WUI-PEM: Wildfire Phased Zone Evacuation Methodology

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ABSTRACT

Wildfires are a growing threat to wildland-urban interface (WUI) communities. Globally over the last decade hundreds of wildfire related deaths have occurred along with hundreds of billions in economic losses. If the encroachment of fire into a community cannot be stopped, evacuation becomes necessary to save lives. In response to the increasing threat, WUI communities must properly prepare and implement an evacuation plan, as orchestrating an evacuation within a limited time frame is a complex challenge. While several fire and evacuation simulation tools have been developed to aid planning, a comprehensive methodology for constructing and assessing evacuation plans is still evolving. This article fills some of the current gaps with a simple six-step process to evaluate wildfire risk, individual evacuation zone traffic demand, and formulate a staged zone-based full evacuation plan. This methodology can be used for wildfire evacuation planning, evacuation plan management, and training.

Keywords:

Wildland urban interface, wildfire, evacuation planning, emergency management, simulation.

INTRODUCTION

A ‘wildfire’ can be defined as an unplanned vegetation fire produced by natural or human causes. Wildland urban interface (WUI) fires involve fire encroaching into populated communities causing loss of life and economic losses, including damage to property, infrastructure, and natural resources, as well ongoing concerns such as businesses and industries (Bento-Gonçalves et al., 2020; Schug et al., 2023). The development of the fire itself will be influenced by geography, weather patterns, and vegetation; the impact on affected buildings by construction materials/techniques and land use planning; while the capacity for communities to cope with an incident will be influenced by the resources available, the information available, and their ability to evacuate. These elements combine to produce the outcome in the context of planning effective mitigation and intervention efforts (i.e. emergency management and response).

Climate change has contributed to the increase of high-profile wildfires globally in recent years. For instance, extreme weather conditions contributed to the 2018 California wildfires, resulting in 100 deaths and an estimated $148.5 billion US dollars in economic losses, including damage to homes, businesses, and infrastructure (CAL Fire; Wang et al., 2021), while extreme heat promoted the 2019-2020 Australian bushfires resulting in an estimated $103 billion Australian dollars in losses and 33 deaths (Ogie et al., 2022). Over the decades, there is a tendency that more frequent and severe wildfires occur at many places around the globe, as illustrated in Figure 1. Figure 2 shows the tree loss by country using 2010 as a reference point. It is apparent that some countries have shown a dramatic loss, e.g. Portugal has a 39% loss, Sierra Leone a 33% loss, and Australia a 17% loss (Global

Forest Change). In response to the threat caused by the wildfire, it becomes a crucial requirement for all communities located at wildland urban interface to prepare for such a disastrous event. This, however, is challenging (Murray et al., 2023). As such events begin to encroach on occupied regions (only made more likely by the migration of people to the WUI), so the risk of exposure and the need for emergency response increases.

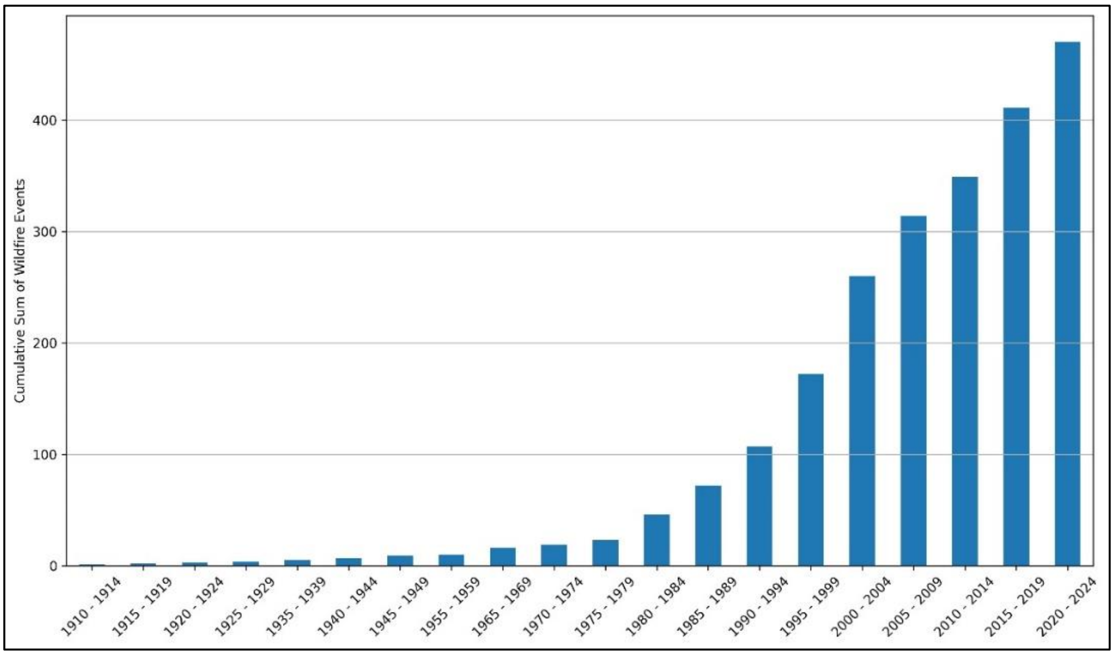

Figure 1: Occurrence of wildfire in five-year intervals. Data: (Global Forest Watch).

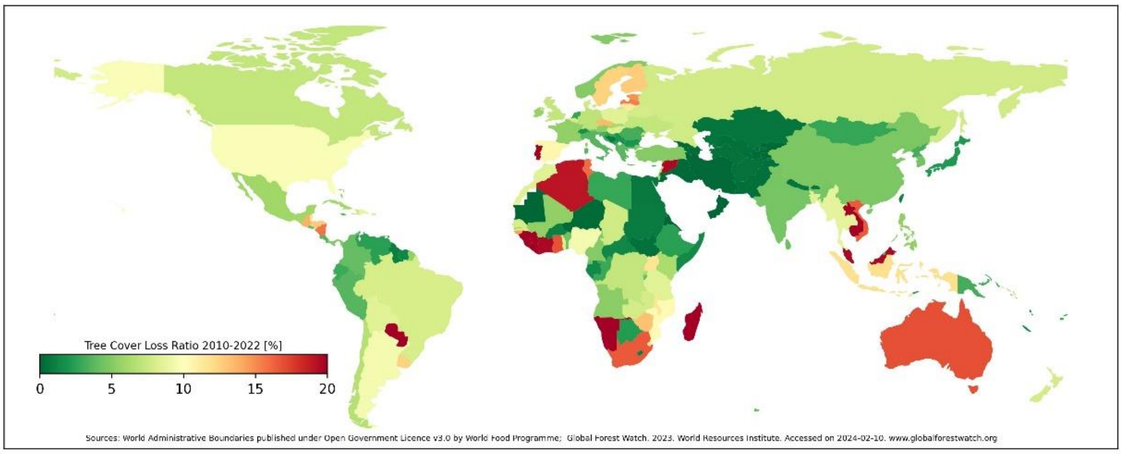

Figure 2. Tree loss due to wildfire between 2010-2022 using 2010 as reference point (Global Forest Watch).

The ability to carry out a large-scale evacuation is a key measure to safeguard communities when a fire threatens inhabited areas. It may be particularly important where mitigation measures have been ineffective and where real-time intervention cannot halt the progress of an oncoming fire front. Conducting such a large-scale evacuation requires a coordinated effort from multiple agencies and stakeholders, including emergency responders, local government officials, and community leaders to work together, taking into account all the relevant factors in evacuation planning and management. These factors include, but are not limited to, the nature of the fire threat (affected by the landscape, the vegetation, and the wind conditions affecting the movement of the fire front and therefore the time available for evacuation); the number, mobility and distribution of people to be evacuated; the availability of evacuation routes and target destinations; and the resources required for the evacuation (e.g., intervention, communication, vehicles and shelter etc.). Given the complex interaction between these factors and the importance of the evacuation performance (for both planning and emergency management), it is necessary to analyse the relationship between these factors.

- **The threat**: When a fire is detected, the direction and speed of fire spread, and its distance to the community combine to determine the fire risk, i.e., the level of threat posed to the community. The threat also affects the range of the area to be evacuated and the available time for evacuation.

- **The evacuation demand**: The demographics, size, and distribution of the population within the community form the demand for evacuation. This demand is also affected by the layout and distribution of the community properties, including the residential streets within the community as well as the demographic and socioeconomic makeup of a community.
- **The routes for evacuation**: In most WUI communities, evacuation will need to be facilitated by the road network. That is, the evacuating population will need to leave the threated area via either familiar routes or designated evacuation routes through the road network to a place of safety. Thus, the layout and capacity of the road network, given their availability and use, will influence capacity and therefore the required evacuation time assuming demand is at a manageable level.
- **The resources required for the evacuation**: The resources required include fire intervention and traffic control, fire prevention and traffic control, the availability of vehicles for evacuation, and the notification system in place to convey the instructions to the residents (assuming that this affects the time to initiate evacuation along with preparatory activities).
- **The evacuation goal**: The availability of safe locations to accommodate the evacuees and their tools for transportation.

An effective evacuation plan for a community should be evidence-based, i.e. involve the assessment of threat level to different regions of the community (over time) and the effectiveness of different evacuation responses (e.g. including an attempt to balance the evacuation demand with the available routes and resources for evacuation), to increase the probability of a safe community evacuation.

The goal of developing this evacuation planning methodology is to take the above factors into account in planning or managing an evacuation, so that it can both minimise the risk of exposure to the fire threat, and stage the evacuation based on a zone-based division of the community, so that the resources are more effectively utilised and any plan put in place is more robustly tested. In other words, the evacuation plan should be designed to ensure that the risk of exposure to the fire threat is minimised, while also ensuring that the evacuation is carried out in a way that makes the best use of available resources. The plan is based on a zone division of the community given its layout, so that the evacuation can be designed, managed, and tested at the zonal level. It is recognized both that this methodology is draft in nature and broadly drawn given that the intention is that it might be generally applied. However, such methods are both uncommon and necessary both to encourage the appearance of evacuation models and structure their use.

QUANTIFYING PERFORMANCE

Ideally evacuation performance would account for all aspects of emergency management, including prevention, mitigation, preparedness, response, and recovery. Given the challenges posed in the collection and analyses of traditional outcomes and the significant variability of fire scenarios (e.g. making reliance on analytical derivations and empirical correlations much more challenging), wildfire evacuation modelling might be employed to quantify the interaction between the various elements and their consequences. Any model applied will inevitably contain multiple approximations and assumptions; however, coupled with subject matter expertise such efforts can reasonably assess the potential impact of certain factors, their interaction, and the sensitivity of the outcome to this interaction. That is, they might provide the means for communities, first responders, and emergency managers to define and explore certain 'what-if' scenarios. The use of modelling tools that consider traffic evacuation dynamics along with wildfire spread and pedestrian response might inform decision-makers about potential outcomes, vulnerabilities in their communities, and the most appropriate strategy to adopt (Ronchi et al., 2019; Kim et al., 2024).

There are a number of evacuation-related simulation platforms available (Ronchi et al., 2019; Intini et al., 2019), for instance, fire models (e.g. Spark, FARSITE, Prometheus, Phoenix, CAWFE, etc.), pedestrian models (e.g. EvacMod, FDS-Evac, Pathfinder, PedGo, Pedestrian Dynamics, JPS, etc.) and traffic models (e.g. OREMS, EVAQ, DYNA-SMART, AIMSUN, SUMO, TRANSIMS, VISSIM, etc.) that can be used to estimate evacuation outcomes. Most models simulate only one of the necessary features (i.e. fire, traffic, or pedestrian). There are several evacuation simulation tools available that attempt to capture the complexity of wildfire evacuation events – by including several aspects of the wildfire events including urbanEXODUS, Simtable, FLEET and WUI-NITY (Grajdura et al., 2022; Veeraswamy et al., 2018; Wahlqvist et al., 2021; Wildland Fire – Simtable; Fast Local Emergency Evacuation Times (FLEET); Genasys EVAC). These tools, amongst others that are emerging, would allow the practitioner to assess the evacuation of a community under different evacuation strategies and route availability – enabling the effectiveness and robustness of such strategies to be assessed. This is a pre-requisite for the methodology described below.

METHODOLOGY

The objective of the proposed evacuation planning methodology is to develop an effective evacuation plan for a threatened community with the aim for those individuals who need to evacuate, to do so safely and effectively. The method is based on a zone-based division of the region. By assessing fire risk and evaluating individual zone and full evacuation performance, the method provides guidance on constructing staged evacuation plans and applying evacuation simulations to select a plan based on performance metrics. It is important to note that this methodology is not tied to any specific modelling tool. However, it is essential to recognize that the development of this methodology imposes certain requirements on evacuation models. Specifically, these models must exhibit the flexibility necessary for effective evacuation planning and the capability to compare the performance of different evacuation plans using the proposed measures. Finally, this methodology can serve as training guidance in preparation for potential wildfire emergencies.

The methodology comprises six essential steps for analysing evacuation procedures and the metrics for selecting an effective plan. The first two are preparatory steps, which identify the geographical area for evacuation planning analysis and create a zone division of the area – the fundamental information for zone-based evacuation planning. Step 3 creates a simple estimate of exposure of different part of the area to the fire threat, based on the zone division. This step generates a rank of the zones with associated weight values, which will be used in the subsequent steps. This rank will be referenced for defining evacuation sequence of the full evacuation plans. And the weight values will be used in performance metric calculations for these plans, so that the fire risk is considered in identifying an effective plan. Step 4 defines three criteria for assessing the required safe evacuation times for the zones and Step 5 assesses the evacuation performance of individual zones through simulations according to these metrics. The outputs of these two steps are essential for determining the timing of the evacuation sequence in the last step. Step 6 (the last step) defines the components of staged full evacuation plans and suggests how to construct the plans using the outputs from previous steps. Step 6 utilises the results obtained from applying simulations to the plans and the proposed performance metrics to identify the final plan. These steps are outlined in detail below.

Step 1: Identify the location and range of the region to be considered for evacuation planning analysis.

The first step is to examine the target region that is susceptible to fire threats and identify the range of the area for evacuation planning or management analysis. Mapping platforms such as OpenStreetMap, Google Maps or Bing Maps can be used to examine the area, with consideration of the following criteria:

- The region should encompass the entire residential area and traffic network, inclusive of unimproved roads, relevant for evacuation analysis. Depending on the scale of evacuation planning, this could be a local community, a town, or even a city.
- The region should include evacuation objectives away from the threatened area. If the evacuation goal is not clearly defined, the region should cover a specific length (e.g., X kilometres) of the roads leading out of the populated area. Such a road segment defines a city exit within the region.

Step 2: Define evacuation group according to emergency management zone (EMZ).

For a large, populated community (e.g., a city), it might not be a credible strategy to order an evacuation of the whole population at the same time – especially if routes are limited and the community is densely populated. This is because the road network is seldom designed and developed with the aim to accommodate the surge of traffic demand from all residents. In practice, officials often divide such a large community into multiple emergency management zones (EMZs) so that the evacuation can be staged / managed at this level of resolution. While there are several factors (e.g., the population distribution, the layout of local road network) that can be considered in this process, the division of the area and the identification of the zone boundaries often follow political or geographical boundaries. This is primarily to facilitate the conveying of the message to people and their interpretation of the emergency management instructions. The development of this evacuation planning methodology is based on the zone division for the planning of emergency response – assuming the zone division is completed. The successive steps will assess the risk of exposure to the fire threat at different zones[1], and stage the evacuation of the zones to make an efficient use of the available road network capacity – assuming necessary resources such as notification and communication systems, and emergency management personals are in place to carry out the staged full evacuation plan.

[1] Zone and EMZ are interchangeable terms used throughout this paper.

Step 3: Assess fire risk to EMZs: Pre-Modelling Ranking.

To plan a staged evacuation for the EMZs, their exposure to the potential fire risk needs to be assessed first to prioritise their evacuation order. While there are many factors influencing the speed of the fire spread, range, intensity, and its subsequent impact on the community, here we propose a simple method to give a basic estimate of risk that can help structure the subsequence modelling. This simplified approach can be used when there is a lack of necessary information to perform a more detailed assessment of the fire risk (especially the spread of the fire itself). The approach should be enriched should both the information for fire modelling and fire simulation capability are available for fire risk assessment (Kalogeropoulos et al., 2023). This is beyond the scope of the description of this planning method.

When a fire is detected, or where there is a high risk of ignition at a nearby region with vegetation as fuel, the distance from the fire front to the EMZs can be used to assess the level of risk to which they are exposed. In general[2], the EMZs that are close to the fire, or the source of a potential fire should be ranked at the top in the evaluation order if the evacuation must be staged. To construct a fire risk factor for an EMZ that allows the comparison of the level of threat with the others, a normalised fire risk (FR_i) for the i^{th} EMZ based on the distance to a fire threat is defined as

$$FR_i(D_i) = \frac{\frac{\sum D_i}{D_i}}{\sum \frac{\sum D_i}{D_i}},$$

where D_i is the shortest distance from the fire front to the perimeter of each EMZ.

The method of assessing the fire risk to EMZs is illustrated using a hypothetical example shown in Figure 3. The community consists of four EMZs labelled from A to D. It is assumed that a fire starts at the top left corner of the region with a red arrow showing the possible propagation direction towards the community. Subject to the distance to the location of fire threat and the direction and speed of potential fire spread, the EMZs may be exposed to different levels of risk. In general, the closer to the fire front a community is when the fire propagation is detected, the higher the fire risk of the place will be. Thus, people living in this region should be evacuated with priority, and the distance can be used to construct a risk indicator (although other factors, such as weather and wind conditions or the geometry of the road network certainly also affect the potential risk at a given location).

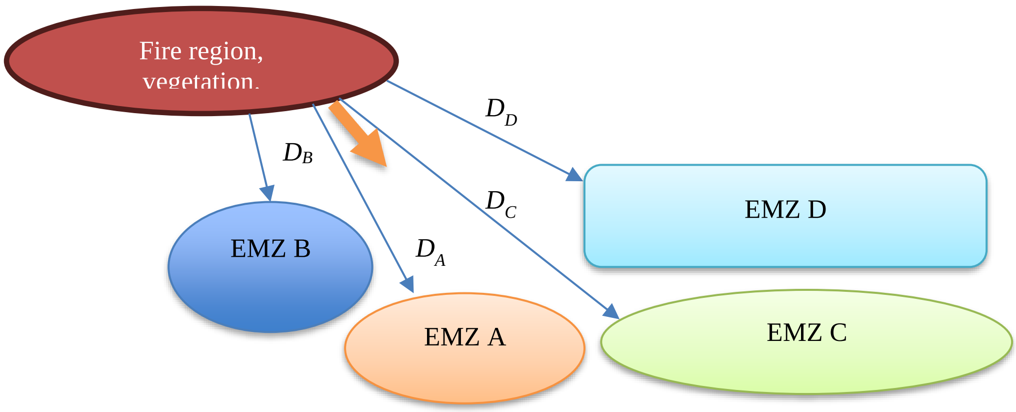

Figure 3. The relative location of EMZs and the fire.

Table 1 lists the values of D_i and the calculated value of FR_i for the four EMZs in the example. The closer an EMZ is to the fire, the higher the fire risk indicator is. For instance, EMZ C is four times further away to the fire than EMZ B, the risk value of EMZ B is about four times of that of EMZ C. Note that FR_i is a signal-factor risk indicator; it does not include the other potential influencing factors in the assessment of the fire risk to the EMZs. For example, equivalent vegetation type and distribution between the fire front and each region is assumed. Additionally, to be fair with the comparison of the fire risk using FR_i, it is also assumed that the EMZs are comparable in size, i.e., none of the EMZs is significantly larger or smaller than the others. If there is any EMZ that is significantly smaller than the others, it may be merged with a nearby EMZ which has similar D_i for planning analysis.

[2] For example, this might not be the case should there be a change of wind direction, or where there are measures to separate or protect the zones, so that some zones may not catch fire. Again, we are not trying to cover all the possibilities but the general concept.

Table 1. The calculation of fire risk based on distance to the source of fire risk.

	EMZ A	EMZ B	EMZ C	EMZ D
D_i (km)	4	1.5	6	4
FR_i	0.19	0.50	0.13	0.19

Step 4: Assess the evacuation performance of individual EMZs: Evacuation Assuming Ideal Management Conditions.

To create an effective staged and zone-based evacuation plan, the traffic demand from each zone and the expected duration of use are two key pieces of information for planning the evacuation and optimising route usage. To be able to estimate the information, this step defines three exit stages from their start location (households) to destination (final place of safety), which set the criteria for estimating the times for people to escape from the danger. Based on this definition, Step 5 introduces the method to estimate the information through simulations.

Unlike the traditional building evacuation planning, which normally includes a signal stage of evacuation to a place of safety, the evacuation route from residential areas to a final place of safety can be broadly divided into three sections, which correspond to three exit stages of the evacuation (see Figure 4 and an example illustrated in Figure 5). The first section includes roadways (primarily for local traffic) within EMZs connecting households and the nearest arteries in the city, which is normally located at the boundary of the corresponding EMZ. The location where the perimeter of the EMZs intersects with the main roads can be defined as **zone exit**. During this stage of evacuation, people who have decided to respond emerge from their homes, join the evacuation traffic follow on local roadways towards the main roads (i.e., zone exit). Progress will have been made once they have arrived at these main roads; however, they still need to continue driving along the main roads towards the boundary of the city and then the place of safety. They are still vulnerable, but less so than when they had first initiated movement.

The second section of the evacuation route is from the main roads within the city towards the city boundary. During this stage of evacuation, there will be merging flows from the same or other EMZs on the main roads. Therefore, people might not be able to drive at their desired speeds and may also experience congestion – depending on the population size/density, demand levels, route capacity and the conditions faced. The location where the perimeter of the city intersects with the main roads out of the city can be defined as the **city exit** (see Figure 5). When people pass the city exits, it usually means they have left the populated area. Therefore, less merging traffic from side roads will be expected, and people should therefore be able to drive at relatively higher speeds as they move further away from the city.

The last section of the evacuation route is normally from major arteries or freeway leaving the city towards the remote **regional exit** (see Figure 5) representing a place of safety, such as planned sheltering places or a remote location far away from the wildfire threat. If there are no planned sheltering places and people are heading towards their own elected destinations once they leave the city, then a location on the freeway that is relatively far away from the area being threatened can be defined as a regional exit for the modelling purpose.

In this step, it is required to perform a static analysis of the zone map including the traffic network. The goal is to identify the three types of exits and determine the evacuation route options to leave through the zone and city exits towards the final reginal exits. When planning the evacuation route for each zone, the consideration for route choice includes nearest, fastest (and route familiarity if the information is available) route towards assigned sheltering places. The planning should also consider the likely use of the roads by people in other zones. The insights gained from Step 4 serve as input for the subsequent evacuation performance analysis in the next two steps.

Step 5: Stress-Testing: individual zone evacuation analysis.

Before complex situations during a full evacuation (for instance, as a result of management or intervention) are assessed, it is essential to develop an understanding of the evacuation performance of individual zones. In essence, how each zone might perform should other zones be successfully delayed in their response. This step conducts a stress test of the response from each zone, given the routes they use, to inform the development of city-wide evacuation plan and the test outlined in Step 6. In the stress test, each zone is evacuated alone with instant response (to encourage the development of peak levels of congestion) and the route choice obtained in Step 4 under two traffic conditions:

1. **Zero background traffic** – representing the assumption that people in the EMZ have priority in the order of evacuation and the attempt to manage the background traffic is successful.
2. **Certain amount of background traffic** - representing the assumption that either (a) the attempt to manage the background traffic is partially successful or (b) the potential for interacting with evacuees

from other zones given they ignored previous instructions (here represented implicitly by a reduction in available route capacity).

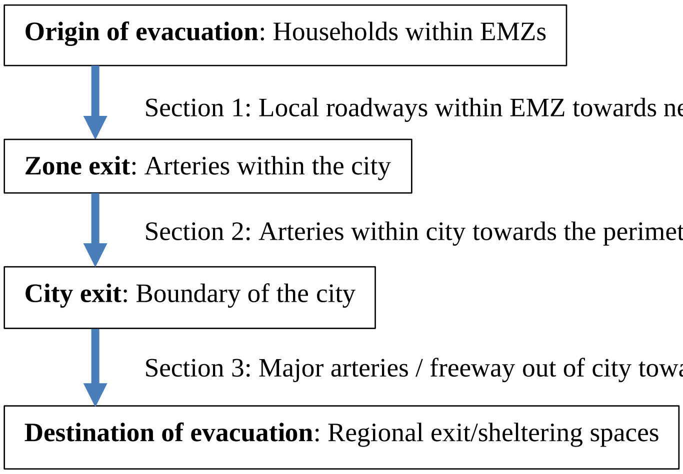

Figure 4. Three stages of the wildfire evacuation.

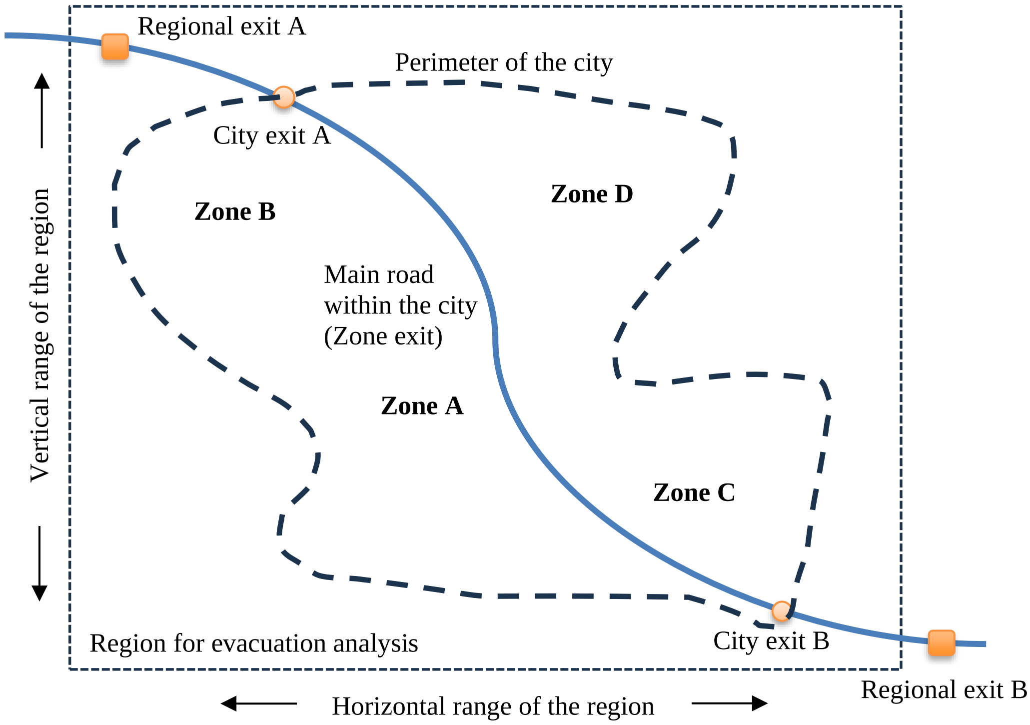

Figure 5. The range of the region for evacuation analysis and three types of exits.

Under the stress testing condition (i.e., instantaneous response / focus on response of individual zones), the simulation results produced from the first test traffic condition give an indication of the minimum time required to move the sub-population to safety, while the results produced from the second test traffic condition indicate a more representative estimate of the time required for the sub-population to evacuate the zone in general. The first time is useful for planning during an emergency in which a particular zone is facing an immediate threat especially in establishing locations of potential route congestion, while the second time is useful for making a city-wide evacuation plan reflecting more representative clearance times for each sub-population. Both might be used to prioritize zone evacuation and suggest design modifications to reduce sources of traffic congestion.

Corresponding to the three stages of evacuation outlined in Step 4, the evacuation performance of each zone has three indicators:

- Ez_{i0} - the time to clear the i^{th} zone alone.
- Ec_{i0} - the time for the subpopulation of the i^{th} zone alone to clear the city exits.

- Er_{i0} - the time for the subpopulation of the i^{th} zone alone to reach the regional exits.

Given these indicators are obtained without considering the interaction with the subpopulations in other zones, these form the baseline for comparison with the evacuation performance obtained from all EMZs evacuation analysis in next step. These indicators are also the bare minimum requirements for safe evacuation of the zones.

Step 6: All EMZs evacuation analysis in response to various potential fire threats.

The final step of developing a city-wide evacuation plan involves determining the order and timing of evacuations for the EMZs. This process considers the factors examined in all previous steps, including the zone divisions (Step 2) within the examined area (Step 1), fire risk assessment for each zone (Step 3), the three evacuation stages (Step 4), and the minimum requirement derived from stress-testing of individual zone (Step 5). A general approach for constructing effective evacuation plans involves:

- **EMZ evacuation sequence**: Define the EMZs evacuation sequence, with reference to the order of the fire risk from high to low, to stage the evacuation that allows those who are closer to the fire risk to leave with priority.
- **Timing Considerations:** Define the timing of the evacuation sequence, with reference to the times to clear the actively evacuating zone(s), and their times to clear city exits. The goal is to give the evacuating zone(s) sufficient time to clear while avoiding overloading the road network with traffic from multiple zones simultaneously or within a short period of time.
- **Route Planning**: Plan the use of route for the EMZs with reference to the availability of the regional exits (i.e., the location and capacity of the evacuation target), the road network connectivity and capacity, and the resources that can be deployed to manage the traffic. The goal is to efficiently utilise the capacity of the road network, while minimising the interaction between evacuation traffic from different zones to prevent bottlenecks and delays. The planning conducted in this step considers the collective traffic demand from multiple zones that may need evacuation within a limited time window. This differs from the route planning in Step 4, which focuses on individual zone traffic demand.

When considering various combinations of the first two components in the planning process (assuming an optimised route planning or a consistent basis), there are two extreme base plans that impact road capacity differently. The first one is to evacuate all EMZs simultaneously (i.e., without any delay gaps). The second one is to evacuate all EMZs strictly in sequence, with gaps set to each zone's clearance time down the line. The first one, which is equivalent to a stress test, exerts maximum pressure on the traffic network and may lead to significant congestion and delays. The second one, which minimises pressure on the traffic network, underutilises the road network's capacity, resulting in unnecessarily extended total evacuation time – in an attempt to manage road conditions. Therefore, these two base plans serve as boundaries for constructing other feasible evacuation strategies. The goal is then to strike an ideal balance between the planning components, while ensuring the safe and efficient evacuation of all residents.

Those feasible plans that strike a balance between evacuation efficiency and pressure on the traffic network involve intricate interaction among evacuating people from different zones. These evacuation plans can be assessed through computer models that represent corresponding evacuation scenarios. However, evaluating these plans based solely on total evacuation time does not fully address safety concerns. For instance, two plans - one accounting for fire risk to decide evacuation sequence and another ignoring it, might yield similar evacuation times. To address this, we propose a composite evacuation time, defined as the sum of the three zone-specific indicators corresponding to the three stages of evacuation, for each plan. This metric, coupled by the fire risk factors for the zones obtained in Step 3, is then used in the assessment of the simulation results to evaluate the effectiveness of evacuation plans.

Assuming a set of evacuation plans have been defined as P_j with the combination of evacuation sequence and timing of evacuations for the EMZs (and a consistent route planning). The performance metrics defined as composite evacuation times weighted by the fire risk factor for these plans are as follows:

- $\sum_i Ez_i(P_j) * FR_i$ - the composite evacuation time to clear the zones,
- $\sum_i Ec_i(P_j) * FR_i$ - the composite evacuation time to clear the city exits,
- $\sum_i Er_i(P_j) * FR_i$ - the composite evacuation time to reach the regional exits,

where $Ez_i(P_j)$, $Ec_i(P_j)$ and $Er_i(P_j)$ are the zone exit times, city exit times and reginal exit times of the corresponding zones within each of the plans. These exit times can be obtained through computer simulations that simulate the evacuation plans for the region.

Finally, the metrics are compared against the baseline defined as the composite evacuation time obtained through individual zone evacuation analysis performed in Step 5 (as shown in Figure 6). The deviations (dz_j, dc_j and dr_j) from the baseline serve as reference for assessing plan effectiveness. The ultimate objective is to identify a plan that minimises deviations while ensuring safe evacuation. For instance, if the priority is to evacuate people from their zones to the main road first, then focus on minimising dz_j when choosing a plan. If the safe evacuation goal also involves clearing city exits and reaching reginal exits, consider minimising dc_j and dr_j as well in the decision-making process.

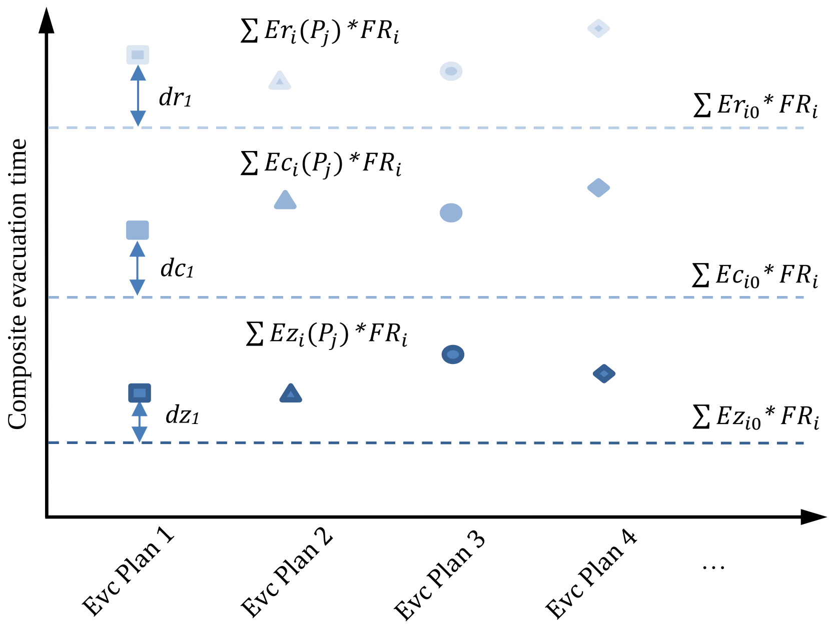

Figure 6. The performance metrics for evaluating the evacuation plans.

In Step 3 of the analysis, one fire condition is assumed. If there are multiple potential fire threats to be considered for the region, the above six-step evacuation planning analysis should be conducted for each of them. The analysis of the fire threat should also include the assessment of its impact on the availability of city exits, and regional escape routes. This information feed directly into route planning in the Step 5 and Step 6 analyses.

The above six-step evacuation planning considers the static status of the fire threat, i.e., the fire risk assessment is only based on its distance to the EMZs in the region. When a final plan is identified from the planning analysis, it should be compared against the projected development of the fire threat to assess the emergency level to further adjust the plan if necessary. The emergency level (EL) can be assessed through

$$EL = \frac{T_t * (1 + S_m)}{T_f}$$

where T_t is the total evacuation time from simulating the identified evacuation plan, S_m is a safety margin and T_f is the projected time for the fire to reach the perimeter of the community. T_f can be obtained through fire simulation, considering vegetation location, weather conditions and wind direction (i.e. direction of approach) etc.

If $EL < 1$, the emergency level is manageable since either the fire front is still far away, or it takes longer time than the required safe evacuation time of the community. The situation can be monitored to decide whether and when to issue an evacuation order.

If $EL \geq 1$, the emergency level is high and the fire can potentially be harmful to the evacuating people, especially to those EMZs ranked high in the fire risk assessment. An immediate response including evacuation should be considered.

LIMITATIONS AND DISCUSSIONS

This paper presents a planning methodology to develop evidence based and quantifiable evacuation strategies for WUI communities threatened by wildfires. This approach is based on the idea that computer models and calculations can be used to describe evacuation performance. As any model, the work presented here, is a simplified representation of the complexities that can be expected in a 'real' incident and it should be noted that the approach selected has certain limitations; for example, it is proposed that Fire Risk can be represented in terms of Euclidian distance from an encroaching fire; however, other metrics (e.g., estimated travel times) might be equally or more representative. Further, how quickly a community needs to issue an evacuation order is determined by multiple factors (e.g., geography, vegetation, weather, wind, community layout, means of transportation, etc.) (Kalogeropoulos et al., 2023), the evacuation process involves heterogenous responses to evacuation alerts, and associated behavioural itineraries (Vaiciulyte et al., 2021). The inclusion of these two and other potential factors is a relatively minor task to complete and is left for future method development. The method shown is therefore presented to show a general application of evacuation model output and the types of insights that might be provided.

CONCLUSION

The evacuation of areas affected by wildfires is likely to become more commonplace and involved an increasing number of communities. Wildfire evacuation pose numerous challenges due to multiple factors and inherent uncertainties involved. Given this, the emergency plans might become more complex and sensitive to increasing numbers of variables. Coupled with the challenges with relying on historical data, the capacity to quantify evacuation performance will be increasingly important – to enhance design and improve between alternative community designs and emergency plans. Despite the existence of various evacuation models tailored for different scenarios, there remains a gap in applying these tools to plan effective response measures. To address this issue, this article has outlined a simple means by which such a quantitative assessment might be structured – a methodology that can be employed to further develop evacuation models and establish common performance metrics. As a work in progress, this method is still in development. We anticipate both further enhancement of the method with practical details and application scenarios that will demonstrate its applicability with the proposed measures.

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