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Wildfire Evacuation Modelling Coupling Traffic and Fire Behaviour

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Abstract

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

Keywords: wildfires, traffic modelling, fire behaviour

1. Introduction

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

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

2. Background

2.1 Importance of Coupled Modelling

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

Table 1: Events during the evacuation of Fort McMurray depicting traffic, fire, and/or human behaviour

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

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

2.2 State of the Art for Coupled Modelling

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

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

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

3. Methodology

3.1 Historical Data Collection

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

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

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

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

3.2 Traffic Scenario Development and Traffic Modelling

Scenario development for the traffic modelling included baseline evacuation scenarios, where there was no fire propagation integrated into the model, and scenarios with fire behaviour coupled into the model. Human behaviour was not considered in the development of the scenarios, however, it is acknowledged that human behaviour would impact traffic behaviour, as observed in Fort McMurray (see Table 1). Human behaviour was not considered due to both ongoing research in human behaviour under emergency conditions[26], and to a knowledge gap in how to incorporate unusual pedestrian behaviour into the traffic model. The traffic modelling will be used as an exploratory step in the coupling of evacuation models, which at the time of writing, has not yet been performed.

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

A simplified model of a case study community was created due to time constraints and to reduce complexities in the road network. The area of interest is composed of 530 permanent cabins in less than a 0.15 km^2 area, with 285 cabins in the back-cabin area and 245 cabins in the front cabin area[29]. The cabin area was reported to be fully occupied in the summer months; therefore, 100% occupancy was assumed for the model[29]. In order to maintain consistency with previously modelled scenarios, despite the simplification of the network, the road width of the inner roads was assumed to be 2.5 m, and the outer roads were assumed to be 3.0 m[29]. For this model, the road width was not expected to impact the simulation[29]. To simplify the cabin area, it was decided to model the community as a square, with 16 individual blocks within. Based on a cabin area of 0.15 km^2, the equivalent square dimension would be approximately 390 m by 390 m. The dimensions were rounded up to 400 m by 400 m to account for area taken up by roads. The road away from the cabin area was traced using the Open Street Map background, included in PTV VISSIM. The original cabin area modelled in PTV VISSIM in a previous study, versus the simplified cabin area, is shown in Figure 1 below. For more detail, a previous study has outlined all considerations and assumptions of the case study community[29].

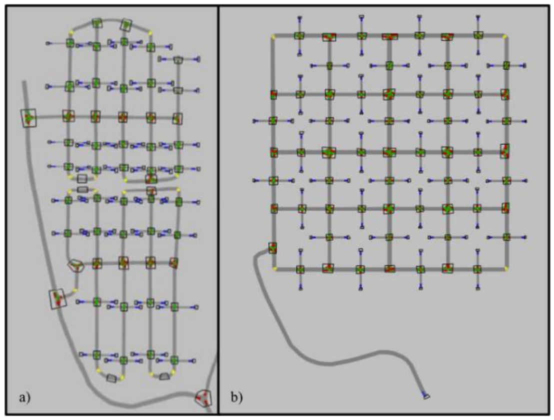

Figure 1: Simplification of the case study community in PTV VISSIM a) Original modelled cabin area[29] b) simplified modelled cabin area

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

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

4. Results

4.1 Historical Data Collection

4.1.1 fort mcmurray

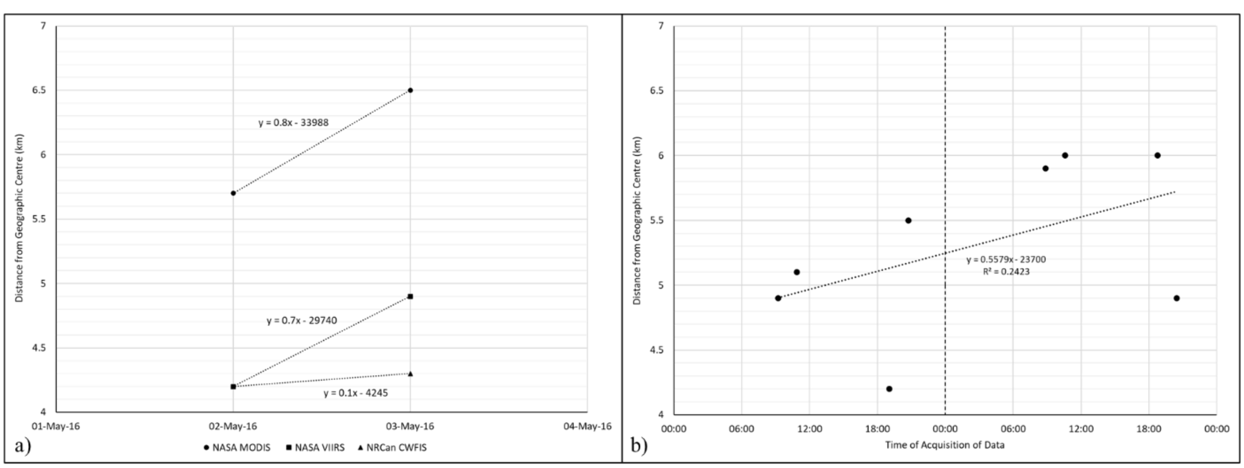

Figure 2: Fort McMurray Results a) over days b) VIIRS data only using time of acquisition data

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

4.1.2 slave lake

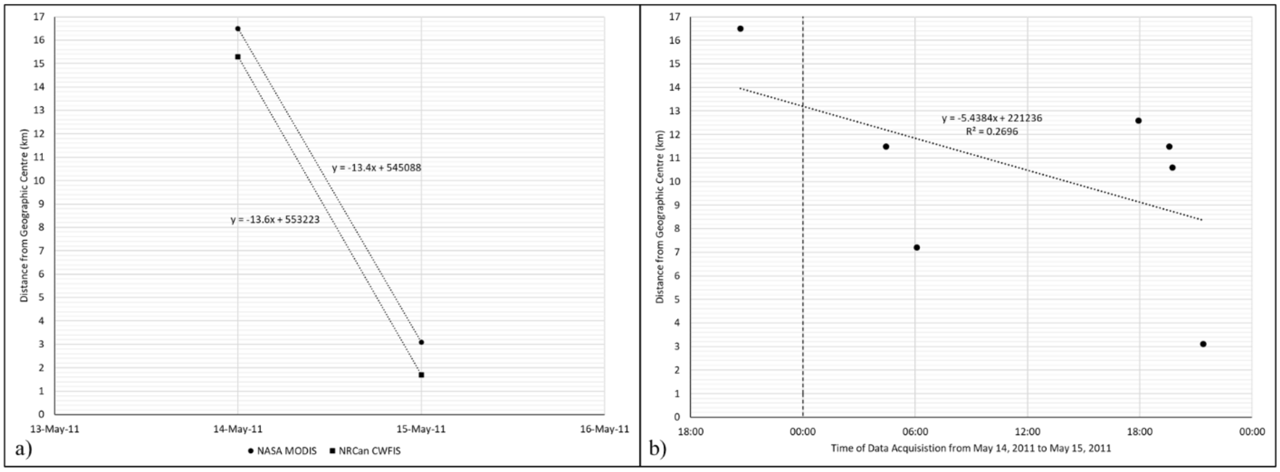

Figure 3: Slave Lake Results a) over days b) MODIS data only using time of acquisition data

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

4.2 Traffic Modelling Scenario Development

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

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

Table 2: Description of baseline evacuation scenarios

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

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

Table 3: Description of coupled fire behaviour scenarios

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

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

5. Discussion

5.1 Historical Data Collection

5.1.1 fort mcmurray

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

5.1.2 slave lake

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

5.1.3 limitations of the methodology

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

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

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

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

5.1.4 implications for coupled model validation

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

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

5.2 Traffic Modelling Scenario Expected Results

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

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

6. Conclusions and Future Work

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

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

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

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9. Endnotes

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