has previously only been used as a measure of centrality with respect to the network topology; in this work, we use betweenness as a measure to help disaster preparedness.

5.1.2. Remoteness index

If a community has a lower *RI*, it is relatively close in distance to central (well-connected) service centers. *RI* values are lower for communities closest to Edmonton and gradually increase as we move away from the center of the province (where the network is densest and most service centers are located). As we move further north away from Edmonton and Calgary into the RMWB, community *RI* values increase gradually, topping out for the northernmost communities connected by highway (figure of results is not shown as *RI* values are well described here). Communities in the RMWB have high *RI* values because the only service center located in the RMWB is Fort McMurray (while all other service centers are quite distant). If RMWB had other service center(s) besides Fort McMurray alone, *RIs* in this region may decrease. Fort McKay (Indian Reserve) 174C, and Namur Lake 174B and 174A have the largest *RIs* at 18 as they are quite remote from the well-connected service centers in the center of the province.

Values of *RI* are largely determined by how well the service centers are connected to communities throughout a network. A well-connected service center represents hub strength and hence better service provision. If a community is located farther from a well-connected service center, it will have a higher *RI* value. In the current network, the service centers of Edmonton,

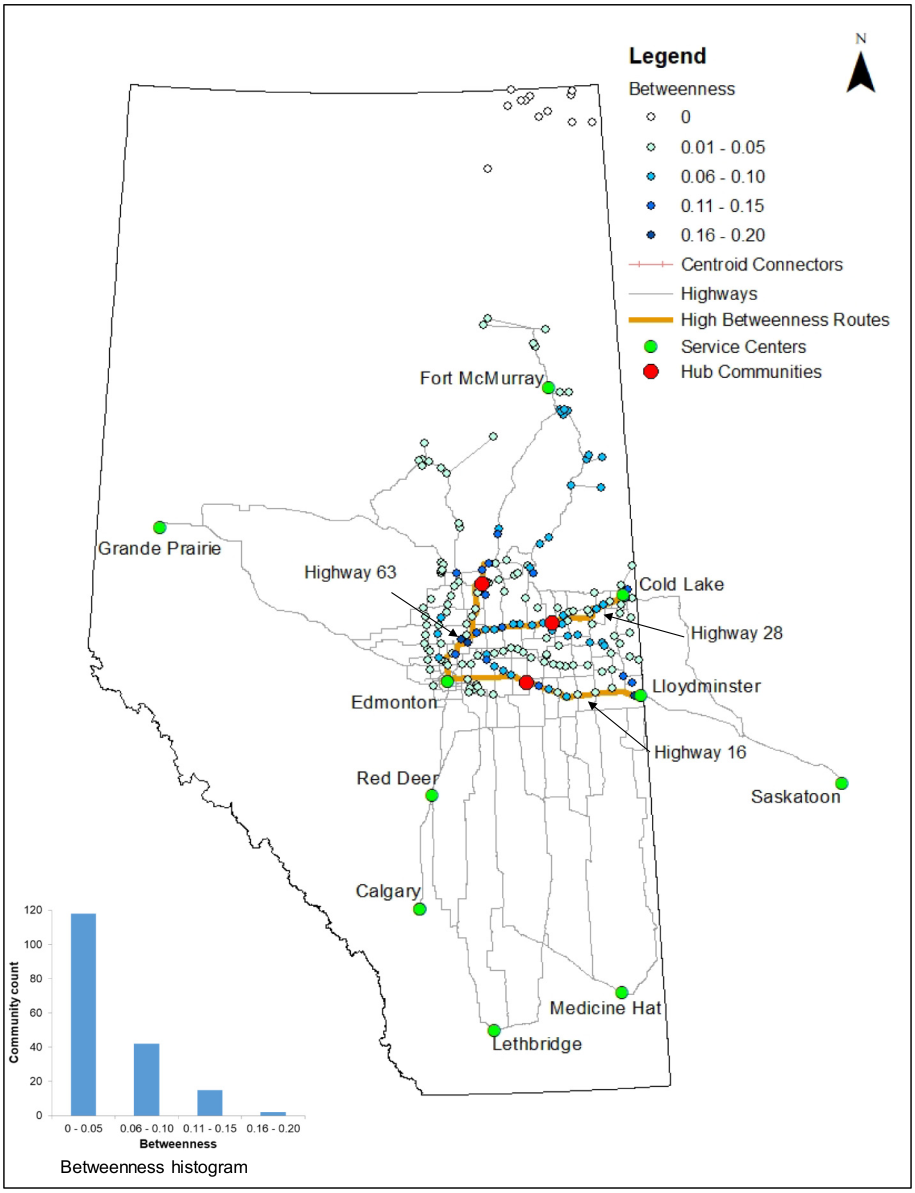

Fig. 2. Betweenness results.

Calgary, Cold Lake, Lloydminster, and Fort McMurray are best connected to communities in the study area. However, if we consider all communities in the province (southern and eastern communities in addition to the currently considered northeastern communities) for the calculation of *RI*, other service centers such as Lethbridge, Medicine Hat, and Grand Prairie would be equally well-connected. This would increase *RI* values. Hence, to measure the true hub strength of service centers, its distance from all communities in the province and not just communities in the sub-set of the province (northeastern Alberta) should be considered in the future.

We also calculated *RI* values for the service centers within our study area (Fort McMurray, Cold Lake, and Lloydminster) to the remaining service centers. Fort McMurray has the highest *RI* of the three service centers, given its location farthest north in the RMWB. Note that the *RI* values of the three service centers are not comparable to the values calculated for the other communities, because their *RI*s were calculated assuming that their service centers included all ten in Alberta (excluding itself). Therefore, for comparison purposes, we normalized *RI*s by the number of service centers considered. Table 1 shows normalized *RI* (and *AI*, discussed in Section 5.1.3) for communities in the Regional Municipality of Wood Buffalo (RMWB), including Fort McMurray. We can observe that Fort

Table 1
Normalized *RI* and *AI* values for RMWB communities.

Community	Normalized *RI*	Normalized *AI*
Anzac	1.51	0.18
Clearwater 175[a]	1.57	0.20
Conklin	1.30	0.18
Cowper Lake 194A	1.38	0.17
Fort McKay	1.73	0.17
Fort McKay 174	1.73	0.17
Fort McKay 174C	1.79	0.16
Fort McKay 174D	1.73	0.17
Gregoire Lake Estates	1.51	0.19
Gregoire Lake 176	1.51	0.19
Gregoire Lake #176A	1.51	0.19
Gregoire Lake 176B	1.51	0.19
Janvier 194	1.38	0.17
Janvier South	1.38	0.17
Namur Lake 174B	1.79	0.16
Namur River 174A	1.79	0.16
Saprae Creek	1.57	0.20
Winefred Lake 194B	1.30	0.18
Fort McMurray (service center)	1.72	0.17

[a] An Indian Reserve is a tract of land set aside under the Indian Act (https://laws-lois.justice.gc.ca/eng/acts/i-5/)

McMurray's *RI* is comparable but somewhat higher than those of surrounding communities. If Fort McMurray were to be evacuated, residents would have to travel much farther to reach a designated service center, while if surrounding communities needed to evacuate, they could travel to Fort McMurray (although as mentioned in Section 4.2, given the movement of the 2016 wildfire, evacuees may be asked to travel out of the region).

5.1.3. Accessibility index

Fig. 3 displays the accessibility index (*AI*) results. A community located at a greater distance from large (population) service centers will have a lower *AI* value. Therefore, *AI* values are highest for communities closest to Edmonton, and decrease sharply for communities farther north.

For northernmost communities not connected to the provincial highway network, $AI = 0$. Fort McKay 174C and Namur Lake 174B and 174A have *RI* values between 1.51 and 2; lower than those of other communities in the study area. These communities are quite distant from the service centers, with exception of Fort McMurray. Ardrossan has the highest *AI* of 4.02, indicating that it is overall closest to the largest service centers.

Like *RI*, the *AI* values of communities also designated service centers (Fort McMurray, Cold Lake, Lloydminster) were also calculated to all remaining service centers (i.e., all but itself; values are again marked with asterisks in Fig. 3). Similar to *RI*, Fort McMurray's *AI* is most critical among the three service centers. Table 1 indicates that Fort McMurray's normalized *AI* is comparable to other communities within RMWB.

The *AI* measure differs from *RI* in that the latter depends on the shortest path distance to the most central service center (the service center closest to communities affected by a disaster), while *AI* considers the shortest path distance to the most populated service center. *RI* assumes that location centrality is the most important characteristic of a service center while *AI* considers the service center's population. The service center population reflects, or is a proxy for, the "draw" of more extensive services in the larger cities.

5.2. Network scanning: capacity reduction

We determined network capacity reductions after disruption, as per Section 4.2, by "disrupting" each grid area individually and scanning the resulting network (Fig. 4). As per Eqs. (4) and (5), greater total capacity reduction (*TC*) values indicate greater impact (to a larger population) after grid disruption. However, regardless of population, $TC = 1$ for grids that

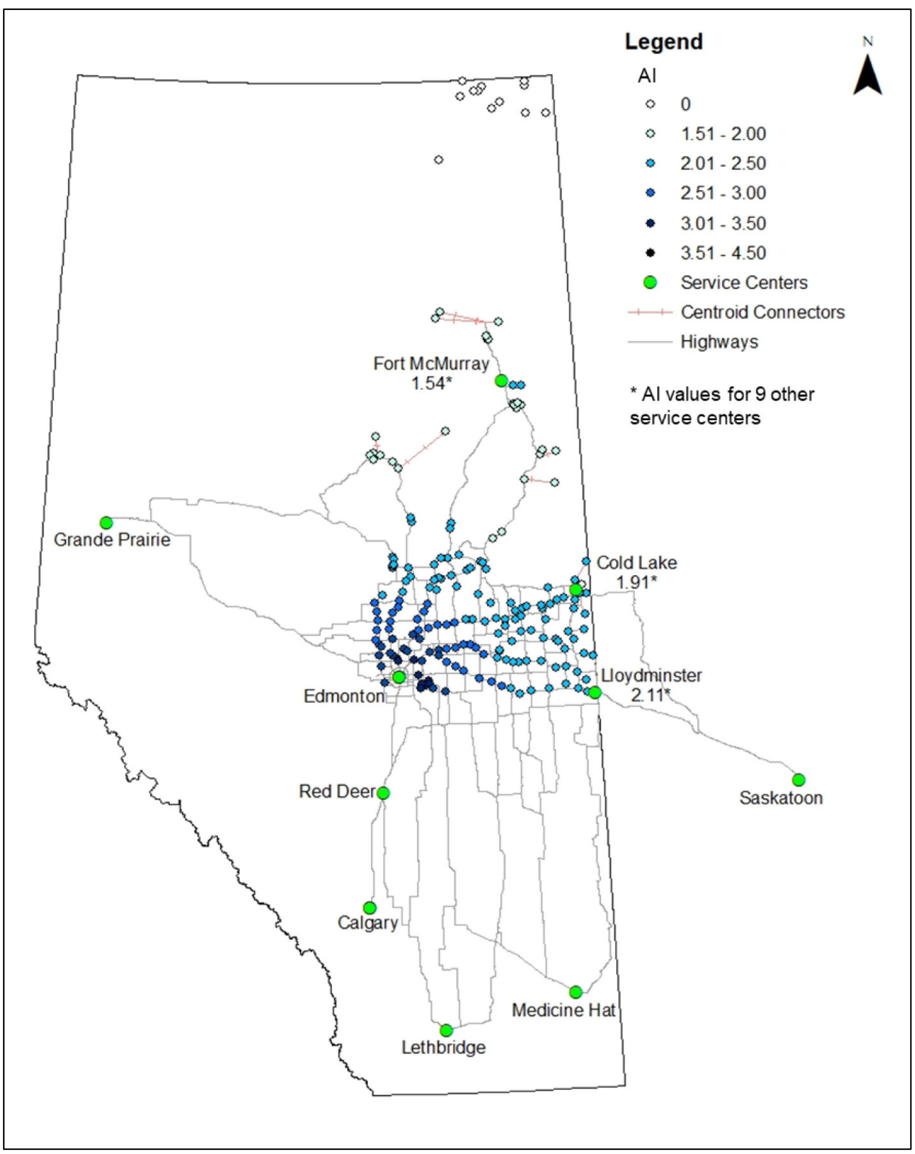

Fig. 3. Accessibility index (*AI*) results.

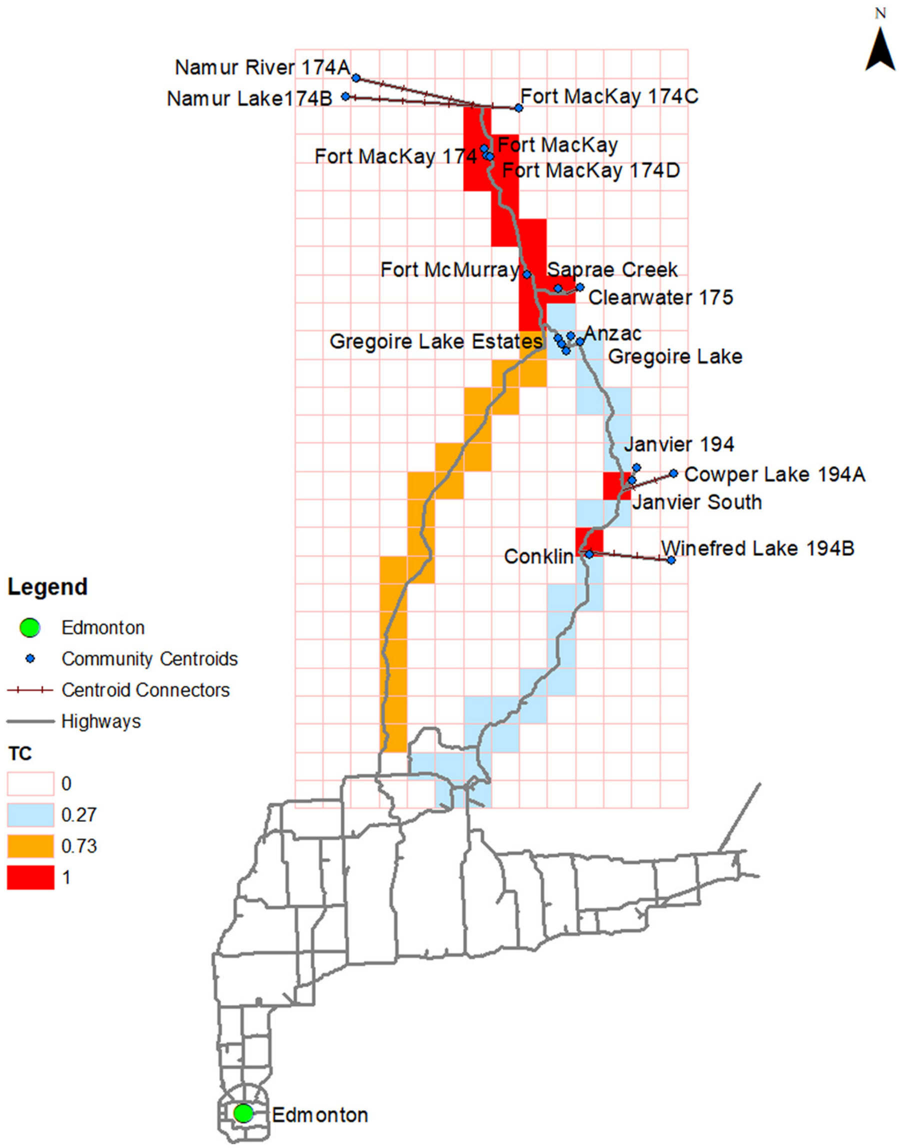

Fig. 4. Total capacity change (*TC*) results.

contain isolating links – those that, if disrupted, completely isolate a community from the rest of the network. Communities that could be entirely isolated from service centers are those served by Highway 63 north of the 63/881 junction (Fort McMurray, Fort McKay 174A, Saprae Creek, Janvier 194) and Highway 881 (Conklin and Janvier South). These communities are located within boreal forest and therefore highly susceptible to wildfires. The rationale for assigning $TC = 1$, even for very small communities, is that isolation of any population on the ground will require air evacuation. This situation occurred in the 2016 Fort McMurray wildfire; portions of Highway 63 south of Fort McMurray become unpassable, and individuals that had initially evacuated north were ultimately able to reach safety (in Edmonton or Calgary) by air.

The next highest *TC* values are 0.73 for grids containing the divided portion of Highway 63. Disruptions to this part of Highway 63 force all evacuating communities onto Highway 881, effectively reducing the total highway capacity (southbound to Edmonton and possibly other points south) from 6400 pc/h to 1700 pc/h. Disruptions to Highway 881 result in $TC = 0.27$, less critical because Highway 63 has a capacity of 4700 pc/h southbound remains available to most communities to the north. Given the very simple configuration of this study network, Fort McMurray's population is almost always impacted by disruptions to highway links. Disruptions to Highway 63 north would result in lower *TC* values due to small impacted populations. However, because these communities are entirely isolated from the rest of the province without Highway 63, $TC = 1$.

5.3. Discussion

Communities in the Regional Municipality of Wood Buffalo (RMWB) can be considered remote as their shortest path distances to designated service centers are high (high remoteness (*RI*) and low accessibility (*AI*) indices values). *RI* and *AI* gives us information on a community's access to services – distance via the shortest path to service centers, whose qualities are measured by a proxy (*RI* by general connectivity within the network, and *AI* by population). However, neither measure tells us whether the shortest path is also the only path – i.e., on an isolating link.

A map that combines *RI* and *AI* results with capacity scan results can identify communities that are most vulnerable by multiple measures. Although we have not included such a figure here due to manuscript length, such a map would indicate that Namur River 174A, Namur Lake 174B, Fort McKay, Fort McKay 174, 174C, 174D, Saprae Creek, and Clearwater 175 have the highest *RI* values in the study area ($RI = 25 - 30$) and are also connected to the network via isolating links. Such communities are not only the most vulnerable for service center access, but also the least robust in that they may be completely isolated in disasters. In fact, their closest service center of Fort McMurray is itself connected to service centers on an isolating link, which was closed during the second stage of the 2016 wildfire evacuation and over 20,000 people were flown out via oilsands camps airstrips (Woo et al., 2017). If betweenness was calculated for Fort McMurray, it would be relatively high for that northern region. A service center with a relatively high betweenness, relatively high *RI*, and connected by an isolating link is problematic in emergencies, as demonstrated in 2016. When scanning results show a significant capacity drop, with some basic population and demographics data of the communities in danger, emergency planners (together with transportation engineers) can ascertain whether demands will lead to congestion. Thus, they can further determine where traffic management measures or alternate evacuation modes (i.e., air) will be required. In the long term, this method can identify regions for further study (i.e., using simulation), to target transportation infrastructure improvements (whether on the highway network or other modes) to such critical locations on the network.

Using betweenness together with network scanning, we can identify communities to locate emergency supplies for citizens evacuating from an emergency, and emergency personnel moving towards it. Additionally, aerodromes and airstrips near these communities can be used as multimodal hubs for air evacuation in cases of emergencies that cause both network disruption and community evacuation. Once these facilities are identified, emergency management planners can consider targeted improvements to ensure their readiness in emergency events. Improvements may be targeted to the facility itself or to roadway infrastructure connecting them to communities and the provincial highway system.

However, some sizable communities that may be completely isolated by facility disruption have aerodromes, such that evacuation can be coordinated by air (for smaller communities we expect that helicopters can be deployed much like in medical emergencies). In our study area, Fort McMurray, Fort McKay 174A, Saprae Creek, Janvier 194, Conklin and Janvier South are identified as communities with populations over 100, connected by isolating links, and served by existing aerodromes (Fig. 5). Local roadway connections from communities to these aerodromes may be incorporated into the network model, such that measures may be adjusted to account for multimodal evacuation should it be an option provided by emergency management plans. In

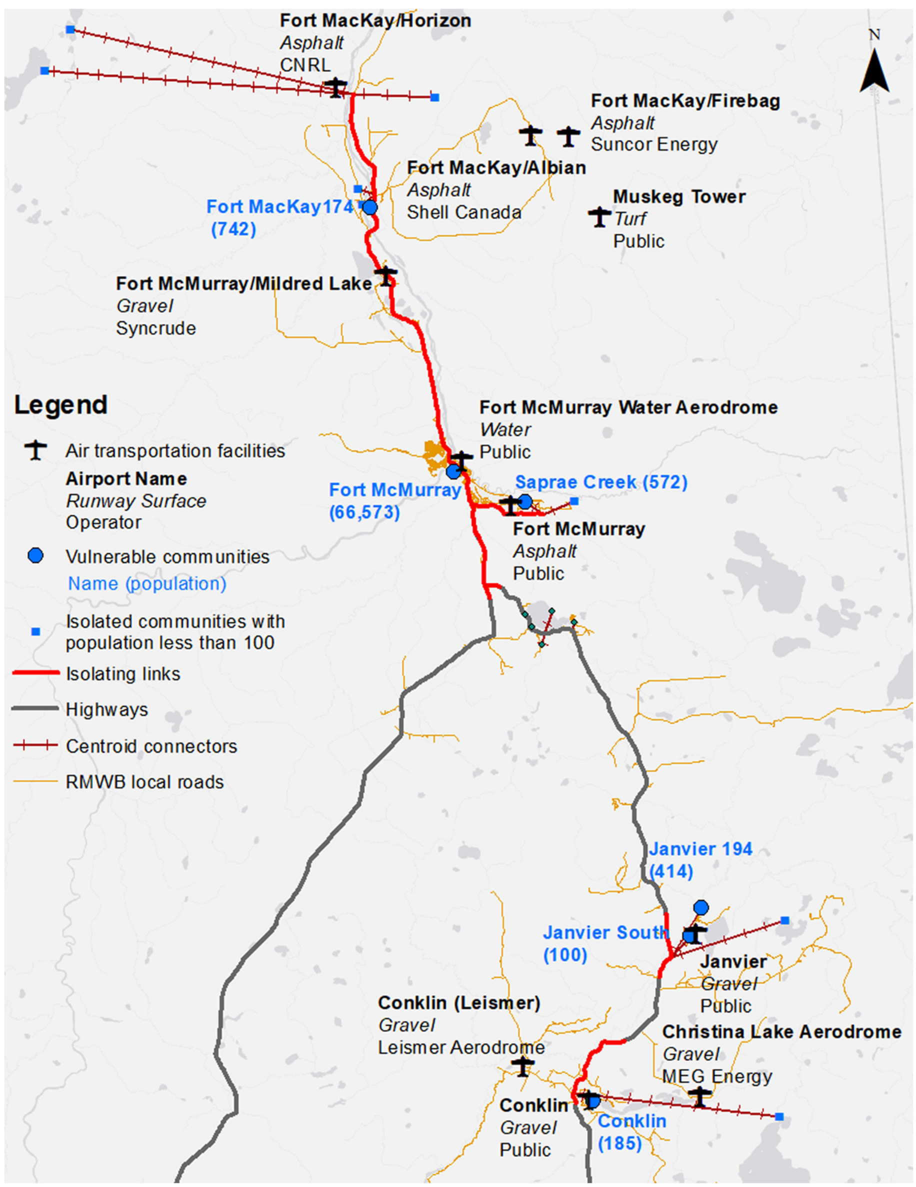

Fig. 5. Vulnerable communities and proximate aviation facilities.

future studies, the planning and logistical costs of coordinating multimodal emergency response versus highway infrastructure expansions may be evaluated.

6. Conclusions and future work

We calculate and present a set of simple but informative and complementary measures that, together, identify: communities vulnerable to disruptive events, vulnerable network locations (that, if compromised, would cause significant operational degradation to the network and reduced mobility), and how to reduce community vulnerability by identifying the most accessible locations for emergency services. We presented the results of measures of network topology (betweenness), community accessibility to safety and emergency services (remoteness and accessibility indices), and network scanning to determine capacity and connectivity shortfalls in disruption. We applied our measures to a network model of Alberta's northeastern quadrant, a sparse geographic region prone to wildfires. The overall purpose of our work is to provide a "package" of basic information about the transportation network – measures that are complementary, and easy to present and understand – for use in strategic planning and preparation by emergency planners.

Communities with the highest betweenness scores are located along major highways in the study area, and may be good candidate locations with capacity to store supplies. Evacuees may access gas, water, first aid, etc. on their way out, and emergency crews can access equipment and other supplies on their way towards the event. The remoteness (*RI*) and accessibility (*AI*) indices measure a communities' access to major cities in the province where evacuating residents can receive emergency services (by distance and city population, respectively). The network scan highlights the importance of Highway 63 in providing most of the ground transportation capacity to RMWB communities, with disruption resulting in a 73% reduction in capacity for these communities. The network scan also identifies isolating links – provincial highway facilities that, if disrupted, disconnect the network into two sub-networks and thus isolate communities from all service centers.

These measures offer further guidance to emergency planners when used in combination. When *RI* and *AI* results are combined with the network scanning results, it is clear that communities in the Regional Municipality of Wood Buffalo (RMWB) are highly vulnerable to network disruptions and in evacuations, given their relatively high population concentrations and remoteness from major service centers in the province, connected to these centers by a very limited transportation network. The network scanning and *AI* or *RI* results can provide further guidance on where to locate emergency supplies, by further assessing the betweenness results against facility capacities and community accessibility to service centers. Identification and use of these key locations, by emergency management planners, can help ease evacuation stress and event impact. Furthermore, we identified existing aviation facilities near communities (and sets of communities) that are connected not only by isolating links, but could also suffer from inadequate highway capacity. Given that the sparse transportation network of northern Alberta has limited to no redundancy, existing air facilities are often the only other means of evacuation; emergency management planners can use these results to identify and consider these facilities in emergency operations plans. Planners can also consider targeted infrastructure improvements at these facilities (roadway access, supply storage, etc.) to ensure their readiness in emergency events.

There are many directions for expanding and improving on this work. First, in continuing study of this sparse network, air transportation facilities (and their connecting roadways) should be incorporated into the network model. The measures presented in this paper may be adjusted to account for multimodal evacuation should it be an option provided by emergency management plans. Second, the planning and logistical costs of coordinating multimodal emergency response versus highway infrastructure expansions may be evaluated. Third, local roadways should be incorporated into the model, to understand how local roadways contribute to providing community access and contributing to network robustness. Finally, we plan to expand our model province-wide, which will present new challenges in representing dense urban areas alongside remote regions like the RMWB.

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Credit statement

Amy Kim: Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Writing – review & editing. **Kasturi Mahajan:** Data curation; Formal analysis; Software; Visualization; Roles/Writing – original draft.

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