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Systematic review and research gaps on wildfire evacuations: infrastructure, transportation modes, networks, and planning

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ABSTRACT
Wildfires pose significant threats to communities, requiring robust pre-event planning for efficient evacuations. Transportation systems are crucial for these efforts, yet global research gaps persist, especially those related to transportation assets and transportation modes beyond privately owned automobiles. This study conducts a systematic review of four under-researched areas – infrastructure, modality, networks, and planning – to build a more comprehensive understanding of wildfire evacuations. Initial research is emerging in these domains, related to post-fire debris flows, air and transit evacuations, network analysis, and shelter planning. However, systematic analyses, evidence, and recommendations remain lacking. This includes wildfire's direct impact on transportation infrastructure, multi-modal evacuations, routing strategies, and community-driven evacuation plans. We underscore the need for empirical evacuation strategies to foster resilience for wildfire-threatened communities, offering valuable context-specific insights, identifying key actions, and highlighting ongoing research gaps.

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1. Introduction

Wildfire disasters are recurrent seasonal events that have grown in prominence in recent years. Spreading quickly under high wind speeds and causing significant damage to life and property, wildfires require prompt actions and resilient infrastructure to ensure minimal loss of life during a short or no-notice evacuation. Some of the most destructive wildfires have taken place this past decade, leading to substantial evacuations. For example in California, over one million people were ordered to evacuate between 2017 and 2019 (Wong, Broader, and Shaheen 2020a). In Australia, the 2020 January wildfires required the evacuation of tens of thousands of people from seaside towns (Gralow and Paul 2020). Canadian fires have also led to significant evacuations of major population centers (Woo et al. 2017), First Nations and Indigenous communities

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(McGee 2021; McGee and Christianson 2021), and small towns (Cecco and Burston 2021). Wildfire evacuations have also impacted many other countries in recent years including Portugal, Spain, France, Greece, South Africa, New Zealand, and Chile (Cambero and Miranda 2023; Imbach, Romain, and Breteau 2022; Rodrigues and Santiago 2022; Ronchi et al. 2021; Roy and de Jong 2020; Sgqolana 2021; Strickland 2018; West 2022). Mass evacuations, significant damage, and tragic fatalities from the Marshall Fire in Colorado (2021) and the Maui Wildfires in Hawaii (2023) underscore the particular challenges of rapid-spread fires.

Globally, these wildfire evacuations point toward transportation and logistics problems which are heavily dependent on (1) the existing state of infrastructure, (2) the multiple forms of modality available (or lack thereof) to evacuees, (3) the transportation network's performance (including identification and communication of egress routes, shelters, and network reliability), and finally, (4) evacuation planning that supports resource allocation, strategies, and policies. Despite the continued threat of wildfires, transportation systems and its associated infrastructure remain largely unprepared to cope with these evacuations. We set out to uncover key insights to describe and link these four under-researched areas and craft directions that can help devise and improve wildfire evacuation plans. This review addresses four research questions based on the limitations of the literature and practice:

(1) How is transportation infrastructure impacted before, during, and after wildfire evacuations?
(2) Which modes of transport other than privately owned automobiles can be (or have been) used during wildfire evacuations?
(3) What role do road networks play during wildfire evacuations?
(4) What transportation planning actions have been taken and what needs still exist?

The above questions are designed to uncover a clearer picture of the role of transportation engineering in wildfires, from a perspective beyond more established research in simulations (see for example, (Beloglazov et al. 2016; Grajdura, Borjigin, and Niemeier 2022; Intini et al. 2019; Pel, Bliemer, and Hoogendoorn 2012; Wahlqvist et al. 2021; Zhao and Wong 2021)) and human behavior (see for example, (Grajdura, Qian, and Niemeier 2021; Kuligowski 2021; Kuligowski et al. 2022; Lovreglio et al. 2019; McCaffrey, Wilson, and Konar 2018; McLennan et al. 2019; Wong, Chorus, et al. 2020; Wong, Broader, et al. 2022)). While these research areas are valuable to evacuation planning, we chose to focus our attention on other aspects of the transportation system to develop key takeaways and find critical gaps in the field.

This paper is organized as follows. First, we present the current research on the resilience of infrastructure to wildfires, modality, transportation networks, and planning. Our choice to focus on these four specific areas stems from a deliberate consideration of critical and overlooked areas within wildfire evacuation literature and practice. While we acknowledge the need for a review of human-centered topics (e.g. equity, management, decision-making) within the larger wildfire evacuation research, existing literature and practical experiences have shown that challenges in infrastructure resilience, diverse transportation modes, network functionality, and effective planning pose substantial barriers to efficient wildfire evacuations. By focusing on these four underexplored areas, we aim to shed light on critical gaps in current understanding and offer insights that can directly inform more comprehensive and effective wildfire evacuation plans. Next, we present an analysis of the four key areas by discussing gaps and overlapping concepts. Finally, we conclude the paper with future research directions and policy recommendations.

2. Methodology

We conducted a systematic review of the literature between 2000 and 2022 to capture recent developments and advancements in the field of wildfire evacuation. This time frame allowed us to focus on studies that reflect the most current understanding of the four key areas we wanted to explore in this review, while also being inclusive of major wildfires in the Western U.S. and Canada during the early 2000s (e.g. Okanagan Mountain Park Fire, Cedar Fire, etc.). We used a combination of keywords in four indexed and peer-reviewed databases – Scopus, Taylor Francis, Web of Science, and TRID (Transportation Research Index). These four databases were chosen for their combined inclusion of wildfire evacuations as a topic, wide range of articles, and ease of keyword searching. Regarding the last point, the databases provided a structured platform for targeted searches, improving the reliability of our systematic review. The keyword search used the following logic to capture English language articles:

- ‘bushfire’ OR ‘forest fire’ OR ‘vegetation fire’ OR ‘wildfire’ OR ‘wildland fire’
  AND
- ‘evacuation engineering’ OR ‘evacuation infrastructure’ OR ‘evacuation planning’ OR ‘evacuation resilience’ OR ‘evacuation transportation’ OR ‘multimodal transport’ OR ‘infrastructure damage.’

Initially, the search query returned a total of 7040 documents, which were screened for relevance based on their titles and abstracts. We found that the greatest number of results were generated for keyword searches that were a combination of a – fire (e.g. bush fire, vegetation fire, etc.), and ‘infrastructure damage’ and ‘evacuation planning.’ Cited references within the articles were also checked for relevance and included if warranted. Multiple synonyms for wildfire were included due to the non-standardization of the term associated with wildland-urban interface (WUI) fires and the need to incorporate as many relevant searches as possible. For instance, most of the literature produced by Australian researchers refers to the hazard as bushfires whereas most American literature cites them as wildfires. Studies were eliminated if they were written in a language other than English, published before 2000, or largely concerned with other disasters (e.g. earthquakes, tsunamis). We supplemented the review by conducting a similar keyword search in Google Scholar to capture reports and other literature with digital object identifiers (DOIs). Our inclusion of Google Scholar broadened the scope of the review by encompassing a wider range of sources that might not have been indexed in traditional databases. We also included news sources and relevant websites to further help describe recent events. We found 82 relevant literature resources as part of the systematic review, which was supplemented by 116 other resources (Figure 1).

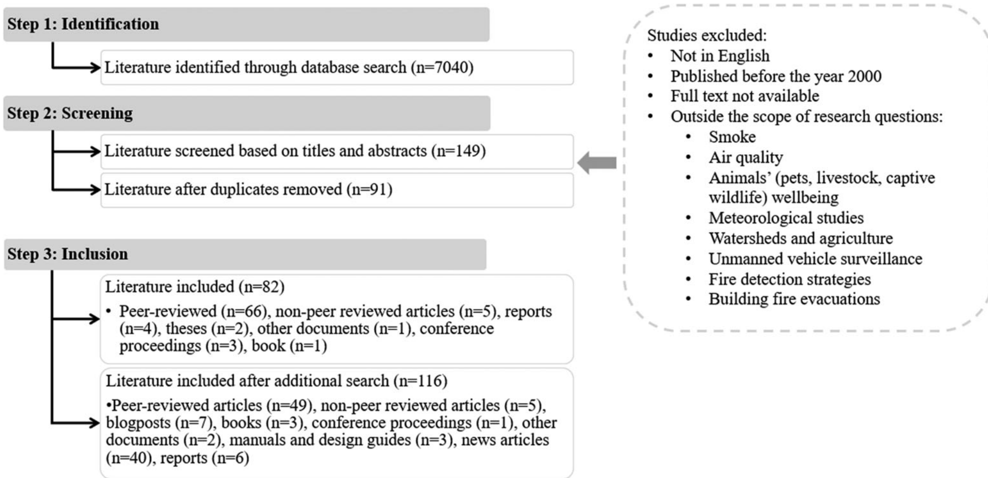

Figure 1. Breakdown of the systematic review and additional resources.

The primary limitation of the review is that our keywords were focused on transportation infrastructure, networks, modality, and planning in wildfire evacuations. This focus was deliberate and informed by the findings of recent reviews and research on simulations (e.g. Intini et al. 2019) and evacuation behavior (e.g. Kuligowski 2021). We chose against searching for and including papers on simulations and behavior in wildfire evacuations to focus on understudied areas and to avoid overlap with recent reviews in the past five years. Another limitation is that some related literature was eliminated from the final review as it focused on elements outside the scope of the research questions. This included smoke, air quality, animals (including pets, livestock, and captive wildlife) wellbeing, meteorological studies, studies on watersheds and agriculture, unmanned aerial vehicle surveillance, fire detection strategies, and building fire evacuations. Another limitation is that we likely did not capture all relevant literature, including all wildfires and their relation to our topics of inquiry. Specific case studies of large outdoor fires can be found in Ronchi et al. (2021), though more global and regular tracking will be needed to capture all relevant and large outdoor fires. In addition, our literature review did not focus on emerging topics in wildfire evacuations related to equity, strategic management, and leadership (i.e. decision-making by officials). As an important limitation of this paper, these human-centered topics will require a thorough analysis and review in the near future.

3. Literature review

We organized our literature review by general area of inquiry – infrastructure, modality, networks, and planning. As a note, the lack of literature in many of these areas prevented us from establishing a strong narrative in some sub-sections.

3.1. Infrastructure

Transportation infrastructure can be directly and indirectly affected by wildfires, both during and after a wildfire event (see Figure 2). Aging transportation infrastructure in

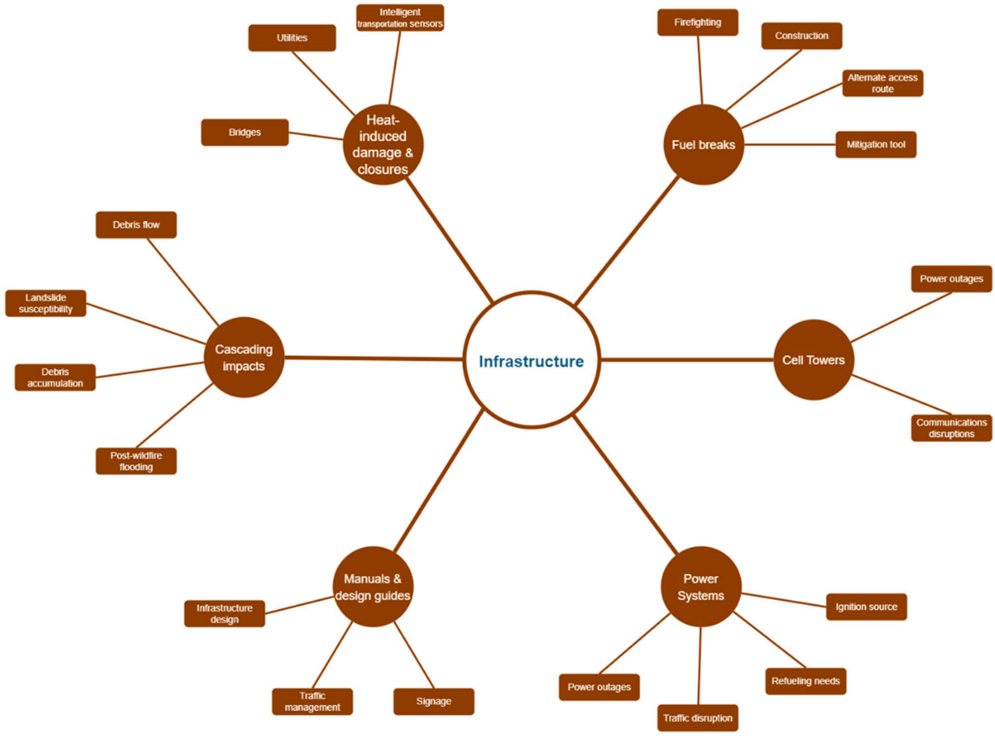

Figure 2. Interconnected themes and tags in 'Infrastructure'.

a wildfire-prone area is especially susceptible to damage. This damage can be caused by a variety of reasons including extreme heat, flooding (due to burned/reduced vegetative cover), fallen vegetation, and other circumstances. Even if the wildfire hazard of a community is lower, limited road networks coupled with the above-mentioned damages increase the overall evacuation vulnerability during a nearby wildfire event.

Robust transportation infrastructure is essential for efficient wildfire evacuations. Kurowski and Bradley (2022) provide a comprehensive listing of vulnerable road infrastructure and the expected types of wildfire impacts. The research also includes industrial infrastructure such as utility towers, poles, and transmission lines, and nearby road infrastructure such as livestock fencing, road signage, and lighting (Kurowski and Bradley 2022). To better document infrastructure, some work has built inventory databases of structures and their fire vulnerability parameters in WUI communities (Abo El Ezz et al. 2022; Maranghides et al. 2014). For resilient functionality, a study focusing on transport infrastructure's recovery time to a flooding event (caused by vegetation loss from a wildfire) indicated a plateauing of recovery time around the 40-day mark (Mojtahedi, Newton, and Meding 2017). With long infrastructure recovery times, research has found that jurisdictions should more closely consider and implement mitigation and rehabilitation strategies for infrastructure assets (Valentin and Stormont 2019). These varied research articles indicate a wide range of topics within the infrastructure field, which we expand on in more defined sub-sections.

3.1.1. Heat-induced damage and closures

Wildfires have caused significant disruptions to surface transportation infrastructure such as bridges, which are not designed to withstand extreme temperatures. In some cases, intense heat from wildfires has melted and damaged infrastructure, such as car wheels and a railway bridge (Cecco and Burston 2021; Fuller and Pérez-Peña 2017). Heat damage from wildfires also extends to buried utilities, such as service lateral pipes and water distribution systems (Richter et al. 2022). Moreover, vehicle sensors on highways are also susceptible to wildfire heat-induced damage. A study looked at the impact of wildfires on traffic data for the 2018 Woolsey wildfire and found a correlation between the damage of vehicle sensors on ramps and the occurrence of wildfires (Menon, Staes, and Bertini 2020). Additionally, past wildfires have led to the closure of access routes during evacuations due to factors such as fire jumps, high proximity to fires, and low road visibility (Sfetsos et al. 2021).

3.1.2. Fuel breaks

Apart from enabling evacuations, surface infrastructure can actively (or passively) function as fuel breaks (Greenwood Sustainability LLC 2011). These breaks in vegetation are purposefully constructed or exist in the form of roads and unpaved access routes to reduce the likelihood of fire spread. Other forms of barriers include non-flammable land cover, recent burns, and ridgelines (Jin et al. 2015). In one example of the use of fuel breaks, the Oregon Ridge fuel break provided a safe place for firefighters to work in the 2006 Marysville fire in Yuba County, USA (Nader and De Lasaux 2015). From a policy perspective, fuel breaks are becoming an important tool for wildfire mitigation. The Wildfire and Forest Resilience Action Plan for California proposed investment for the year 2021–2022 of $335 million (USD) to complete 45–60 strategic fuel break projects across the state (Thorne et al. 2021). These breaks can also provide alternate access routes toward and away from fire.

3.1.3. Debris, landslides, post-wildfire flooding, and vegetation management

Wildfires can result in accumulated debris, such as burned branches, fallen trees, rocks, and sediments (Fuller and Pérez-Peña 2017; Guth et al. 2019; Lancaster et al. 2021), which can disrupt roadways, damage infrastructure, and cause short to long term road closures. Debris flow events usually depend on the burn severity of vegetation and the topography of the area. A study reported that high debris flow risk persists for up to three years after wildfires due to reduced vegetative cover and ash-laden soil, especially during intense precipitation events (Jordan 2015). This is because wildfires create hydrophobic soil conditions that prevent infiltration of water and thus result in larger runoff during rains (French, Miller, and Dettling 2005; Jordan 2015; Moody and Ebel 2012). Another study investigated the risk of debris flows to California's roadways after wildfires and revealed that areas with high burn severity, steep slopes, and low vegetation cover were more susceptible to post-wildfire debris flows, which pose a significant threat to transportation infrastructure in the state (Li and Chester 2023).

The aftermath of wildfires followed by precipitation events can lead to increased soil erosion and landslides due to debris flow (De Graff and Gallegos 2012). In addition, landslide susceptibility has been linked to vegetation loss severity (Abbate et al. 2019;

Carabella et al. 2019; De Graff and Gallegos 2012; Lainas, Depountis, and Sabatakakis 2021; Rengers et al. 2020), leading to localized damage to mobility routes and disruptions in the supply chain, such as fuel (KPMG 2017). Most of the information about landslide locations is collected through a combination of field analysis, satellite imagery, and more recently seismic monitoring (Porter et al. 2021). Cases of these debris flows have also occurred with devastating consequences. In Santa Barbara County after the Thomas Fire in 2017, debris flows killed 21 people and significantly damaged infrastructure including bridges and culverts (Tiwari et al. 2020). Some roads were impassable for weeks, even requiring the start of an ad hoc ferry service between Santa Barbara and Ventura (Boone 2018).

Post-wildfire precipitation can also result in the flooding of roadways due to reduced soil permeability (Moody and Ebel 2012). These flooding events can inundate miles-long routes, cutting off essential supplies and affecting regional mobility and commerce (a common occurrence during hurricanes (IFRC 2022; Williamson 2022)). The closure of US Highway 101 after the 2017 Thomas Fire highlights the infrastructure vulnerability to such events (Golembo and Winsor 2018). An analysis of post-wildfire flooding in Arizona showed serious disruptions within the regional transportation system, including rural roadways and highways (Fraser, Chester, and Underwood 2022). Research to manage and mitigate these events has included exit route protocols for flash floods (Ortega-Becerril et al. 2022).

The spread of wildfires is influenced by various natural factors (e.g. fuels, weather) as well as the geography of the area. To reduce wildfire risk, Indigenous communities, government agencies, and residents have used prescribed burns, forest/brush thinning, and clearing for defensible space (Christianson et al. 2022; Hankins 2013). This practice is also used around roads in wildfire-prone areas to create fire breaks and reduce the likelihood of blocked roadways. Research has noted that residents with different evacuation preferences exhibit varying behavior in vegetation management, with those intending to remain at home and defend their residences showing higher rates of forest thinning (Paveglio et al. 2014). In the wildfire-prone state of California, Caltrans has spent more than $590 million from 2015 to 2020 to repair highways damaged by 81 wildfires. Caltrans has also focused on reducing wildfire risk along roadways by removing some vegetation (Thorne et al. 2021).

3.1.4. Manuals and design guidelines for disasters and transportation infrastructure

Manuals and guides provide engineers and planners with mechanisms and instructions based on research and practice to construct and evaluate infrastructure. However, the majority of manuals and design recommendations for surface infrastructure (roadways, railways, and runways) do not explicitly address hazardous events or provide mitigation strategies. Most disaster-related design guidelines are available for buildings (vertical structures) and other similar superstructures for tsunamis, earthquakes, and floods (American Society of Civil Engineers 2017) or occupant and building fire safety (ISO 2018).

Wildfires have received limited attention in design guidelines. Impact load design considerations on transport infrastructures such as roads and bridges are mostly limited to automobile axle loads, not from possible disaster events (e.g. boulders from landslides or heat from wildfires). Some guidance exists on traffic incident management areas and signage (FHWA 2009), while other guides list the hazards that could impact transportation systems (Pande and Wolshon 2016). AASHTO's section on risk assessment lists adverse events that may cause service disruption to evaluate potential damage and serviceability issues of critical links (AASHTO 2018). Similarly, Meyer (2016) listed the potential impacts of climate change and extreme weather on roads and highways, noting that the expected impacts on infrastructure design from extreme heat can result in premature deterioration and closure of roads due to wildfires from operations and maintenance perspectives. Based on this review, guidance for surface transportation that considers wildfire evacuations during road or infrastructure design remains largely missing.

3.1.5. Power systems

The transportation sector is significantly impacted by the interaction of wildfires with electrical infrastructure. In the California context, several past wildfires have been started by electrical systems (Eavis and Penn 2019; Gold, Blunt, and Smith 2019). Concurrently, transportation can be heavily impacted by power outages that are caused by disasters. To mitigate wildfire risk, California has begun implementing public safety power shutoff (PSPS) events, which de-energize the grid during periods of high fire danger (Jahn, Urban, and Rein 2022; Wong, Broader, and Shaheen 2022). While helping to reduce wildfire ignition sources, these events can be inconvenient and disruptive, creating additional challenges for transportation by disrupting traffic signals, impeding the refueling and recharging of vehicles, and altering travel behavior (Wong, Broader, and Shaheen 2022). In light of these challenges, communities require preparation for shutoffs or load-shedding plans (Sfetsos et al. 2021), especially in the context of evacuations. At the same time, power systems can impact evacuation routes and escape options. Early reports from the Maui Wildfires in Hawaii (2023) indicate that downed power lines and poles from high winds blocked key roads leading out from the town of Lahaina (CBS News 2023).

3.1.6. Cell towers

Cell tower infrastructure can also be impacted by wildfires. Direct damage from fires, power outages, weak networks, or high volumes of calls and data can cause communication interruptions during evacuation processes (Thériault et al. 2021). Cell towers that remain operational during a wildfire serve as a vital source of information, providing up-to-date information about the fire's location and facilitating the dissemination of evacuation orders to the general public (Kuligowski et al. 2022). However, due to geographical limitations, this method of information gathering may not be accessible to everyone, such as those without technology experience, those with medical conditions, or those who cannot access cell reception due to mobility issues (Spayne 2021; Wong 2020).

In addition to these limitations, WUI areas that serve as recreational hubs, attracting seasonal visitors and tourists, may pose a greater risk to these transient populations in the event of a wildfire. These populations may not be as familiar with local communication networks as residents or may have limited access to mobile phone services in the area due

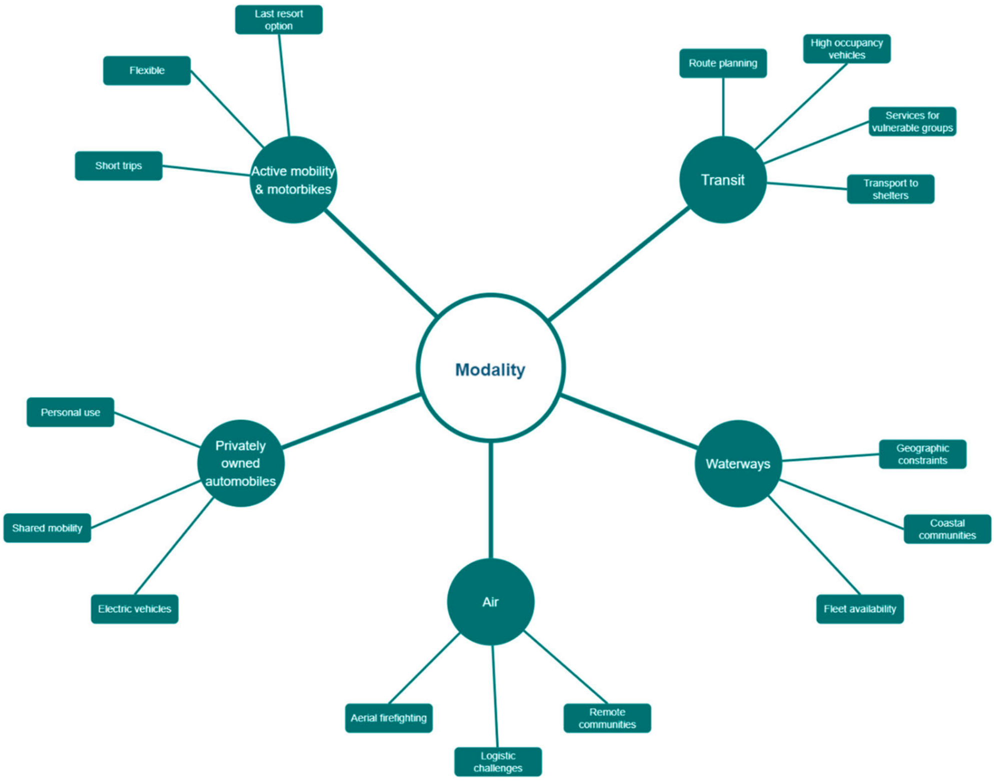

Figure 3. Interconnected themes and tags in 'Modality'.

to poor coverage (Soga et al. 2021). Furthermore, their unfamiliarity with egress points may increase their vulnerability to wildfires.

3.2. Modality

Evacuees choose their mode of transportation based on a variety of factors. Factors can include when an evacuation order is issued, the location of the evacuee, the distance to a safe place, the severity of the disaster, mode availability, mode speed, and perceived safety (Wong, Broader, et al. 2022). Figure 3 provides a visual for each discussed mode. The following sub-sections review the literature on the multiple transportation modes that have been used and studied for wildfire evacuations.

3.2.1. Privately owned automobiles

3.2.1.1. Cars, pickup trucks, and recreational vehicles (RVs). Most evacuations, especially in the U.S., Canada, and Australia, are conducted using privately owned automobiles (e.g. cars, pickup trucks, and recreational vehicles (RVs)). For example, hurricane evacuation studies have found that many evacuees use a privately owned automobile, ranging from 87% to 96% of evacuees (Lindell, Kang, and Prater 2011; Wilmot and Gudishala 2013; Wong, Shaheen, and Walker 2018; Wu, Lindell, and Prater 2012). In the case of three California wildfires, Wong, Broader, and Shaheen

(2020a) reported that between 34% and 45% of evacuees took one privately owned automobile, and 49% to 62% took two or more privately owned automobiles. For each fire studied, the lowest privately owned automobile mode choice rate was 94% (Wong, Broader, and Shaheen 2020a). Moreover, Kearns (2017) reported that 91% of the 2016 Fort McMurray wildfire evacuees evacuated using either their privately owned automobile or someone else's.

3.2.1.2. Electric vehicles (EVs). Most evacuating vehicles are powered by gasoline and diesel. More recently, the rising market share of EVs introduces several new opportunities and difficulties in the process of planning for a wildfire evacuation. Problematically, EVs require electricity as a fuel source which may not be readily available in a disaster. The lack of public charging infrastructure and the incompatibility of charging infrastructure and manufacturer's make and model also presents a challenge. Currently, EVs are perceived as more of a liability than an asset (Erskine, Seipel, and Seipel 2022; MacDonald, Kattan, and Layzell 2021; Purba, Kontou, and Vogiatzis 2022) during evacuations. The research recommends future work in incorporating behavioral dynamics of charging or refueling before evacuations to better understand arrival times to stations and queueing behavior.

Additionally, Erskine, Seipel, and Seipel (2022) note that perceived environmental benefits and at-home charging leisure of battery electric vehicles (BEVs) may erode during evacuations due to refueling challenges such as longer charge times when compared to fossil-fuel-powered vehicles. Similarly, research by Purba, Kontou, and Vogiatzis (2022) noted that evacuation routing plans for each vehicle fuel type naturally change as heterogenous driving ranges and different refueling needs on the path to reach safety are considered. Moreover, research has found that using EVs during wildfires causes stress on systems even at 20% penetration (Donaldson, Alvarez-Alvarado, and Jayaweera 2022), noting the first few hours of evacuation as the most challenging.

Research has indicated the need to improve planning for future emergencies involving EVs. While benefits have not been fully studied, EVs could become a power source, offering the opportunity to charge electronic devices, home systems, and medical equipment (Oloriz, Vangala, and Sadowicz 2022; Romo 2019; Wong 2020). Paired with microgrids and battery technology, EVs could be more resilient to a disaster than internal combustion engine (ICE) vehicles, which require the transportation of liquid fuel. Moving forward, critical efforts toward guaranteeing public safety during emergencies include advancing battery technology and integrating electrification goals in evacuation plans (Oloriz, Vangala, and Sadowicz 2022).

3.2.1.3. Shared mobility. Shared mobility often leverages privately owned automobiles and automobile-based sharing has been employed during some wildfire evacuations. About three percent of evacuees from the 2017 Northern California Wildfires were reported to have used rental car service, and 1.1% and 1.2% of evacuees carpooled with strangers (non-household members) during the 2017 Southern California Wildfires and 2018 Carr Wildfire, respectively (Wong, Broader, and Shaheen 2020a). Current research has also indicated that there is a general willingness of residents to share transportation in a wildfire evacuation, with elements of social capital playing a key role in increasing willingness (Wong, Walker, and Shaheen 2021). Based on focus groups of people impacted by wildfires, research has also found that vulnerable populations could gain significant equity benefits from shared transportation, though key barriers remain in implementation (Wong, Broader, and Shaheen 2020b). Other research on sharing in evacuations and disasters (Ahmed, Sadri, and Hadi 2020; Borowski et al. 2022; Borowski and Stathopoulos 2020; Wang, Ozbay, and Bian 2021; Wong, Broader, and Shaheen 2020b; Wong, Yu, et al. 2022) presents some feasibility for this transportation option.

3.2.2. Public transit

The use of public transit, including subways, light rail transit, buses, and trams, during evacuations, has been explored in several studies. Buses have been employed in major hurricane evacuations in the US (Bian and Wilmot 2018; Garnham and Pablo 2020; South Florida Times 2017; Urbina and Wolshon 2003; Vera et al. 2022), wildfire evacuations in the U.S. (Afshar 2022; Sallinger 2022), and wildfire evacuations in Canada (Drinkwater 2022; French 2016; Kearns 2017; McGee 2021). Buses are especially important for transient, low-mobility, low-income, carless, and other underserved populations who do not have reliable access to vehicles or cannot drive an automobile. Public transit (and charter bus companies) have the potential to play an important role during evacuations. For example, research indicates that British Columbia (BC) Transit buses in Canada could be used as an accessible transportation option during a wildfire evacuation, especially for those who would be unable to secure alternative transportation (Metcalfe 2021; Vespaziani 2019). This was the case for the 2021 Marshall Fire in the U.S. where school bus drivers volunteered to help people evacuate (Sallinger 2022).

Research on route planning problems for buses during emergency evacuations has been conducted in different regions as well. For instance, a study looked at bus evacuation problems in the case study of the Great Fire of Valparaiso in Chile (Vitali, Riff, and Montero 2017), finding the best route: (1) for each vehicle in a public transportation system, (2) to move people from a risk zone to open shelters located in safe zones, and (3) to minimize evacuation time. Similarly, Shahparvari and Abbasi (2017) presented a robust stochastic vehicle routing and scheduling model for emergency bus evacuation during bushfires in Australia. The model considered various uncertainties such as road closures and changing traffic conditions, to ensure efficient and effective evacuation planning. Literature generally points toward a need to involve local transit agencies, emergency managers, and researchers to best leverage public transit for more efficient and equitable evacuations.

3.2.3. Waterways

Coastal evacuation during wildfires can be challenging due to modal availability and geographic constraints. Despite the relatively lower wildfire hazard of many coastal towns, wildfires have occurred in these locations and communities face high wildfire evacuation vulnerability due to a limited road network (CBS News 2023; Dye et al. 2021). Evacuation success through water-based modes can be highly dependent on fleet availability and mainland route connections. Islands may face additional challenges during wildfire events due to limited infrastructure capacity to handle multiple catastrophes and the presence of a transient population during the summer season (Vaiciulyte et al. 2019). Multiple events of tourists being evacuated from coastal towns and vacation hotspots have been reported in Italy, Turkey, Canada, Australia, and the US (BBC 2017; CBS News 2023; Connett 2021; Gralow and Paul 2020; Hooper 2019; Kurjata 2017). Krutein, McGowan, and Goodchild (2022) investigated a case study of Bowen Island in western Canada and applied a routing model to minimize the evacuation time by up to 3 hours. Such studies are important in highlighting the intricate challenges that come with not only a single mode of evacuation, such as privately owned automobiles and ferries, but also the development of plans that consider multi-modality.

3.2.4. Air

Air evacuations are common for remote communities, islands, or when egress routes are blocked. Taking place in stages due to limited capacity and resources, air evacuations can be a quick but logistically challenging mode to remove people from high-risk zones. These evacuations are conducted in conjunction with ground transportation at a destination. In addition, aircraft assist during wildfire events through aerial firefighting and operations (Cambero and Miranda 2023; Connett 2021; Ellis, Kanowski, and Whelan 2004; Nihad 2022; Press 2022; Roy and de Jong 2020; Shahparvari et al. 2021).

The 2016 Fort McMurray fire prompted the largest air evacuation in Canada, with 33 aircraft and 40 flights used to evacuate patients, residents, and staff members to other cities (Matear 2017). Kearns (2017) reported that 3% of the evacuees evacuated via plane. The evacuation was a multi-modal effort, with some hospitals using a combination of air evacuation, ground ambulances, and buses to overcome the challenges of take-off locations. Air transportation was conducted with the assistance of the Canadian Armed Forces (KPMG 2017). For the same wildfire, Woo et al. (2017) described a challenging airlift process and presented the importance of multi-modal evacuation plans for regions with sparse networks.

Several other instances of air-based evacuations have occurred in Canada, the U.S., and Australia. Air transport has been frequently employed for remote First Nation communities such as the Sandy Lake First Nation (Asfaw, McGee, and Christianson 2020; McGee 2021; McGee, Nation, and Christianson 2019), the Mishkeegogamang Ojibway Nation (McGee, Nation, and Christianson 2019), and others (McGee 2021). In the U.S., people have been helicoptered to safety in various wildfires in California such as the 2017 Northern California Wildfires (ABC News 2020; Dastin 2017; Gralow and Paul 2020; Lewis 2018), the 2018 Atlas Peak fire (Lewis 2018), and the 2019 Creek Fire in California (ABC News 2020). More recently during the 2023 Maui Wildfires, evacuees were airlifted from the island with the help of added flights by commercial airlines (Sampson 2023). Older adults and those in medical need in southeastern towns in Australia were also airlifted during the bushfires in 2020 (Gralow and Paul 2020).

From a management perspective, adaptive air traffic routing can play a significant role during such wildfire evacuations since air transportation is a centralized system. Yang et al. (2021) optimized airport coordination for dispatching evacuation flights and developed a delay prediction model. In Canada, the municipality of Whistler and the District of Squamish in British Columbia have a multi-modal evacuation plan that considers all hazards. The plan explores opportunities and limitations to mass evacuations through rail, air, marine, and ground transport (Resort Municipality of Whistler and District of Squamish 2019).

3.2.5. Active mobility and motorbikes

Pedestrian-based evacuations remain relatively rare for wildfire events as they can increase heat-induced risks to evacuees. However, a few examples exist including those who faced an imminent threat from the heat (either due to slow traffic or entrapment in a vehicle or shelter) (Vonberg, Bell, and Vandoorne 2018) or faced road blockages and tried to outrun the fire (Rosato 2018). A study looked at various scenarios that considered either walking or driving for the 2018 wildfires in Mati, Greece and provided insight into the mortality rates of choosing these modes (Siam et al. 2022). Using a series of models, the research reported a minimized mortality rate when the mode split was 70% pedestrian to 30% driving (Siam et al. 2022). Another study assessed ways to improve the safety conditions for wildland firefighters by collecting hiking data from firefighters totaling over 200 km (Sullivan et al. 2020). The results indicated that firefighters hike relatively consistently and exhibit faster travel rates than non-firefighting personnel, especially in steeper terrain (Sullivan et al. 2020).

Walking has been reported in additional wildfires, such as when some residents resorted to quickly walking toward the ocean since privately owned automobiles were blocking the roads during the 2018 Attica Wildfire in Greece (Vonberg, Bell, and Vandoorne 2018). Some other instances include the 2017 British Columbia wildfire where campers had to trek to be evacuated by boats (Kurjata 2017). While some data has found that less than 1% of evacuees left by walking in three California wildfires (Wong, Broader, and Shaheen 2020a), the road network, disaster conditions, and community design may lead to higher walking rates, especially if a flexible mode is needed. For example, pedestrians can make use of public paths, shortcuts, and narrow roads, thereby increasing the number of egress points and allowing people to avoid congestion on roadways (Wong, Martin, and Halpern 2020).

Other alternative and smaller modes of transport have also been used by people to evacuate from critical areas with difficult terrains to traverse faster. For example, one man in Greece evacuated multiple people out of the danger zone by giving them a ride on his motorcycle (Smith 2019). In two separate instances, two women fled from the devastating 2017 Northern California wildfires on their bikes (Bevilacqua 2017). Motorcycles have also been employed as a quick means of deploying personnel to fight fires in remote or difficult terrain. Chinese off-road bikers have volunteered to help the firefighters in Chongqing, and Australian firefighters have used dirt bikes and portable water guns to contain remote bushfires (Firehouse 2015; Whitworth 2022). While these reports are anecdotal, they provide a glimpse of the flexible (and sometimes critical) nature of active transportation and smaller modes in disasters.

3.3. Transportation networks

Recent research has identified that the breakdown of transportation road networks (either through congestion or blocked routes) can significantly increase evacuee risks (Chen, Shafi, and Chen 2020). This section will explore network-related studies, insights generated from evacuation curves of past evacuations, and the role of GPS data in congestion identification (refer to Figure 4 for a quick overview).

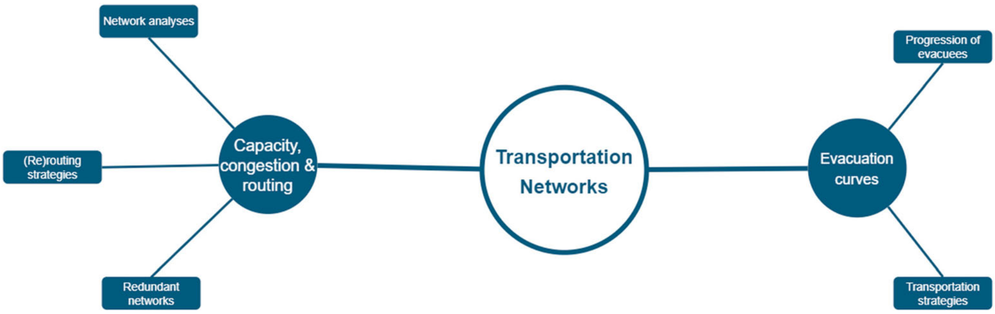

Figure 4. Interconnected themes and tags in 'Transportation Networks'.

3.3.1. Network capacity, congestion, and routing

Multiple studies have examined the vulnerability of road networks during wildfire evacuation (Chen, Shafi, and Chen 2020; Mahajan and Kim 2020; Ohi and Kim 2021). Networks in wildfire evacuations are often assessed through network analysis (i.e. remoteness, accessibility, and connectivity). Studies have investigated the importance of evacuation paths with connectivity and redundancy to reduce fatalities (Mahajan and Kim 2020; Niu et al. 2022) and explored the adoption of traffic management strategies to alleviate bottlenecks (Chen, Shafi, and Chen 2020; Mahajan and Kim 2020; Ohi and Kim 2021). Several studies propose ways to enhance traffic flow and reduce evacuation times (Gan et al. 2016; Parr et al. 2022). Concurrently, emerging practice has begun to offer designs that can temporally increase evacuation capacity during emergencies (Caltrans 2021).

During a wildfire evacuation, traffic and delays can be further exacerbated by road closures and rerouting. Reported congestion along major arterials, such as during the 2016 Fort McMurray Fire (Thériault et al. 2021), indicated the need for more robust optimization strategies to ensure the flow of evacuees. Similarly, firefighters and fire trucks can be trapped due to limited egress points, capacity issues, blocked passageways, or dangerous fire exposure (Campbell et al. 2019; Kourmpa and Tsigdinos 2020). Evacuation research has shown that even minor changes to an arterial road or intersection can significantly improve traffic flow and reduce average delay times (Parr, Wolshon, and Murray-Tuite 2016). Traffic growth uncertainties emphasize the need for adjustments and upgrades during the infrastructure's lifetime (Fawcett et al. 2015). Effective evacuation routing (and rerouting) can help to avoid excessive traffic congestion during a wildfire. This has been studied through spatiotemporal computation (Li, Cova, and Dennison 2019) and modeling realistic situations (Hou, Darr, and Zhang 2022; Shahparvari and Abbasi 2017). For instance, a 2009 Australian bushfire case study applied a rerouting problem model to determine the safest routes and shelter assignments for late evacuees in different scenarios (Shahparvari et al. 2019). Additionally, a post-fire survey for the 2009 Jesusita fire in Santa Barbara found that 70% of evacuees chose longer routes, suggesting that the elevation and gradient of routes may be factors that influence this decision (Brachman et al. 2020). In addition, one longitudinal community assessment study in Texas identified route accessibility and traffic as the two biggest challenges during wildfire evacuations (Kirsch et al. 2016).

In an emerging area of inquiry, studies are leveraging large-scale GPS and cellular datasets to analyze network performance and understand human behavior. These datasets can provide transportation agencies with information on the most used routes (travel demand), reconstruct traffic densities, identify bottleneck situations, study the behavior of a community, and be used to monitor activity on routes (Melendez, Ghanipoor Machiani, and Nara 2021; Wu et al. 2022; Zhao et al. 2022). GPS data can be especially helpful for sparse networks that lack traffic-counting devices.

3.3.2. Evacuation curves

Evacuation departure curves represent the progression of people leaving a specific area during an emergency evacuation. These curves provide insights into the timing and progression of people loading onto a road network, including how quickly people leave the area and how evacuation patterns change over time..

For wildfire evacuations, Woo et al. (2017) found that an evacuation curve can display a sudden surge in the number of evacuees at the beginning, followed by a slower but steady increase until reaching a cumulative peak. Similarly, Grajdura, Qian, and Niemeier (2021) developed detailed response curves for departure time, awareness (of the wildfire) time, when evacuation notice was received, and when a code red message was received for the 2018 Camp Fire in California. Other studies have analyzed these curves for different evacuation times (Wolshon and Marchive 2007) and electric vehicles (MacDonald, Kattan, and Layzell 2021), though gaps exist for curves that specifically represent wildfires.

3.4. Planning

Evacuation planning is region-specific and requires communication and collaboration between multiple stakeholders (Matherly et al. 2014). Planning tasks typically involve coordination among entities to protect lives, allocation of resources in a disaster, and preparation for multiple risk scenarios. While goals for evacuation planning can be varied, several more regular goals include congestion reduction, effective communication, and shelter management (as seen in Figure 5). Though emergency response plans are widely developed across North America, a large number of the largest cities in the U.S. do not have publicly available evacuation plans that specifically focus on vulnerable populations (Renne and Mayorga 2022).

Research has also indicated that wildfire evacuation planning should incorporate and consider the unique factors at the community level (Asfaw, McGee, and Christianson 2020). At a finer scale, neighborhood-level evacuation plans can provide more customizable guidance that considers housing density and generates insight into localized traffic (Cova and Johnson 2002; Wolshon and Marchive 2007). Planning and preparedness activities can also improve awareness. In communities where wildfire management was performed, homeowners were more likely to discuss wildfires, perceive a high risk, and describe a higher sense of awareness (Faulkner et al. 2009). Together, these studies indicate how planning requires community-centered details to reach key evacuation goals.

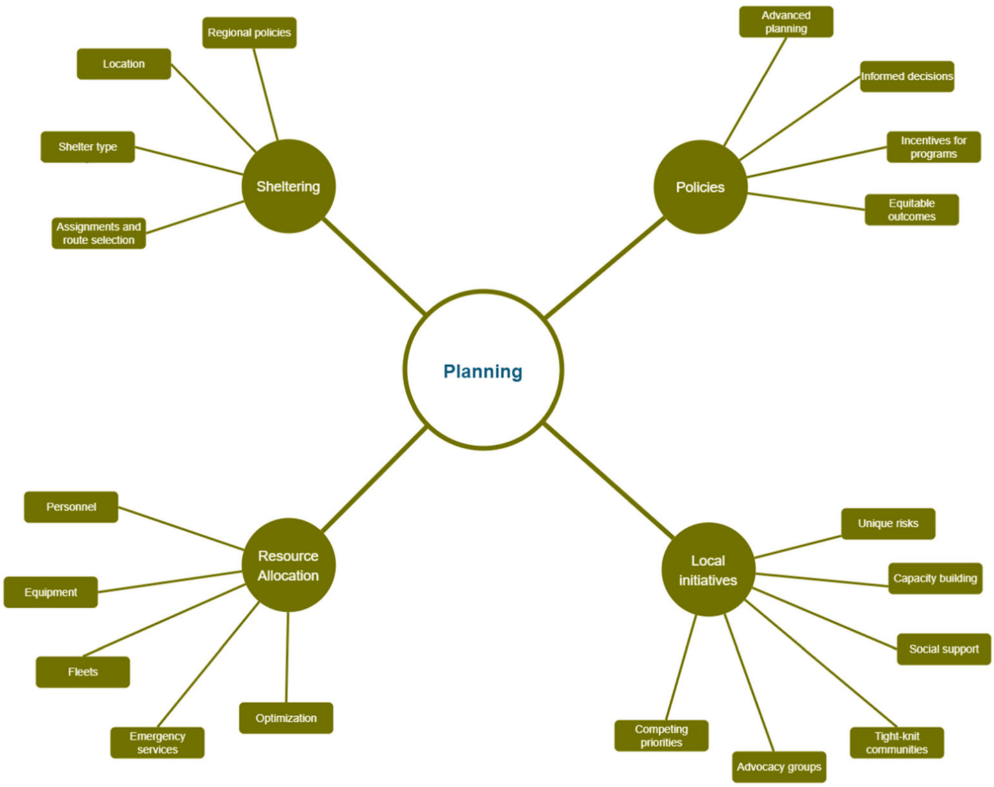

Figure 5. Interconnected themes and tags in 'Planning'.

3.4.1. Sheltering strategies during wildfire evacuations

Sheltering during wildfire evacuations typically involves evacuees traveling to temporary locations away from fires. Most people decide to shelter with friends/family, stay at hotels/motels, or go to public shelters, though a select few also shelter in recreational vehicles or at home-sharing options such as Airbnb (Wong, Broader, and Shaheen 2020a). Wong et al. (2020a) reviewed 11 wildfires in California from 2017 to 2019 and noted key similarities between them, finding that local organizations and non-profit humanitarian organizations played a critical role in sheltering evacuees. The same review also found public shelters to be one of the least popular sheltering preferences for evacuees based on limited resources (accessible facilities, medical supplies, trained staff), the potential for the spread of illness, and reaching capacity.

Some regions, such as Australia, have promoted a 'leave early or stay and defend' policy in the past. Reviews and discussions of this policy, including its benefits and drawbacks, can be found in McCaffrey and Rhodes (2009), Paveglio, Boyd, and Carroll (2012), and McLennan et al. (2019). Recent literature has also reported that in the southern regions of France, a distinct preference for 'confinement' (also widely known as shelter-in-place) instead of evacuation (as studied by Vaiciulyte et al. (2022)) exists. These staying and shelter-in-place policies are not generally recommended by governments and inadequately prepared individuals are more likely to be forced into dangerous responses (such as late evacuation and passive shelter) (Whittaker et al. 2013). However, shelter-in-place may become a necessity in select situations, such as when roads become impassable due to debris, low visibility, and closures (Soga et al. 2021).

Recent research has focused on improving evacuation planning in dynamic environments, stressing the importance of addressing various constraints when devising sheltering strategies. Some studies have looked at shelter assignment and route selections in wildfire conditions (Shahparvari et al. 2016; Shahparvari, Abbasi, and Chhetri 2017; Shahparvari et al. 2019). Two studies, Shahabi and Wilson (2018) and Afkham, Ramezanian, and Shahparvari (2022), developed approaches to improve evacuation planning in different dynamic environments for shelter assignments. The first study created a scalable evacuation routing algorithm on a directed graph that considered road capacity and evacuation time limits to update an evacuation plan in real time (Shahabi and Wilson 2018). Afkham, Ramezanian, and Shahparvari (2022) focused on optimizing traffic flow and minimizing congestion in mass self-evacuation networks through a bi-level model and presented a sensitivity analysis of evacuation time to the number of shelters and routes. The studies recommended that the highest priority in disaster preparation should be establishing safe and effective evacuation routes to shelters.

From a wildfire evacuation behavior perspective, Wong, Yu, et al. (2022) developed multiple models (binary choice and portfolio choice models) to determine the dependencies and joint behavior for multiple choice dimensions that included departure time, transportation mode, and shelter type among others. The research found a joint preference by evacuees for traveling to private shelters and evacuating nearby (within the same county) for the 2017 Southern California Wildfires and the 2018 Carr Wildfire.

The effectiveness of designated wildfire 'shelters' depends on the unique characteristics of the fire, such as the location of the ignition point and environmental conditions. For example, the placement of shelters should remain effective across several likely wildfire-spread scenarios (Steer et al. 2017). To avoid hazardous conditions, shelters will need to be designed to withstand intense heat and embers, similar to resilient homes in wildfire-prone areas (Cova, Dennison, and Drews 2011; Quarles et al. 2010). These building improvements are necessary for shelters that are used closer to the fire front, especially for late evacuees (Cova et al. 2009).

Moving away from traditional shelters, ongoing research has identified an opportunity to build resilience hubs, which can operate in both normal and disaster conditions. A comprehensive review of resilience hubs by Ciriaco and Wong (2022) provides insights into the need for planning and integrating essential services (especially transportation) to these hubs.

3.4.2. Resource allocation

To minimize the damage caused by wildfires, efficient resource allocation, which includes personnel, equipment, fleets, and other emergency services can help improve safety and efficiency. For example, Bodaghi et al. (2020) and Shahparvari et al. (2016; 2021) proposed probabilistic approaches to allocate personnel and equipment for bushfire emergencies, optimizing response and outcomes. A study by Pérez, Maldonado, and López-Ospina (2016) aimed to address fleet allocation problems of fire departments. To achieve this, the study used mixed integer formulations as a means of mitigating disparities in service based on response times. In addition, Fragkos et al. (2022) addressed emergency supply using a heterogeneous fleet problem (ESHFP), which minimized the time to supply resources (i.e. consumable and non-consumable goods as emergency supplies) to evacuees and intervention groups.

Focusing more on the road network, Ohi and Kim (2021) developed a systematic approach for resource allocation during an area-wide disruption by identifying critical corridors. This approach evaluated the network bottleneck capacity and routing needs of the affected area and allocated emergency planning resources to the most important corridors to improve evacuation efficiency. Meanwhile, a review by Lessan and Kim (2022) outlined network optimization-based evacuation planning studies for various disaster types and the decision choices involved, including destination, route, departure time, departure location, and shelter selection. Other ways to consider the allocation of resources include prioritizing based on community feedback (to share mobility and sheltering resources) (Wong, Walker, and Shaheen 2021), identifying communities at higher risk for evacuation problems (Ohi and Kim 2021), determining vulnerable segments on a highway network (Mahajan and Kim 2020), and focusing on equitable outcomes in disaster evacuation processes (Menon, Staes, and Bertini 2020). Research has also shown benefits to policymakers that inform the allocation of resources (such as emergency service resources for medical assistance) to effectively reduce waiting times by improving communication and bolstering residents' preparedness (Vaiciulyte et al. 2022).

3.4.3. Policies

Wildfires are a growing concern for many communities, and clear and flexible policies are needed to accommodate the wide-ranging demands of evacuations. For example, Wong (2020) highlighted the benefits of advanced planning, including reduced evacuation time estimates (ETEs), improved life safety, and more equitable outcomes. Programs such as FireSmart Canada, Firewise in the U.S., and Community Fireguard in Australia provide recommendations based on physical science and are designed to help residents make informed decisions, maintain fire-resistant homes and gardens, and promote community collaboration in reducing the risk of wildfires (Country Fire Authority 2023; NFPA 2022; Partners in Protection 2003; Thompson 2016). For example, the FireSmart manual focuses on three key themes to reduce wildfire threats: assessing the situation, resolving existing problems, and avoiding future problems (Partners in Protection 2003). Despite the benefits associated with the adoption of these programs, participation of WUI communities remains far from universal. A study of over 2,000 survey responses showed that respondents preferred positive strategies with incentives to increase participation in the FireSmart program, with the strongest support for tying insurance premiums to program compliance (Ergibi and Hesseln 2020).

3.4.4. Locally-led initiatives

Locally-led initiatives can be valuable for specific communities and their unique risks. Through interaction between residents and emergency managers, communities can determine their existing ability to handle fire risk, build capacity, and decide how to approach evacuations (Paveglio, Carroll, and Jakes 2010). Researchers have suggested that locally-led initiatives influenced by the lived experiences of wildfire-impacted communities can bring benefits to these communities and lead to future resilience (Christianson, McGee, and L'Hirondelle 2012; Jakes and Langer 2012; Slowikowski and Motion

2021). During the 2011 wildfire evacuation of the Dene Tha' First Nation, several community-centered decisions (e.g. keeping families together, providing social support, and using familiar host communities) helped the evacuation and improved community resilience (Mottershead, McGee, and Christianson 2020). Tight-knit communities and advocacy groups can also influence policies. In one example, members of a wildfire-awareness advocacy group in Colorado asked the planning commission to include a study on emergency evacuation on the west side of the city in the final master plan of the city (Jent 2023). On the other hand, if external agencies are leading an evacuation and the priorities of the governing body and the impacted community do not align, challenging evacuation experiences can arise and negatively impact evacuees (Asfaw, McGee, and Christianson 2019b). For example, residents of a remote community in the Yukon Territory in Canada did not evacuate due to the fear of losing harvested meat, sled dog teams, and livestock (Cote and McGee 2014).

Importantly, recent research in Canada on recent wildfire evacuations in First Nations communities has focused on improving communication mechanisms and governmental policies to increase local capacity and community resilience (McGee and Christianson 2021). Finally, local leadership should be prioritized in improving evacuation outcomes, which can keep members of large households together (Christianson and McGee 2019),

Table 1. Summary of key recommendations.

Key Areas	Key Recommendations
Infrastructure	● Agencies should create an easy-to-use tracking list for wildfire-related infrastructure damage, debris removal, and subsequent repair works to ensure comprehensive documentation. ● Jurisdictions should consider designs that could protect critical or flammable transportation infrastructure to reduce wildfire impacts. ● The implementation of ITS with sensors for real-time data on traffic, damage, wildfire location, and evacuation progress could aid decision-making and post-disaster evaluations. ● Interdependencies of transportation infrastructure with other systems (e.g. power, communications) require further study and preparedness to reduce cascading failures.
Modality	● Evacuation plans require modifications that consider the emerging EV market, including the planning of fixed and mobile charging stations. ● Jurisdictions should develop shared mobility and transit-based evacuation plans to increase transportation options and equity. ● Governments should explore the potential of water and air-based evacuations for coastal and remote communities, factoring in operational needs, costs, geography, and planning requirements. ● Certain geographies may benefit from evacuations on foot or micromobility options, though further research is recommended to assess safety, efficiency, and use cases.
Networks	● Further development of computational models at the local and regional scale can help assist in devising system-optimal rerouting strategies and coordinating traffic across a region. ● Researchers and agencies should coordinate on data-sharing practices and develop departure curves for communities with previous wildfire evacuation experience.
Planning	● Evacuation strategies should be designed to be adaptable to varying wildfire conditions across jurisdictions, while actively involving NGOs, CBOs, and underserved populations in planning. ● Jurisdictions should also plan for other key needs, including shelter locations, relief supply transportation, personnel needs, and wildfire response partners. ● Engineers, planners, and decision-makers should continue to work together to enhance local capacity, identify innovative financial sources, and build dynamic evacuation plans for a range of scenarios.

plan accommodations and health care for identified persons in advance (Asfaw et al. 2019a), and designate multiple pick-up locations for both abled and disabled persons (Baou et al. 2018).

4. Discussion

This literature review uncovered key concepts related to recent research conducted at the intersection of wildfires and transportation. In this section, we discuss each key area and connect them, highlighting interdisciplinary research needs and recommendations for future directions. At the end, Table 1 summarizes the key takeaways and recommendations from this review.

4.1. The missing component of infrastructure

First, we found minimal literature related to damaged infrastructure, in particular how wildfires affect infrastructure and what designs could mitigate wildfires and associated hazards. This gap likely results from the rarity of large wildfire evacuations, differing sizes of large wildfire evacuations, low or non-continuous media coverage, and/or the relative resilience of roadway infrastructure to fires. Given the sometimes localized impacts of wildfires, information on infrastructure damage and debris removal may not have been recorded. We recommend that researchers and governments create an easy-to-use tracking list of damages and recovery efforts related to infrastructure. Special attention should be given to potentially flammable infrastructure, including infrastructure that could melt or experience reduced functionality when exposed to intense heat.

Aging infrastructure coupled with wildfire exposure could lead to increased damage over time. Our review found that damages could be direct or indirect, such as strength degradation due to heat and impact loads due to debris flow (following a wildfire). The risk of hazards that are exacerbated by wildfires, especially flooding, landslides, and mudslides, presents one of the larger threats to infrastructure (Fraser, Chester, and Underwood 2022). Nevertheless, these related hazards have not been fully researched or considered, especially related to the design, maintenance, and operation of roads and highways. The seasonal occurrence of wildfires likely warrants a more comprehensive design and rehabilitation strategy. We also note the lack of documentation available for post-disaster maintenance, operations, and repair for chosen transportation routes. Sharing this information, including best practices, could be useful for varied regions.

Another issue that requires further attention is the usage of different sensors to actively monitor infrastructure and wildfires in real time. Our review found only minimal research on sensors and infrastructure monitoring (Menon, Staes, and Bertini 2020). A variety of intelligent transportation systems (ITS) focusing on sensors could be useful for real-time data on traffic, damage, wildfire location, and evacuation progress. Opportunities might exist to integrate this monitoring with a traffic management center or an emergency operations center. Existing sensing technology, such as the Road Weather Information System (RWIS) (Kwon and Fu 2013), could also be re-purposed for wildfires. This data would be helpful for decision-making and post-disaster evaluations.

Even if road infrastructure remains operational and undamaged, two key issues persist related to other infrastructure. First, our review found that there are broad concerns related to communication systems. For example, individuals may struggle to evacuate, especially if they do not have mobile phone coverage (Gralow and Paul 2020; Soga et al. 2021). Their unfamiliarity with traditional or advanced communication channels could also present a problem. Second, transportation infrastructure is linked to power systems, which makes it susceptible to other system failures. Our review found only minimal research in connecting these systems, beyond a few examples related to communication issues (e.g. Thériault et al. 2021) and PSPS events (e.g. Wong, Broader, and Shaheen 2022). We recommend that future research and practice consider how people interact with communication systems and develop linkages among different infrastructure systems to highlight interdependent failures and opportunities.

4.2. Thinking beyond privately owned automobiles

Our review indicates that wildfire evacuations require multimodal coordination, despite the emphasis on privately owned automobiles in existing studies and plans (see Kearns (2017) and Wong, Broader, and Shaheen (2020b) as examples). However, organizing multiple modes poses significant challenges for government agencies. For instance, privately owned automobiles are difficult to coordinate (e.g. departure time, destination, etc.) in an emergency and are the most dominant form of evacuation mode in most evacuations. We also note that shared mobility (mostly from privately owned automobiles) could increase transportation capacity and offer equity benefits for vulnerable groups without access to any other mode of transportation during evacuations (see for example Wong, Broader, and Shaheen 2020b). Local ride-hailing companies have an opportunity to partner with communities and enhance capacity, but a rapid matching system for demand and supply remains undeveloped in research and practice.

Limited cases of transit-based responses during wildfires tend to be ad-hoc (Wong, Broader, and Shaheen 2020a; Woo et al. 2017). Transit-based evacuation planning could be developed based on strategies from hurricane evacuations, including pick-up locations, evacuation registries, registration centers, and improved public shelters. Transparent sharing of pick-up and drop-off locations in advance, along with community-needs analyses, can optimize resource utilization (fleet, drivers, and any emergency services).

Evacuations using marine and air transportation are still emerging as viable modes. Past evacuations suggest success under certain circumstances, but limitations exist due to costs, operational needs, departure/landing requirements, geography, and planning needs. Government agencies should explore the role of water – and air-based evacuations for coastal and remote communities, especially when the road network is impeded by fire, debris, or congestion.

Though safety is questionable in wildfires, active transportation and micromobility could be a flexible and redundant option for evacuees, especially those without access to a privately owned automobile or public transit. While new studies are beginning to emerge (Fitch-Polse, Chen, and Wong 2023), we recommend further research and consideration of these modes in wildfire evacuations, including use cases, best practices, and equity-building opportunities.

4.3. Navigating traffic and capacity challenges

Our review found some studies related to community design, especially related to networks. During evacuations, peak demand on roadways (and other transportation infrastructure) leads to a capacity issue, resulting in congestion, delays, and potential exposure to smoke and wildfire heat. Multiple studies have explored rerouting problems to address this issue (Hou, Darr, and Zhang 2022; Shahparvari and Abbasi 2017). Putting these rerouting strategies into practice during typical roadway congestion can be the first step in familiarizing people with the potential of an efficient travel experience and for transportation agencies to test evacuation strategies. We recommend the development of computational models at local/regional scales to account for concurrent wildfires. These models could provide insights into how major egress routes could be overwhelmed and assist in devising system-optimal rerouting strategies that coordinate traffic with all neighboring wildfire-prone communities.

Moreover, we discovered minimal work on developing and studying departure curves for wildfires. These graphs can provide transportation, planning, and emergency communication agencies with rich travel behavior trends that are community-specific. More importantly, the curves can provide insight into when an evacuation surge is likely to take place. For example, Grajdura, Qian, and Niemeier (2021) developed a detailed account of the departure time of evacuees with additional information about when residents were officially notified of the 2018 Camp Wildfire. There is a critical need for similar studies that analyze other wildfire events at this granular level to identify community and agency response. This can lead to more efficient deployment of resources and reduce overall evacuation time. We recommend researchers and agencies coordinate on data sharing practices (traffic and GPS data) and develop curves for communities and nearby jurisdictions.

4.4. Enhancing advanced evacuation planning

Comprehensive wildfire evacuation planning is essential for preparing jurisdictions for these scenarios, reducing injuries and fatalities, alleviating congestion on evacuation routes, and moving more people to safety under resource and time constraints (Gan et al. 2016; Ohi and Kim 2021; Wong, Walker, and Shaheen 2021). Effective planning requires collaboration among decision-makers and should consider the community's unique characteristics (e.g. culture, resources) (Brachman et al. 2020; Zhao et al. 2022). These community-specific plans tend to generate tailored guidance for residents and consider housing density and local traffic. Despite this localized value, evacuation planning remains under-resourced and missing in many jurisdictions. Consequently, there remains a need to build evacuation strategies that are more generalizable yet still adaptable across different jurisdictions faced with varying wildfire characteristics. We found that successful evacuation planning is more than drafting plans and performing analyses: planning also engages non-governmental organizations (NGOs), community-based organizations (CBOs), and underserved populations (Asfaw, McGee, and Christianson 2019b; Baou et al. 2018; McGee 2021; Paveglio, Carroll, and Jakes 2010).

Information on evacuees' sheltering preferences can assist agencies in assigning and setting up a dedicated number of shelters during a wildfire evacuation. We found that several studies looked at the allocation of resources such as shelters, fleets, personnel, and other emergency services. However, our systematic review failed to determine if these optimized allocation strategies have been implemented yet. This indicates that evacuation responses for wildfires may currently rely on ad hoc strategies and responses, which could lead to inefficiency and safety problems. We recommend that communities formally draft plans that identify key shelter locations, methods to transport relief supplies, personnel allocation and staff needs, and partners for wildfire response. Moreover, new shelter development projects and existing shelter upgrades should aim to serve the communities equitably, accounting for the needs of vulnerable residents (Ciriaco and Wong 2022).

Enhanced local capacity can also help address key evacuation challenges. Our review indicated that local leadership played a key role in some major evacuation events and encouraged residents to evacuate. We recommend providing communities with well-researched policies and innovative financial resources to stimulate planning at the local level and foster initiative to test new strategies, gain insight from residents, and build connections between engineers and planners. Table 1 summarizes the key recommendations from this discussion across the four topical areas.

5. Conclusion

Wildfire evacuations are complex processes that require holistic planning, engineering, and operations. Within this challenge, transportation is a vital support element as it facilitates the rapid movement of people away from danger and resources into a hazardous area. In this review, we focused on four key areas related to wildfire evacuations: infrastructure; modality; transportation networks; and planning. Our review found significant gaps in understanding and implementing wildfire evacuation planning, especially in the areas of modality beyond privately owned automobiles and network analysis for congestion management. First, there is limited research on direct and indirect damages to infrastructure and interdependent infrastructural failures. Hazard mapping and sensing technologies along critical corridors could help reduce infrastructure failures and improve road design guidelines. Second, minimal evidence exists on how to incorporate multi-modality in wildfire evacuations, despite its widespread usage among carless populations. More research and strategic planning can increase the viability of public transit, active transportation, and shared mobility to improve equitable outcomes for underserved populations. Third, there is scarce application of rerouting strategies to eliminate congestion during evacuations. However, recent work focusing on wildfire travel behavior (departure curves) at the community level and the location of shelters could help inform rerouting, especially by mapping services (e.g. Google Maps, Waze). Last, there is limited evidence of advanced and collaborative evacuation planning in many jurisdictions. Practice-oriented policies and financial assistance to communities with strong local leadership can encourage wildfire evacuation planning that considers the unique characteristics of the community, accounts for the underserved/underrepresented groups, and facilitates resource management. By considering transportation analyses beyond decision science and simulations, the resilience benefits of well-rounded and empirically-based evacuation planning and response can be more realized across wildfire-prone geographies.

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