Literature Review of the State-of-the-Science in Wildfire Evacuation

Marin Wildfire Prevention Authority

STi Sonoma Technology

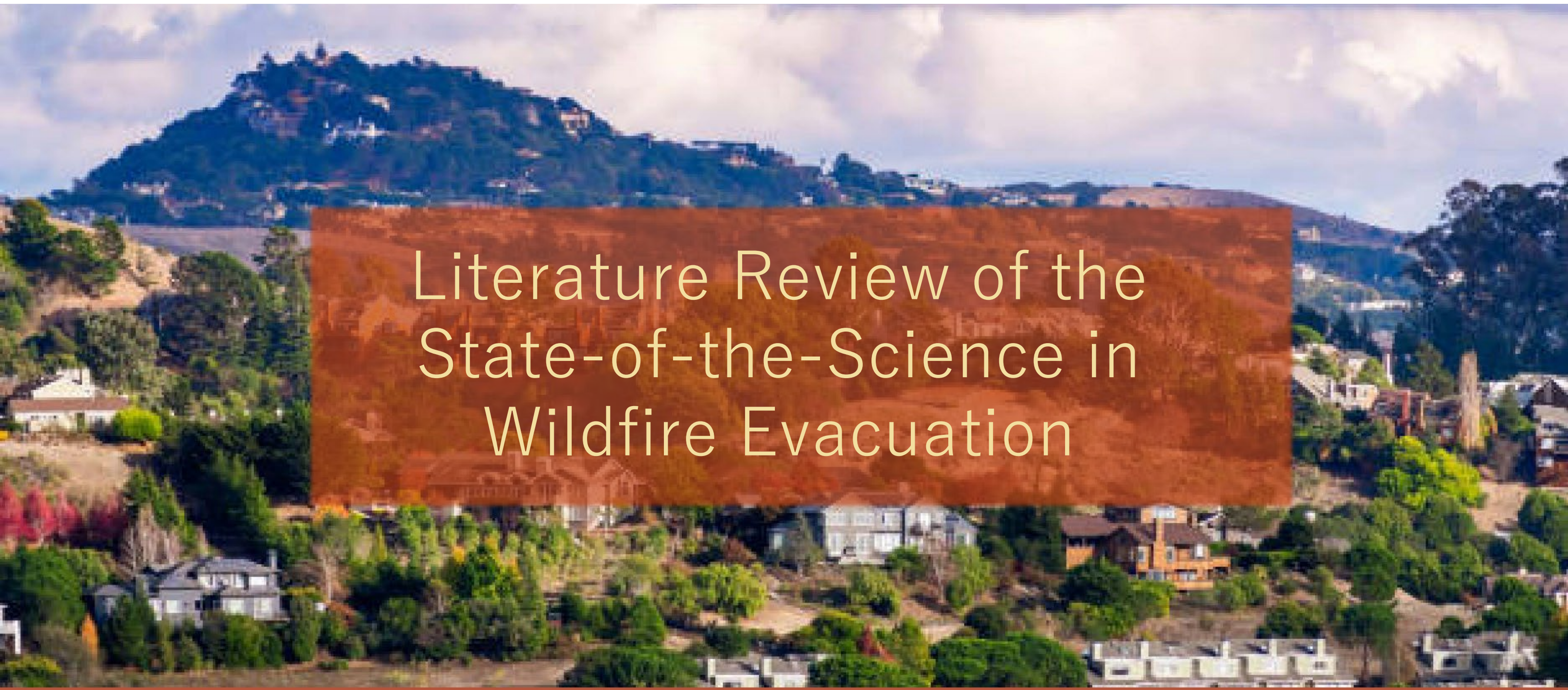
Berkeley University of California

Spatial Informatics Group

Fehr & Peers

Zonehaven

This document contains blank pages to accommodate two-sided printing.



Literature Review of the State-of-the-Science in Wildfire Evacuation

Prepared by

Dr. Samantha Kramer, Tami Lavezzo, Hilary Hafner, and Dr. Douglas Eisinger at Sonoma Technology, Petaluma, CA

Dr. Kenichi Soga, Dr. Bingyu Zhao, and Dr. Louise Comfort at University of California, Berkeley, Berkeley, CA

Robert Grandy and Kevin Johnson at Fehr & Peers, San Francisco, CA

Dr. Chris Lautenberger at Reax Engineering, Berkeley, CA

Jason Moghaddas at Spatial Informatics Group, Pleasanton, CA

Prepared for

Mark Brown at Marin Wildfire Prevention Authority, San Rafael, CA

October 7, 2022

Final Report

STI-922025-7776

Contents

Figures iv

Tables iv

Executive Summary 1
- Literature Review Objective and Motivation 1
- Causes of Civilian Fatalities in Wildfires 2
- What Does a Successful Evacuation Look Like? 4
- Practical Implications: Best Practices in Evacuation Planning 5
- What Models and Tools Are Available to Support Planning? 7

1. Introduction 9

2. Background 11

3. Wildfire Evacuation Goals And Success 15

4. Leading Causes Of Civilian Fatalities During Evacuation 19

5. Wildfire Evacuation Risk Factors 23
- 5.1 Extreme Fire Behavior 26
- 5.2 Communications are Delayed or Insufficient 27
  - 5.2.1 Timeliness 27
  - 5.2.2 Content of the Alert 28
  - 5.2.3 Communication through Multiple Channels 28
- 5.3 Residents Depart Too Late 29
  - 5.3.1 Social Economic Factors Informing the Decision to Evacuate 30
  - 5.3.2 Preparation Time 30
  - 5.3.3 Departure Time 31
  - 5.3.4 Arrival Time 31
  - 5.3.5 Decision to Stay 31
- 5.4 Evacuees Exposed to Danger Enroute and/or Traffic Congestion Persists 31

6. Current Modeling Studies 33
  - 6.1.1 Short-Term Visitors 36
  - 6.1.2 Evacuees Lacking Vehicle Access 36
  - 6.1.3 Evacuation Route Selection 36
  - 6.1.4 Traffic Management Resources 36

7. Summary Of Mitigation Implications 37

8. Citations 39

Figures

ES-1. Color-coding scheme used to share information in this report about the key determinants to evacuation success. 4

1. Map of Marin County and the wildland urban interface boundaries. 12

2. Color-coding scheme used to share information in the report about the key determinants to evacuation success.... 15

3. Summary of wildfire evacuation goals identified in the literature. 17

4. Civilian evacuation fatalities by location during the 2018 Camp Fire.... 21

5. Summary of wildfire evacuation risk factors..... 24

6. References to supporting literature for summary of wildfire evacuation risk factors in Figure 5...... 25

Tables

1. Number and percent of civilian fatalities by age for the Camp Fire 22

2. Summary of the modeling studies reviewed as part of this literature review. 34

Executive Summary

Literature Review Objective and Motivation

The Marin Wildfire Prevention Authority (MWPA) asked our team to review available studies and identify practical wildfire evacuation lessons. MWPA sought answers to several questions:

1. What have been the leading causes of civilian fatalities in past wildfire evacuations?
2. What risk factors contributed to those deaths?
3. What are the practical implications for Marin County?
    - What does a successful evacuation look like?
    - What actions (mitigations) can the county take to better support future evacuation?
    - What tools or computer modeling simulation methods can improve evacuation planning?

Several factors motivated this effort. Most importantly, California's firefighting community has observed that a growing number of wildfires involve extreme weather and wind conditions that can overwhelm community preparedness and evacuation planning. The 2018 Camp Fire is a prime example, as extreme wind-driven fire conditions overwhelmed residents of Butte County. Despite prior evacuation planning, 85 civilian fatalities were confirmed.

This report draws insights from over 50 studies. It summarizes findings from numerous events, including the 2013 Yarnell Hill Fire in Arizona, which resulted in 19 firefighter deaths; the 2016 Chimney Tops 2 Fire in Tennessee, which was a high wind event with 14 fatalities, 191 injuries, 2,500 structures destroyed, and 14,000 residents evacuated in four hours; the 2017 Northern California (North Bay) Fires, which resulted in 31 civilian fatalities; and the 2018 Camp Fire in Butte County California, which resulted in 86 civilian fatalities. It also summarizes assessments from Oregon, Washington State, and fire-prone regions of Australia. Our review reinforces a central tenet of wildfire emergency response: **In most cases, evacuation is the safest option for residents even if the roadways used for evacuation are impacted by nearby fire or smoke**. Relative to the total number of civilian fatalities, very few have occurred in enclosed automobiles on unobstructed roadways[1] or in temporary refuge areas (TRAs).[2] As an example, during the Camp Fire, 7 of the 85 confirmed civilian deaths occurred in vehicles. However, specific conditions contributed to these fatalities, including inadequate time to evacuate, vehicle accidents, and obstructed roadways. In addition, **most civilian**

[1] In this report, we define "unobstructed roadway" as a roadway that is not blocked by debris or abandoned vehicles.

[2] It should be noted that the term temporary refuge area (TRA) has a specific definition for firefighting operations. A TRA is anything that protects firefighters from radiant or convective heat. If an escape route to a safety zone becomes compromised, firefighters can use a TRA until it's safe to move to the safety zone. A TRA is not considered a replacement for an identified safety zone; it is a temporary, short-term solution that firefighters can use when needed (https://www.wildlandfirefighter.com/2020/09/15/temporary-refuge-area-considerations-and-options/#gref).

fatalities happen when people try to flee a fire area at the last minute. Studies show some people are slow to evacuate for various reasons, leaving them vulnerable. Our literature review identified obstacles that impede successful evacuation, as well as practical steps Marin County can take to overcome those obstacles.

Causes of Civilian Fatalities in Wildfires

Studies showed three major factors contribute most to civilian fatalities:

1. Extreme fire behavior conditions
2. Failures and/or delays in alerting and communications systems
3. Delays in evacuee departure due to last-minute evacuations or an inability to evacuate

Civilian Fatalities

Most recent U.S. civilian wildfire fatalities occurred when people attempted to evacuate too late or chose not to evacuate and were overtaken by fire or smoke. In general, most fatalities occur in people's homes or on their property (outdoors, in the open air) as they attempt to flee. Very few fatalities occur in enclosed automobiles on unobstructed roadways or in temporary refuge areas (TRAs).

Extreme fire behavior conditions. The primary risk factor and threat to a successful evacuation is extreme and uncontrollable fire behavior in or near populated areas and along evacuation routes. In situations with extreme, wind-driven fires, (1) flames can spread very quickly, (2) spot fires can merge and create a multi-fire complex, and (3) fires can expand into the wildland urban interface (WUI) or suburban neighborhoods before people are able to evacuate. Extreme conditions exacerbated the impacts of many recent fires, including the North Bay, Yarnell Hill, and Camp fires. In Butte County (Camp Fire) for example, extreme winds and rapid shifts in fire conditions simply overwhelmed prior evacuation plans.

Failures and/or delays in alerting and communications systems. Communication failures of various types resulted in time being lost to evacuate safely from numerous fires, including the North Bay, Chimney Tops 2, Yarnell Hill, and Camp fires. Compounding the problems observed with past fires, Marin County is also at risk from PG&E Public Safety Power Shutoffs (PSPS) during extreme fire weather conditions that could leave residents without power and impede their ability to receive communications through traditional avenues, such as television and radio. Communication failures have also resulted from fire impacts (1) directly, such as lost cell towers, and (2) indirectly, such as an inability to successfully contact portions of the population. Marin has population subgroups at greater risk for communication obstacles, including:

(1) Elderly individuals who may have limited access to technology

(2) Homeless individuals

(3) People who are less trusting of government-issued information

(4) Individuals dependent on public transportation systems

(5) Tourists and visitors who may not be familiar with wildfire risks, road networks, or evacuation alert systems

Delays in evacuee departure due to last-minute evacuations or an inability to evacuate. Finally, a main contributor to civilian fatalities is delayed evacuation – a lesson learned in both the U.S. and Australia. A key insight from past studies is *the importance of age*. Most civilian fatalities during the Camp Fire, for example, were individuals aged 65 and older who became trapped in their homes or on their properties for reasons including: failure to receive alerts and evacuation orders, inability to mobilize due to lack of transportation or health condition, inability to perceive an immediate threat, or their decision to remain at home. We also identified demographic characteristics of those more likely to delay evacuation. In addition to the elderly, examples include (a) males, (b) residents who had been living in their homes for 15 years or longer, (c) disabled residents, and (d) those with pets. It should be noted that studies showed households with children were more likely to evacuate immediately. Fire departments are thinking of these population subgroups in terms of their "capacity to evacuate." Some examples of key obstacles to evacuations are individuals' or household residents' age, health condition, and lack of transportation access. Separate from the characteristics of *people* are the characteristics of *where people live*. A key insight from Oregon and Washington state is that the towns with the poorest road networks have the highest wildfire evacuation vulnerability – an insight of special relevance to Marin given the county's many neighborhoods and dwellings located at the end of narrow, winding, limited-access streets. There are also groups who decide not to evacuate for reasons such as mistrust of the evacuation order source, a lack of understanding of the risk, or a desire to stay and defend their property. This can result in unprepared residents attempting to evacuate once flames or smoke have overtaken their property. Overall, the key finding is that **there is a need to identify and address vulnerable population groups that need assistance evacuating or may need additional education on the risks of remaining in the wildfire evacuation zone**.

What Does a Successful Evacuation Look Like?

Through the literature review, we identified five goals for a manageable and successful evacuation:

1. Immediate identification of wildfire threat and ongoing understanding of the fire's behavior
2. Timely and successful dissemination of evacuation alerts and communications
3. Timely and organized departure of residents and the public
4. Safe and efficient evacuation
5. Arrival at designated or pre-determined safe spaces unharmed

> **Evacuation Goals**
>
> *Once an evacuation begins, the goal is for evacuees to have ample time to safely evacuate beyond the threatened area while avoiding traffic congestion and interference with emergency vehicle ingress.*

Successfully achieving all five of these goals is necessary in determining evacuation success. We have color-coded these determinants in Figure ES-1 with a color scheme that we use in later sections of this report to share related information about each goal.

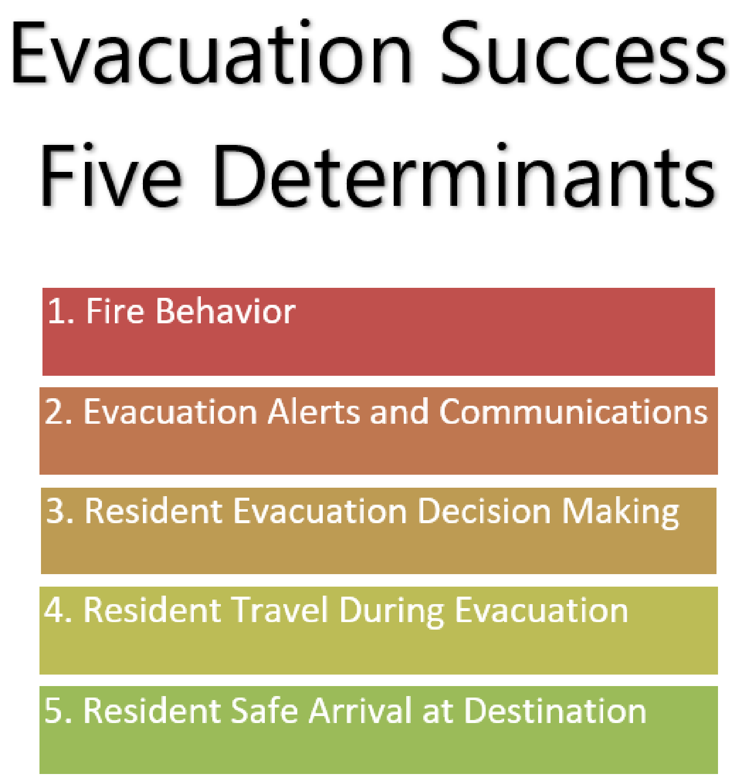


Figure ES-1. Color-coding scheme used to share information in this report about the key determinants to evacuation success.

Practical Implications: Best Practices in Evacuation Planning

The wealth of information from past fire management efforts helped to identify two sets of practical actions. These can be grouped as actions taken (1) *prior to* and (2) *during* a Red Flag day or fire event.

Actions to take prior to a Red Flag day or fire event. The more work that can be done in advance of a fire event to (a) educate the public and (b) prepare roadway and landscape infrastructure to support evacuations, the better the response will be during evacuation events.

Public education actions can support the following:

- Increased public understanding of different emergency notification systems and platforms, including social media, and their intended purpose
- Increased public understanding of communication options, such as weather radios, that the public can use during event-related power outages
- Identification of population groups that may be less likely to evacuate or may need assistance during an evacuation by analyzing census and demographic data so that plans can be developed to provide support to these groups (For example, vulnerable population groups that may need assistance evacuating due to age, health condition, lack of transportation, or other factors like pet ownership)

Roadway and landscape infrastructure actions can include the following:

- Prepare the landscape to suppress fire, decrease fire line intensity, and increase the available time for evacuation by, for example, creating strategically located fuel breaks (As an illustration, case study work following the Camp Fire found that increasing the width of fuel breaks from 200 meters to 400 meters would have doubled the available evacuation time in parts of Butte County)
- Prepare roadway and evacuation infrastructure:
    - Clear or reduce vegetation, restrict parking, and improve signage along evacuation routes
    - Pre-determine "safe spaces" to shelter in place if evacuation is not possible, including gathering spots with high-capacity parking

During a Red Flag day or fire event. Similarly, practical actions taken during fire events fall into two groups: (a) traffic management and (b) communication.

Traffic management includes the following:

- Temporarily modifying traffic flows can aid quick and efficient evacuation. For example, case studies of fires in Paradise and Bolinas show that setting up contraflow travel can reduce the amount of time that people are exposed to fire while in their vehicles, and that shifting travel on narrow roads to one-way can speed vehicle flows.
- Improve traffic flow by reducing the number of evacuating vehicles, increasing GPS-based rerouting, and phasing or staging evacuation orders to reduce traffic congestion.
- Reduce parking at key intersections and roadways to avoid bottlenecks.
- Pre-allocate emergency resources at strategic locations and support active traffic management (e.g., public safety officials directing traffic) to minimize congestion.

> **Risk Management**
>
> *The primary threat to a successful evacuation is extreme and uncontrollable fire behavior in or near populated areas and along evacuation routes. It is critical to work in advance of events to lay the groundwork for rapid evacuation, and to continue working during events to help support this goal.*

Communication actions during an emergency should include the following:

- Repeat actionable information on evacuation needs, routes, and fire status through a variety of communication channels, including social media, to ensure more people get the information. Insights from North America and Australia show that clear and actionable messaging prompted people to evacuate immediately, decreased departure time, reduced the intention to return home, and decreased the intention to shelter at home. Research also shows social media to be an effective tool for real-time evacuation information if the information is repetitive and from a reliable source, although social media messages will miss some people, such as those who lack smart phones.
- Inform Marin visitors who lack local roadway knowledge and may be delayed in understanding emergency conditions. In a normal travel year, Marin County sees 12-14 million visitors.
- Properly define and sequence which areas to evacuate early. If evacuation areas are too small and are expanded too late, residents may not have enough time to evacuate safely. If the evacuation area starts out too large, routes may become congested and shelter resources may be overwhelmed.

What Models and Tools Are Available to Support Planning?

Through the literature review, we identified models and tools that have been used in Marin and elsewhere to support planning for fire events. Although these resources have limitations that are discussed below, they can assist in providing support to:

- Simulate how traffic management changes can speed evacuation times, such as planning work done by Mill Valley
- Illustrate the vulnerability of areas with limited routes available to leave an area, such as planning work done for Rancho Cucamonga
- Compare (1) how quickly fires can move and (2) how quickly people can evacuate to help understand when to issue evacuation orders, for example, using tools developed for PG&E and others

Although there are valuable tools available to support planning, existing tools have important limitations and restricting assumptions that should be recognized and used to inform the work for Marin County, including:

1. A lack of accounting for visitor and tourist populations, particularly in remote areas (i.e., hikers, campers, equestrian users, mountain bikers)
2. A lack of accounting for evacuees without access to vehicles
3. Assumptions that evacuees chose the shortest, most direct route, and reroute if needed
4. Assumptions that available emergency staff and resources are adequate to direct traffic

1. Introduction

In 2022, the Marin Wildfire Prevention Authority (MWPA)[3] funded a project to assess evacuation route vulnerability and develop a planning tool. The planning tool can be used by MWPA member agencies, county officials, public works departments, and transportation planners to help identify and prioritize actions and/or projects that can mitigate risks associated with evacuation throughout the county. The scope of the Marin Evacuation Ingress/Egress Risk Planning Tool project will include constructing an inventory of risk factors and using dynamic models of wildland fire spread, communications processes, and traffic flow to simulate wildfire evacuation scenarios. The modeling and risk analysis will be used to develop a risk index for each roadway in the county to help identify the most vulnerable evacuation routes and prioritize mitigation projects that would improve the most vulnerable routes. Using the risk factor inventory, scientific modeling scheme, and the results of the risk analyses, a geographic information system (GIS)-based evacuation risk planning tool will be developed.

MWPA member agencies and other partners will use this tool to inform their mitigation work plans, evaluate the impact of proposed or completed improvements, prioritize distribution of funds, and seek new funding for projects. Fire and law enforcement agencies are expected to use the tool to obtain a detailed picture of risk at various levels of aggregation, which will inform evacuation preparedness activities and decisions. This planning tool and the underlying data will help assess the need for mitigation projects and is not an evacuation management tool.

Before beginning the evacuation risk assessment work, a literature review was performed to evaluate the state-of-the-science in evacuation dynamics, and specifically to:

- Define evacuation goals and evacuation success
- Identify the leading causes of injuries and fatalities for past wildfire evacuations and key risk factors based on these past incidents
- Identify current best practices and recommendations related to evacuation planning
- Identify and understand models and tools developed by other organizations and evaluate their application for use in Marin County

More than 50 scientific articles, reports, and documents were reviewed and synthesized as part of this literature review including peer review articles, incident reports such as those produced by CAL FIRE, incident status summary reports (ICS-209), evacuation planning documents, and policy briefs

[3] The Marin Wildfire Protection Authority (MWPA) is a newly formed 17-member Joint Powers Authority (JPA), created with the support of Marin County residents who passed Measure C in March 2020 with 70.8% voter approval. The MWPA was formed to develop and implement comprehensive wildfire prevention, mitigation, and emergency preparedness activities throughout almost all of Marin County, in coordination with its 17 local member agencies. One key element of MWPA's mission includes the improvement of evacuation routes for safe and orderly evacuation, which grounds the need for the evacuation route risk assessment project.

(examples include policy briefs written by the Transportation Research Board and Dr. Soga). A review of the literature of previous wildfire evacuation modeling studies and methods was performed to help inform the evacuation risk assessment that will be conducted for Marin. This review of current modeling methods and best practices provides insights into information gaps and opportunities to improve wildfire evacuation simulation and planning. The key findings from the collective body of literature are organized and documented in this report.

2. Background

Marin County is in the north San Francisco Bay Area in California. The county is approximately 520 square miles (332,800 acres) with a population of approximately 260,000 (United States Census Bureau, 2021) and is largely rural. It is bordered by Sonoma County to the north and east, the east San Francisco Bay Area to the southeast, San Francisco County to the south, and the Pacific Ocean on the west. Most of the county's population resides in the eastern, urban-developed region of the county along the Highway 101 corridor. The southern and western regions of the county (in and around Marin Headlands, Muir Woods, Mt. Tamalpais, Stinson Beach, and Pt. Reyes National Seashore) are popular tourist regions covered by hiking and cycling trails, parklands, and recreation areas. The northwestern portion of the county is mostly agricultural rangeland, which is home to large animals and livestock.

Approximately 60,000 acres (18% of Marin County's land area) falls within the WUI where homes and structures are adjacent to or intermixed with open space and wildland vegetation (**Figure 1**). Because of the mix and density of structures and natural fuels combined with limited access and egress routes, pre-fire preparation and evacuation planning are more complex. In Marin County specifically, many of the access and egress roads within the WUI are narrow and winding and are often on hillsides with overgrown vegetation, making it even more difficult and costly to reduce fire hazards and prepare for evacuation in these areas.

The anomalous fire behavior regimes experienced throughout California and the Pacific Northwest over the past decade have prompted agencies that handle fire operations and planning to rethink how wildland fires are managed, from both operational fire and evacuation management perspectives. Specifically, recent wildfires have raised awareness and increased governmental actions to improve evacuation capability. Perhaps no single fire event has heightened concern as much as the November 2018 Camp Fire, which destroyed the town of Paradise and killed 86 civilians. As cited by the California Legislature, "One reason the Camp Fire was so deadly was that the Town of Paradise lacked adequate evacuation routes to simultaneously allow residents to leave and public safety personnel to enter" (Senate committee on governance and finance, 2019).

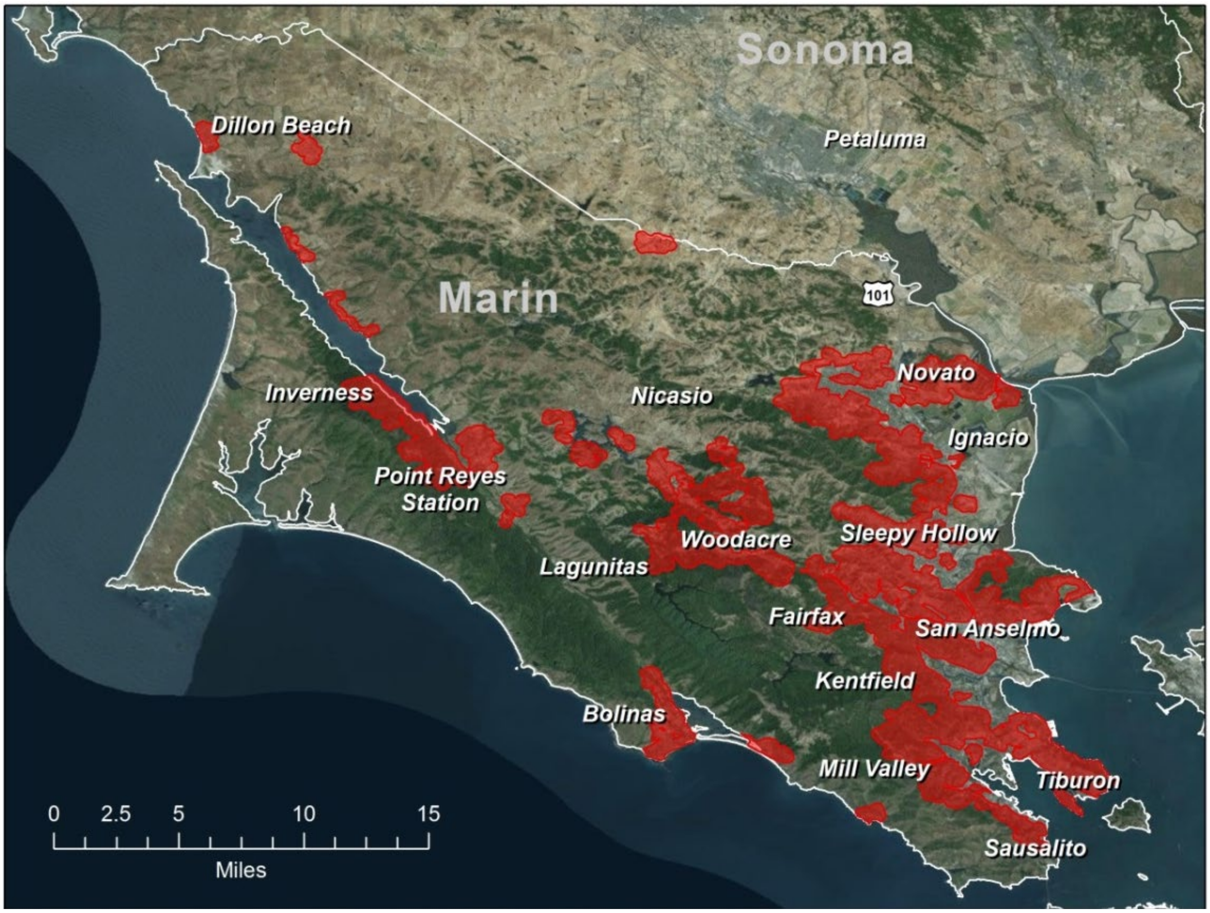


Figure 1. Map of Marin County and the wildland urban interface (WUI) boundaries (red).

In 2019, California enacted important laws following the Camp Fire. One of these was SB-99, which requires cities and counties to (1) identify residential areas without adequate exit routes for evacuation and (2) include mitigation measures in their general plans to overcome those issues. Another was AB 747, which requires local governments to plan evacuation route capacity needs under a range of emergency scenarios. These initiatives were built on previous government actions taken in the wake of the destructive 2017 wildfire season. For example, in 2018 the State Legislature passed SB 901 to help prevent catastrophic wildfires, SB 1260 to improve local fire hazard planning, AB 2911 to (among other things) identify at-risk subdivisions at least every five years, AB 1956 to establish local CAL FIRE grants, and SB 465 to improve financing available to help property owners protect against wildfires. All of these laws are intended to help local government agencies address the issue of evacuation route vulnerability.

The devastation resulting from the North Bay Fires of 2017, which occurred just north of Marin County, prompted local action. In April 2019, the Marin County Civil Grand Jury report on wildfire preparedness noted "the majority of Marin's population is concentrated along the Highway 101 corridor. Access from residential neighborhoods to the freeway is usually crowded, through narrow corridors, and often deliberately constricted. Some smaller communities in West Marin are situated along Highway 1, Sir Francis Drake Boulevard, and Novato Boulevard, the county's main east/west routes. These roads, and Highway 37, would be main evacuation routes to or from Highway 101 to escape a wildfire. None of these arteries is designed to accommodate mass evacuations." The Grand Jury made eight evacuation-related findings and developed a half dozen follow-up policy recommendations (Marin County Civil Grand Jury, 2019).

This literature review was focused on understanding the specific circumstances under which fatalities occur during wildfire evacuations, the risk factors that contribute to these circumstances, and how these factors are modeled. Evacuation dynamics are complicated and include physical and social risks. Physical risk factors include natural environmental and geographic characteristics that contribute to wildfire, such as topography, vegetation, weather, and burn probability. Physical risk factors also include anthropogenic environmental and geographic features, such as roadway characteristics, land use, and infrastructure, which affect risk at any given location. Social risk factors include demographic and behavioral parameters, such as age, ethnicity, and gender, which influence an individual's risk perception and personal actions. Modeling such a large variety of risk factors and data presents its own set of technical issues that need to be carefully examined to produce reliable model outputs. This document focuses on mitigation actions that have the greatest practical potential to reduce risk factors.

3. Wildfire Evacuation Goals and Success

The principal objective of a wildfire evacuation is to protect the public from the threat of wildfire without injury or death. Based on a review of the current literature, the goals for a manageable and successful evacuation in an ideal scenario include:

1. Immediate identification of wildfire threat and ongoing understanding of the fire's behavior
2. Timely and successful dissemination of evacuation alerts and communications
3. Timely and organized departure of residents and the public
4. Safe and efficient evacuation
5. Arrival at designated or pre-determined safe spaces unharmed

As shown in **Figure 2**, we have color-coded these five key goals and identified them as key determinants for evacuation success. We repeat this color scheme in other figures to share related information about each goal.

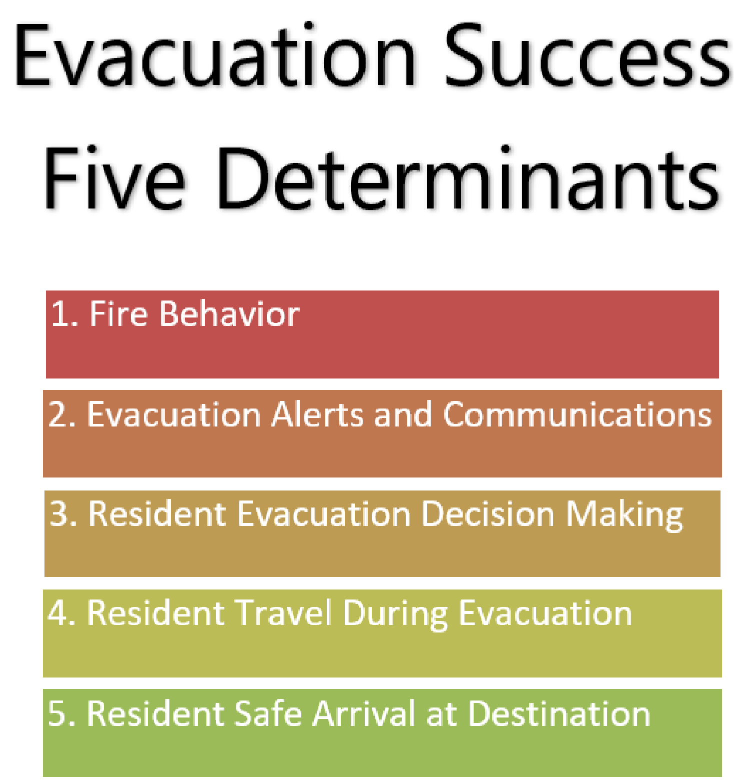


Figure 2. Color-coding scheme used to share information in the report about the key determinants to evacuation success.

Figure 3 expands on the framework provided in Figure 2 and summarizes the consensus of wildfire evacuation goals identified in the literature. Considering fire behavior, wildfire evacuation goals include (1) rapid identification of a wildfire threat or ignition and ongoing tracking of fire behavior, (2) deployment of resources, (3) assessment of potential fire behavior and spread, and (4) assessment of the likelihood of containment. If it is likely that a wildfire will exceed resources and spread quickly, emergency officials act rapidly to identify at-risk communities and issue timely, valid communication of risk with evacuation notices across multiple platforms. Identifying at-risk populations in advance of a wildfire event can allow officials time to plan evacuation assistance to populations in need. The goal of timely evacuation orders is to make residents aware so they can understand the risks, decide what to do, and begin to act. Once an evacuation begins, the goal is for evacuees to have ample time to safely evacuate beyond the threatened area, avoid traffic congestion, and avoid interference with emergency vehicle ingress. The final goal is to have all residents in a safe location until re-entry to the evacuated area is permitted. This includes minimizing the number of vehicles on the road network to avoid further road congestion in the instance that additional evacuations are ordered. Given the dynamics of past wildfires, the safe location may change as the event unfolds. Once at the designated safe space, effective management of people, resources, and communication is critical.

Regarding evacuation goals, research shows that evacuations are unpredictable and rarely proceed exactly as planned. In addition, the definition of evacuation success for emergency response agencies may differ from the public's definition of success. The definition of evacuation success for many response agencies and as defined in this document is *the safe relocation of people without injury or death*. The public's definition of success may be broader, more nuanced, and more focused on comfort and convenience. Planning, preparedness, and education that consider each of the determinants can help align agency and public definitions of success.

While planning should be aimed at achieving the evacuation goals such that everyone comfortably and calmly evacuates to safety, numerous variables of real-life situations make it possible to have a successful evacuation that falls short of the primary goals. Ingress and response to the fire may contribute to public perception and expectations of a successful evacuation, as the same agencies that manage an evacuation simultaneously respond to the fire. For example, during an evacuation, evacuees may be threatened by the fire but are able to shelter in a safe location without injury or death. Safe locations, such as buildings or spaces within the wildfire danger area that have ample hardening and defensible space for firefighting crews to protect, are intended to be used by emergency response staging as a last resort.

Public perception and opinion may be more influenced by the amount of evacuation notice given, quality of communication, the conditions during the evacuation, the conditions at the designated safe space, and the longer-term personal impact (including the time it takes to return home). While public perception is important, several of these factors are beyond emergency management personnel's control and are secondary to the success metric of safe relocation without injury or death.

Wildfire Evacuation Goals

Wildfire Threat Identified, Fire Behavior Tracked	• Ignition Detected • Resources Deployed • Fire Spread/Growth Estimated • Containment Projected • Ongoing Fire Behavior Tracked
Evacuation Alerts Initiated	• At-Risk Communities Determined • Evacuation Ordered • Communications Issued

Residents Depart in Timely, Organized Way	• Information Received
	• Decision Made to Stay or Go
	• Evacuation Method (Egress) Chosen
	    • Vehicle
	    • Bicycle
	    • Walk
	    • Transit

Evacuation Takes Place Safely and Efficiently	• Travel Begins to TRA*/Shelter or Beyond • Blocked Roadways and Collisions Avoided • Travel Occurs with Limited Stops • Obstructions Removed from Roads

Residents Arrive at Designated Safe Space	• Designated Location Beyond Evacuation Zone
	    • TRA/Shelter
	    • Beyond
	• Stable Information and Crowd Management

** TRA = temporary refuge area (temporary space inside or outside of the danger zone typically used as a short-term contingency measure for shelter when a safe space cannot be immediately accessed)*

Figure 3. Summary of wildfire evacuation goals identified in the literature.

4. Leading Causes of Civilian Fatalities During Evacuation

Analyses of recent wildfire incidents show that a combination of physical and social risk factors affect evacuation outcomes. An assessment of recent incidents involving injuries and fatalities (2013 Yarnell Hill Fire, 2016 Chimney Tops 2 Fire, 2017 Northern California Fires, 2018 Camp Fire, and 2022 McKinney Fire) indicate common themes in fire conditions, communications issues, and resulting traffic conditions. Namely, a combination of extreme fire behavior conditions, failures and/or delays in alerting and communications systems, and delays in evacuee departure all contributed to civilian injury and fatality in all cases.

- **2013 Yarnell Hill Fire, Arizona**. The 2013 Yarnell Hill Fire resulted in the death of 19 firefighters and involved a combination of extreme fire behavior and delays or failures in communication systems, including no direct line(s) to communicate and low perception of fire threat as compared to other fires burning during the same period (Hardy and Comfort, 2015).
- **2016 Chimney Tops 2 Fire, Tennessee**. The Chimney Tops 2 Fire occurred during a high-wind event, which contributed to extreme fire conditions. Over a span of four hours, the fire resulted in 14 fatalities, 191 injuries, 2,500 destroyed structures, and 14,000 residents evacuated. There were downed trees and power lines, widespread power loss, and major disruptions to communications systems, including wireless emergency alerts not being sent due to miscommunication between state and local agencies that caused delays in evacuation alerts and notification. Of the fatalities and injuries, many were due to last-minute evacuations or an inability to evacuate (Kuligowski et al., 2022).
- **2017 North Bay Fires, Northern California**. On October 8-9, 2017, under Red Flag[4] conditions, several fires ignited in the North Bay Area of California. The Tubbs, Atlas, Nuns, and Pocket fires burned in Sonoma, Napa, and Solano Counties, and collectively resulted in 31 civilian fatalities (NOAA, 2017). The weather conditions created extreme fire behavior with fast moving, wind-driven fires. Most fatalities occurred because people did not receive alerts and evacuation orders in time to evacuate safely and were overtaken by the fire before or as they were leaving their homes (The Press Democrat Staff, 2017).
- **2018 Camp Fire in Butte County, California**. The Camp Fire was the deadliest California fire in recent years with 85 confirmed civilian fatalities. Prior to the 2018 wildfire season, emergency response agencies had a detailed evacuation plan, residents were well-informed on wildfire risk, and communities had been engaging in evacuation exercises. However, given the

[4] A Red Flag Warning is issued by the National Weather Service when warm temperatures, very low humidity, and strong winds are expected to combine to produce an increased risk of fire danger (https://www.weather.gov/mqt/redflagtips).

weather and extreme fire conditions during the Camp Fire, all plans and protocols became overwhelmed. The loss of cell towers and the rollover of 911 calls to Chico, CA, had a major impact on evacuation. Some residents were unaware of the fire threat until the fire was close enough to see. Traffic congestion during the event was amplified due to limited traffic control resources. Several unplanned actions by emergency responders saved lives, including temporarily sheltering civilians inside of a newly built Walgreens and using bulldozers to clear obstructed roadways (Comfort et al., 2019; Comfort and Zhang, 2020).

- **2022 McKinney Fire in Siskiyou County, California**. The McKinney Fire burned in the Klamath National Forest in western Siskiyou County, CA, during July and August 2022. The fire was fast-moving, consumed more than 50,000 acres in less than 36 hours, burned through much of the unincorporated community of Klamath River, and caused four fatalities. Of the four fatalities, two occurred in separate residences and two occurred in a car located in a private driveway while a couple was trying to flee their home.[5]

Literature on the 2013 Yarnell Hill, 2016 Chimney Tops 2, 2017 Northern California, and 2018 Camp fires give examples of the compounding effects from physical and social risk factors. Extreme fire behavior due to weather and fuel conditions can overwhelm evacuation plans. Road quality and egress issues can also be affected in extreme fire scenarios, especially in cases with short notice, as communication is a key factor in wildfire evacuation. Unfortunately, communication infrastructure can be at physical risk from fire, and the capacity and reliability of these systems can be exceeded in an emergency. Chosen communication systems and information dissemination can also greatly impact risk perception and community response during an evacuation. It is important to note that the compounding effects of extreme fire behavior that overwhelm evacuation plans and result in last-minute communication often occur at night or during early-morning hours when people are sleeping and are less likely to receive the information.

Limited information exists on the specific causes and circumstances of civilian injury and death during evacuations. Based on a review of scientific literature, incident reports, and a summary of the ICS-209 report archive,[6] **the majority of recent civilian fatalities in the United States have occurred when people attempted to evacuate too late or chose not to evacuate and were overtaken by fire or smoke**. Based on the sources of data analyzed, most civilian fatalities occur in people's homes or on their property (outdoors, in the open air) as they attempt to flee. Very few civilian fatalities occur in enclosed automobiles on unobstructed roadways or in temporary safe locations used in contingency situations. Figure 4 shows the number and locations of civilian fatalities during the 2018 Camp Fire (Ramsey et al., 2020).

A study that analyzed data from bushfire-related fatalities in Australia from 1901-2011 (Blanchi et al., 2012) also confirms what data from the Camp Fire suggests. It is important to note that fire policy

---

[5] Information from multiple media outlets.

[6] ICS-209-PLUS is a dataset mined from the public archive (1999–2014) of the U.S. National Incident Management System/Incident Command System Incident Status Summary Form (a total of 124,411 reports for 25,083 incidents, including 24,608 wildfires). More information is available via https://data.nal.usda.gov/.

and management practices differ between the United States and Australia. In the United States, homeowners are generally expected to evacuate an area (egress) while emergency response professionals enter the area (ingress) to fight a fire. In Australia, homeowners are instructed to either "stay and defend or leave early" (SDLE) and training is provided to teach homeowners how to stay and defend. However, in both countries, **research on past fires suggests that the majority of civilian fatalities happen when people try to flee a fire area at the last minute** (McCaffrey et al., 2015).

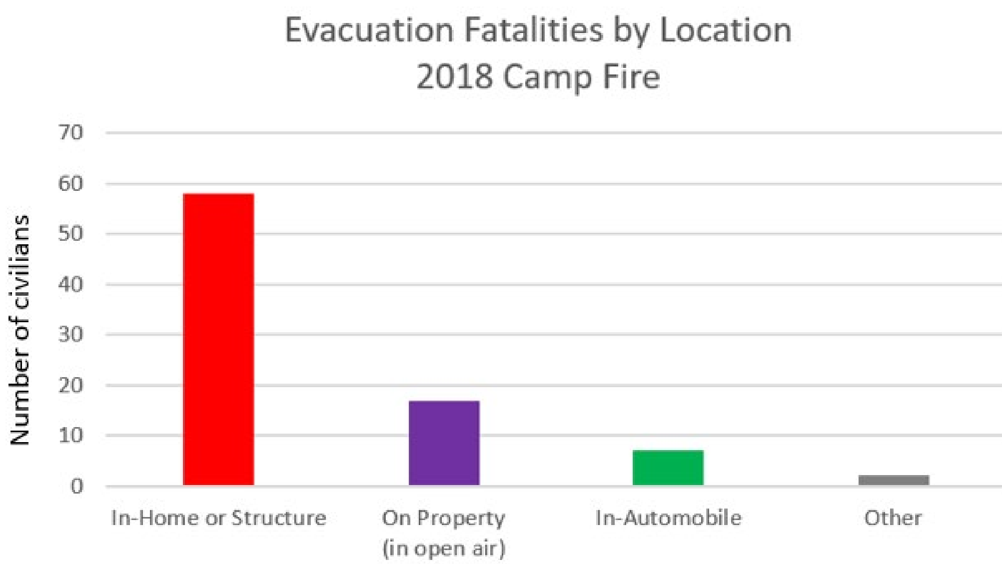


Figure 4. Civilian evacuation fatalities by location during the 2018 Camp Fire (Ramsey et al., 2020).

In addition to assessing the circumstances and locations of civilian fatalities, data from the Camp Fire were analyzed to understand the demographic and social risk factors that contributed to civilian fatalities. Table 1 shows the number and percent of civilian fatalities by age for the Camp Fire. Most civilian fatalities during the Camp Fire were individuals aged 65 and older (as shown in Table 1) who became trapped in their homes or on their properties for reasons including failure to receive alerts and evacuation orders, inability to mobilize due to lack of transportation or health condition, inability to perceive immediate threat, or decision to remain at home. This finding has important implications for Marin given the considerable proportion of older adults.

Table 1. Number and percent of civilian fatalities by age for the Camp Fire (Ramsey et al., 2020).

Age	Number of Fatalities	Percent of Total
65+	68	80%
46-64	13	15%
26-45	3	4%
0-25	1	1%
Total	85	100%

It is important to assess a community's **capacity to evacuate**, or the ability of population groups to easily mobilize, when planning for evacuation. Capacity to evacuate has been identified by fire department personnel as a key factor in several studies, including an evacuation study in Bolinas, CA. Evacuation planning should consider vulnerable population groups that may need extra evacuation assistance due to age, health condition, lack of transportation, or other factors that would limit a person/household's ability to evacuate.

In summary, studies of recent fires showed a combination of extreme fire behavior conditions, failures and/or delays in alerting and communications systems, and delays in evacuee departure contributed to civilian injury and fatality in all cases. Very few civilian fatalities occurred in enclosed automobiles on well-constructed, unobstructed roadways or in TRAs. In addition, most civilian fatalities happened when people tried to flee a fire area at the last minute.

5. Wildfire Evacuation Risk Factors

During a wildfire evacuation, there are numerous risk factors that can affect the outcome (**Figures 5 and 6**). Once a wildfire threat is identified, there is potential for extreme fire behavior that can supersede resources or planning (e.g., Camp, North Bay, and Yarnell Hill Fires). Factors such as communication method, information quality, and timing will have a major impact on community awareness and action. Human behavior is unpredictable, especially in high-stress situations and/or when people are unprepared. Once an evacuation order is sent, there are many considerations which may influence a resident's departure time, including the time it takes to make the decision to evacuate or to stay and defend. In most cases, evacuation is the safest option for residents even if the roadway is impacted by nearby fire or smoke. However, in extreme fire behavior conditions (suppression resources are outpaced by the rate of spread of the fire and wind-driven embers create spot fires far ahead of a fire front), there is always the potential that roadway obstruction, poor visibility, and/or traffic congestion will affect residents' ability to completely avoid danger during an evacuation. The risk factors shown in Figures 5 and 6 are discussed below.

Wildfire Evacuation Risk Factors

Extreme Fire Behavior	• Vegetation Species are Highly Flammable • Vegetation and Soil are Dry • Weather Conditions are Extreme (Wind, Temp, RH) • Home Hardening Insufficient • Fire Line Intensity • Burn Probability • Resources are Limited

Communications Insufficient or Delayed	• At-Risk Area is Uncertain
	• Information is Unclear
	• Language Barrier
	• Communication Tools are Down
	• Evacuation Order Does Not Reach All Populations
	    • Homeless
	    • Elderly
	    • Visitors/Tourist

Residents Depart Too Late	• Residents Do Not Start from Home
	• Seek Information Before Depart
	• Access to Transportation or Medical Assistance
	• Pets or Livestock
	• Demographics or Family Dynamics
	    • Age
	    • Ethnicity
	    • Number of Persons

Evacuees Exposed to Fire or Danger Enroute	• Routes Become Blocked • Lack of Information to Re-Route • Multiple or Erratic Stops on Route • Traffic Congestion or Collisions Prevents Egress • Destination Unknown • Not Enough Time to Avoid Danger

Congestion and Continued Risk	• Evacuees Return Home Too Soon
	• Evacuees Do Not Have Current Information
	• Road Congestion Persists on Evacuation Route
	    • Vehicles Still in Network
	    • Unknown or Multiple Destinations

Figure 5. Summary of wildfire evacuation risk factors.

Risk factor	References	References (continued)
Extreme Fire Behavior	• Hardy and Comfort, 2014 • Zhao and Wong, 2021 • Dye et al., 2021 • Seto et al., 2022 • Larsen et al., 2021	• Soga et al., 2021 • Pishahang et al., 2022 • Castro-Basurto et al., 2021 • Wahlqvist et al., 2021 • Haynes et al., 2020
Communications Insufficient or Delayed	• Comfort et al., 2021 • Grajdura and Niemeier, 2022 • Li et al., 2021 • McCaffrey et al., 2015 • Grajdura et al., 2022 • Soga et al., 2021 • Vickery et al., 2022	• Mehta et al., 2022 • McLennan et al., 2019 • Grajdura et al., 2021 • Pishahang et al., 2022 • Comfort et al., ?
Residents Depart Too Late	• Comfort et al., 2021 • Grajdura and Niemeier, 2022 • Kuligowski et a., 2022 • Zhao et al., 2022 • Zhao and Wong 2021 • Larsen et al., 2021 • Grajdura et al., 2022 • Soga et al., 2021 • Vickery et al., 2022 • Meta et al., 2022	• McLennan et al., 2019 • Grajdura et al., 2021 • Thompson et al., 2016 • Sebastian et al., 2001 • Rosenkoetter, 2007 • McGuire et al., 2007 • Bateman et al., 2017 • Pishahang et al., 2022 • Wahlqvist et al., 2021
Evacuees Exposed to Fire or Danger Enroute	• Comfort et al., 2021 • Grajdura and Niemeier, 2022 • Zhao and Wong 2021 • Dye et al., 2021 • Hsiao et al., 2022 • Grajdura et al., 2022 • Soga et al., 2021	• Wetterberge et al., 2021 • Pishahang et al., 2022 • Castro-Basurto et al., 2021 • Wahlqvist et al., 2021 • Fehr and Peers, 2021 • Haynes et al., 2020
Congestion and Continued Risk	• Grajdura and Niemeier, 2022 • Grajdura et al., 2022 • Na and Grace, 2022 • Vickery et al., 2022	

Figure 6. References to supporting literature for summary of wildfire evacuation risk factors in Figure 5.

Implications for Planning and Mitigation

It is not possible to prevent extreme weather conditions. However, it is important to understand where and when these hazards are elevated or converge to mitigate the risk of extreme fire behavior to the greatest extent possible. From an agency perspective, mitigation actions can include:

- Vegetation management along primary evacuation routes
- Creating strategically located fuel breaks
- Identifying pre-determined "safe spaces" to shelter in place
- Temporary modifications that improve traffic flow (such as contraflow)
- Pre-allocating increased emergency resources during forecasted high-threat conditions (i.e., Red Flag Warning)
- Effective and redundant communication to the public

5.1 Extreme Fire Behavior

The primary risk factor and threat to a successful evacuation is extreme and uncontrollable fire behavior in or near populated areas and along evacuation routes. In situations of extreme, wind-driven fires, it is possible for fires to spread very quickly. Often embers spread far ahead of the fire front, igniting spot fires miles downwind, which can merge and create a multi-fire complex that may expand into the WUI or suburban neighborhoods before people are able to evacuate.

Vegetation information, land use, community layout, road quality, weather conditions, topography, modeled fire behavior, burn probability, and fire return interval[7] are all commonly identified physical risk indicators in the literature for assessing evacuation vulnerability. Dye et al. (2021) used burn probability, fire return interval, fire line intensity[8], road data, and population data to develop wildfire evacuation vulnerability rankings for 696 rural communities in Oregon and Washington (United

[7] The number of years between two successive fires in a specified area. (https://www.fs.usda.gov/database/feis/glossary2.html#FireInterval)

[8] The rate of heat release per unit time per unit length of fire front. Numerically, the product of the heat of combustion, quantity of fuel consumed per unit area in the fire front, and the rate of spread of a fire, expressed in kW/m. (https://www.fs.usda.gov/database/feis/glossary2.html#:~:text=fireline%20intensity%3A,kW%2Fm%20%5B83%5D)

States Forest Service, 2022). The results showed that the most vulnerable towns with the poorest road networks have the highest wildfire evacuation vulnerability rankings.

Physical risk mitigation strategies have also been assessed in recent literature. A case study for the 2018 Camp Fire performed by Seto et al. (2022) found that fuel breaks can be effective at increasing available evacuation time. Furthermore, in this case study, increasing the width of the fuel break from 200 meters to 400 meters doubled the available evacuation time. Soga et al. (2021) performed case studies for the towns of Paradise in Butte County and Bolinas in Marin County and found extreme fire spread combined with ember spread can derail existing evacuation plans and may cause multiple towns to evacuate simultaneously. The study recommends safe shelters in case evacuation is not a viable option. The study also found that, for the scenarios modeled, contraflow reduced the amount of time that people were exposed to fire in their vehicles, and redundancy in communication to the public is key.

5.2 Communications are Delayed or Insufficient

To initiate an evacuation, an evacuation order must reach residents. People use different communication systems and sources to receive information (e.g., cellular phones, landline telephones, VOIP, the internet, social media, etc.), which creates a challenge for issuing emergency alerts and ensuring the alerts are received. To compound this issue, during extreme fire weather conditions, California utilities often issue preemptive Public Safety Power Shutoffs (PSPS) to minimize the risk of electrical lines igniting fires. Failures in the communication infrastructure are the primary risk factors related to communications systems. These include power outages, downed cellular towers, and delayed or insufficient communications that do not reach all intended recipients. Complications and failures in communication systems have been shown to be one of the most impactful risk factors during wildfire evacuations (e.g., Camp, North Bay, Chimney Tops 2, and Yarnell Hill fires). Communication systems and methods should cover multiple platforms in case any single system fails.

5.2.1 Timeliness

Timely communications require fast and precise identification of communities that are at risk. If an evacuation area is determined too late, residents may not have enough time to evacuate safely. Similarly, if the evacuation area is too large because of an overabundance of caution, evacuation routes may become oversaturated, resulting in evacuees being exposed on roadways for extended periods of time and shelter resources becoming overwhelmed. The decision to issue an evacuation warning or order is therefore critical.

The information provided during an evacuation order must reach residents through multiple channels. Some populations are at increased risk of being caught unaware in a wildfire evacuation, such as elderly and homeless populations that may have limited access to technology. Also, tourists and visitors are common in both populated and wilderness areas of Marin County, and may not be familiar with wildfire risks and evacuation alert systems. Delayed notification due to technology disruptions or single-method announcements can prevent awareness of a wildfire threat.

5.2.2 Content of the Alert

The quality of the alert content and communication channel have a significant impact on individual response. A survey-based study in Australia by Mehta et al. (2022) found that receiving a warning was the most important cue for evacuation. McLennan et al.'s (2019) literature review for North America and Australia covering 2005-2017 found that residents will take steps to look for more information if communicated alerts are not detailed enough. Specifically, it is important that alerts contain location-specific information, graphics that occur frequently, and repetitive messaging from an authoritative and trusted source for the threat to be perceived as real. Adding behavior inputs (specific protective actions with rationale) to warnings distributed through social media channels enhanced the clarity of the message and prompted action. Clear and actionable messaging prompted people to evacuate immediately, decreased departure time, reduced the intention to return home, and decreased the intention to shelter at home. Inclusion of a color-block visual aid also helped to increase message clarity.

The key takeaway here is that if communications are unclear or lack actionable information, residents will seek additional information before acting. Residents may also wait for information from a more trusted source or wait until they see fire cues like smoke, embers, flames, and/or heat if messaging is ambiguous or unauthoritative.

5.2.3 Communication through Multiple Channels

In addition to traditional emergency alerting systems (e.g., AlertMarin, Nixle, etc.), Li et al. (2021) assessed the use of social media to disseminate evacuation information. An analysis of tweets during the 2020 wildfire evacuations in the United States Pacific Northwest determined the times and locations of the tweets to be generally consistent with official information. The most popular social media users tended to dominate the information dissemination and prompted reactions from other users. Real-time broad outreach with social media proved to be a good tool for disseminating evacuation information if the information was repetitive and originated from an authoritative, trusted source.

Implications for Planning and Mitigation

Timeliness: During a wildfire event, disseminating information that is clear and actionable repeatedly throughout an event has been shown to be effective.

Content of the Alert: Location-specific information, graphics that occur frequently, and repetitive messaging from a known and trusted source is important for the threat to be perceived as real. Adding behavior inputs (specific protective actions with rationale) to warnings enhance the clarity of the message and prompt action.

Communication through Multiple Channels: It is important to educate the public on the different emergency notification systems and platforms and their intended purpose prior to an emergency event. During a wildfire event or periods of extreme fire weather, informing the public of potential power outages may prompt them to consider methods of receiving information that do not require power, such as weather radios. Weather radios are battery powered or have an emergency crank, so they can operate without electricity. Social media channels have shown to be an effective mechanism for disseminating information during an emergency if the information is from a reliable source.

5.3 Residents Depart Too Late

The majority of recent civilian fatalities in the U.S. have occurred when residents evacuated at the last minute or chose not to evacuate and were overtaken by fire or smoke. Once a resident is aware of an evacuation order, they make the decision to stay or to leave. There are numerous social risk factors associated with making this decision, including demographics (age, ethnicity, gender), family status, income, length of residence, prior home hardening, and owning pets or livestock. These combined factors contribute to personal risk perception.

Many physical, time-based factors also affect an individual's response to an evacuation order, including awareness time (the time a resident becomes aware of the need to evacuate), preparation time (the time it takes for a resident to decide to leave and prepare), departure time (the time it takes for a resident to leave their home), and arrival time (the time it takes to arrive at a safe space and leave the road network).

5.3.1 Social Economic Factors Informing the Decision to Evacuate

The decision to evacuate is affected by socio-demographics. Grajdura et al.'s (2021) case study of the 2018 Camp Fire found that people who were white and had an annual income greater than $50,000 generally had shorter awareness times. Residents with access to a smartphone also generally had shorter awareness times. Conversely, residents 65 and older generally experience a longer awareness time.

Households with children were approximately two times more likely to evacuate than households without children, and households with pets were less likely to evacuate overall. Bateman and Edward's (2017) survey of 1,050 households effected by 1998 Hurricane Bonnie found that women are more likely to evacuate than men. Thompson et al.'s (2016) review of 83 articles on natural disaster evacuations found that households with elderly and/or disabled residents were less likely to evacuate, and larger households took longer to evacuate. Thompson et al. (2016) also found differences among ethnic groups and their likelihood to evacuate. For example, white individuals were more likely to evacuate than black individuals, who reported greater intent to evacuate in a future disaster, but were less likely to evacuate in an actual disaster. Hispanic individuals were more likely than other ethnicities besides white individuals to evacuate in an actual emergency. Using geographic data from Sonoma County during the 2019 Kincade Fire evacuation, a study by Zhao et al. (2022) found that the percent of people who evacuated varied widely by census tract.

5.3.2 Preparation Time

The time needed to prepare for departure is influenced by multiple factors. Unprepared residents may take more time to depart because they are doing things like packing items before leaving their homes.

Implications for Planning and Mitigation

Understanding the socio-demographic factors that influence decision-making tendencies can help agencies develop more targeted and effective evacuation outreach campaigns to reach diverse audiences. Analyzing census and demographic data can also help agencies identify areas with population groups that may be less likely to evacuate or may need assistance during an evacuation, and plans can then be developed to provide support to these groups.

5.3.3 Departure Time

Grajdura et al.'s (2021) case study of the 2018 Camp Fire also found that familiarity with local evacuation protocols and preparedness led to faster departure times, while males and residents who had been living in their homes for 15 years or longer generally had longer departure times.

5.3.4 Arrival Time

Evacuation destination and arrival time are largely dependent on a person's social network. People with family and/or friends nearby generally travel shorter distances to their destinations.

5.3.5 Decision to Stay

Even if a wildfire evacuation is ordered (which is mandatory by law to follow in Marin) and communications are timely, some residents may choose to stay and shelter in place. The McCaffrey et al. (2015) analysis of resident response to evacuation orders with data collected for Ventura County, CA, Santa Barbra County, CA, and Santa Fe, NM, found that some residents felt it was their 'duty' to stay and protect their home. However, not all were well prepared to do so. In the 2018 Woolsey Fire, some volunteers decided to 'stay and defend' and become active participants in firefighting. The Jensen et al. (2019) study found there will always be residents and volunteers who emerge in this manner during wildfire scenarios, and emergency response should anticipate and plan for these groups.

5.4 Evacuees Exposed to Danger Enroute and/or Traffic Congestion Persists

Smooth traffic flow is key to reducing the exposure of evacuees to danger enroute to safety. The key risk factors (Figure 5) that impede smooth traffic flow include obstruction or blockage of key evacuation routes; lack of information for people to reroute themselves if needed; multiple trips or erratic driving; vehicle collisions and/or extremely heavy traffic; lack of knowledge of safe sheltering destinations; and lack of adequate time to avoid danger.

Several studies have examined the best practices for facilitating traffic flow during evacuations. A study by Zhao et al. (2021) used traffic simulation combined with survey accounts of the 2017 Northern California, 2017 Southern California, and 2018 Carr fires, and found that reducing the number of evacuating vehicles, increasing GPS-based rerouting, and phasing or staging evacuation orders can be effective at improving traffic flow. A study by Wong et al. (2021a) assisted the town of Kensington, CA, with the development of an actionable evacuation plan to help mitigate physical risk factors in and around the WUI. As part of the study, Wong et al. reviewed literature, maps, and other documentation, performed a field study, and ran traffic model simulations. The results of the assessment suggested the following improvements to ease congestion and speed traffic flow:

- Reduce the number of pinch points by increasing road width and/or vegetation clearance where possible
- Consider street parking limitations permanently or on Red Flag days
- Consider one-way travel directions on narrow two-lane roads on Red Flag days
- Reduce parking at key intersections
- Manage underbrush and trees on narrow roads
- Deploy traffic coordinators at key intersections during evacuation events
- Improve overall signage on evacuation routes
- Establish gathering spots with high-capacity parking
- Educate and engage the community
- Encourage evacuees to use main roads during an evacuation

Chen et. al. (2021) completed a modeling study on Mill Valley, CA, to support traffic management improvements. This work found that policies such as contraflow, removing traffic lights, forbidding lane changes, implementing detours, and changing exit routes during an evacuation event can reduce the amount of time required to evacuate a community.

Implications for Planning and Mitigation

Vegetation management, roadside clearance, and parking limitations along winding, narrow roads are all preemptive measures that can be taken to improve egress/ingress routes and traffic flow in WUI environments. Improved signage along evacuation routes can aid evacuees and help improve traffic flow. Actions can be taken during periods of high fire danger (i.e., Red Flag days) to ensure roadways are clear and available for egress/ingress, including designating one-way travel directions on narrow two-lane roads and reducing parking at key intersections and roadways. Planning for strategic, active traffic management and allocating increased resources during an evacuation event has the potential to reduce the amount of time required to evacuate a community.

6. Current Modeling Studies

Several research groups have recently conducted evacuation modeling studies and/or have developed evacuation modeling software tools (**Table 2**). The studies reviewed include the physical and social risk factors discussed throughout this report and how these risk factors can influence evacuation simulations and arrival times to safe destinations. While in some ways the modeling schemes are conceptually similar, the underlying data and application of the model results vary significantly. The model developed by Chen et al. (2020) and applied in Mill Valley considers the impacts of changes in traffic management strategies during an evacuation. However, aside from the work by Chen et al., none of the other models in Table 2 were developed to assess the impact of mitigation projects.

Four main modeling deficiencies in current evacuation modeling practices have been identified through this literature review: (1) lack of accounting for visitor and tourist populations; (2) lack of accounting for evacuees without access to vehicles; (3) assumption that evacuees will chose the shortest, most direct route and will reroute themselves if/when needed; and (4) assumption of adequate emergency staff and resources to aid in directing traffic during an evacuation.

Table 2. Summary of the modeling studies reviewed as part of this literature review.

Location, Study Name, Citation	Description	Application/Purpose(s)
Mill Valley. "Simulation pipeline for traffic evacuation in urban areas and emergency traffic management policy improvements through case studies." Chen et al., (2020)	To support the development of traffic management policy improvements, Chen et al. (2020) built a traffic simulation pipeline to model travel demand, vehicle behavior, and identify bottlenecks in the roadway during evacuation. The pipeline was applied during case studies in Paradise and Mill Valley, CA. In Mill Valley, the model was applied specifically to assess the effectiveness of different traffic management actions, including contraflow, removing traffic lights, forbidding lane changes, implementing detours, and changing exits. The analysis found that new traffic management policies can substantially reduce the amount of time required to evacuate a city.	Assess the effectiveness of traffic management policy improvements Test the application of new Google technologies
Paradise and Bolinas Case Study Analysis Soga et al., (2021)	Soga et al. (2021) performed evacuation case studies for Bolinas and Paradise, CA, using the communications and traffic models developed by researchers at UC Berkeley. Extensive scenario analysis led to three key conclusions and recommendations. (1) Fast-moving fires can frequently lead to no-notice evacuations without sufficient time to execute pre-planned evacuation strategies. (2) Damages to the communications system should be considered, especially for communities with low redundancy in their evacuation order dissemination system or those that rely on regional collaborations. Actions such as sending out evacuation orders, coordinating contraflow operations, and adjusting signal timing along an evacuation route may not be easily achievable with disruptions to the communications infrastructure. (3) The effectiveness of evacuation strategies is context-specific. Dedicated investigations, modeling analysis, and drills should be carried out to identify local bottlenecks and unique evacuation characteristics.	Assess the contributing factors to evacuation success Determine strategies for evacuation planning

Location, Study Name, Citation	Description	Application/Purpose(s)
Rancho Cucamonga. “Rancho Cucamonga Evacuation Assessment.” Fehr and Peers (2021)	The Fehr and Peers 2021 evacuation assessment for Rancho Cucamonga evaluated travel distance and the time needed to get from evacuation areas to safe locations based on Fehr & Peers EVAC+ tool. The results were used to provide information to help inform the ongoing Rancho Cucamonga General Plan Update (especially related to network redundancy and connectivity) in addition to meeting the legislative requirements associated with SB 99 and AB 747. The results showed that areas with only one egress route have (1) the farthest distance to travel in an evacuation, (2) the highest number of dead-end roads, (3) are closest to the WUI and historical fire perimeters, and (4) are at-risk from multiple natural hazards.	To inform the Rancho Cucamonga General Plan Update (especially related to network redundancy and connectivity) and meeting the legislative requirements associated with SB 99 and AB 747
PG&E Service Area. “Wildfire Egress Model and Simulation Platform (WISE).” Pishahang et al. (2022)	The Pishahang et al., 2022, WISE model platform was developed for Pacific Gas & Electric (PG&E) and includes a fire model, human decision model, and traffic model to evaluate the time it takes a wildfire to reach a community border and the time the community needs to safely evacuate. The model was developed to assess evacuation times based on different socio-demographic characteristics. The underlying population and socio-demographic data considers the Center for Disease Control’s Social Vulnerability Index. This model does not include topography, intermediate stops, multiple shelter destinations, time of day, or other modes of transportation.	Modeling WUI evacuation for planning and decision-making Assessment of vulnerable populations during different evacuation scenarios
WUI Communities. “The simulation of wildland-urban interface fire evacuation: The WUI-NITY platform.” Wahlqvist et al. (2021)	The Wahlqvist et al., 2021, WUI-NITY platform is built using Unity3D game engines, virtual reality (VR) capabilities, simulated human behavior, and simulated wildfire spread during evacuations using three coupled models: fire, pedestrian, and traffic. The model outputs the number of vehicles arriving at their final destination, at each roadway segment over time, and not yet at the final destination, as well as evacuation time curves for each destination, number of remaining residents, and traffic density over time. The model output indicates when an evacuation order should be initiated based on the movement of the fire.	Used to determine when to initiate an evacuation based on the location and movement of a fire

6.1.1 Short-Term Visitors

Recent modeling studies do not include some population groups that could be important to consider for evacuation planning. Specifically, none of the studies reviewed consider short-term visitors or tourists in their evacuation assessments. In many areas, this may not pose an issue when modeling evacuation dynamics. However, in a normal travel year, Marin County sees 12-14 million visitors (Marin Convention and Visitors Bureau, 2021). In the context of evacuation planning, tourists visiting Marin tend to park in neighborhoods or alongside narrow roadways while recreating, which can create egress and ingress issues during a wildfire emergency and evacuation. During an evacuation, tourists will add more vehicles to the roadways, likely in rural areas where roadways are narrow and already congested during normal travel conditions.

6.1.2 Evacuees Lacking Vehicle Access

Most previous literature and modeling studies do not account for evacuees without vehicle access, despite many reports of people evacuating by public transit, bicycle, or on-foot. These transportation modes should be accounted for in both planning and in evacuation modeling, especially in certain areas where a large portion of people do not have access to vehicles, such as low-income areas, hospitals, colleges or universities, elderly facilities, and homeless-serving institutions.

6.1.3 Evacuation Route Selection

In previous implementations of traffic models, the models assume evacuees take the shortest, most direct route to safety and will reroute themselves if/when needed. Surveys show that evacuees often make several stops during an evacuation and may not have immediate access to re-routing information. Local residents may also take less direct routes if they are familiar with the local road network. This is a limitation of previous modeling that can greatly impact the modeling results.

6.1.4 Traffic Management Resources

Most modeling studies assume an adequate number of emergency staff and resources are available to aid in directing traffic away from blocked roadways and at major intersections. Previous case studies determined there is often a lack of personnel available to provide these services. Case studies have shown that a lack of available and coordinated resources can negatively impact evacuation efficiency and vice-versa. This is especially true for traffic models, where most assume there are personnel to re-direct evacuees from debris and facilitate traffic flow at large intersections. Case studies show it is important to consider resource allocation in scenario modeling and planning.

7. Summary of Mitigation Implications

Key considerations for planning and mitgation actions include the following.

Extreme Conditions

It is not possible to prevent extreme weather conditions. However, it is important to understand where and when these hazards are elevated or converge to mitigate the risk of extreme fire behavior to the greatest extent possible. From an agency perspective, mitigation actions can include

- Vegetation management along primary evacuation routes
- Creation of strategically-located fuel breaks
- Identification of pre-determined "safe spaces" to shelter in place
- Temporary modifications to improve traffic flow (such as contraflow
- Pre-allocation of increased emergency resources during forecasted high-threat conditions (i.e., Red Flag Warning)
- Effective and redundant communication to the public

Communications

Key elements for communications include early notification and alerts, timeliness, the method of communication, and messaging.

Early Notification and Alerts: Early notification and alerts can provide residents with enough time to evacuate safely.

Timeliness: During a wildfire event, repeatedly disseminating information that is clear and actionable throughout an event has been shown to be effective.

Communication through Multiple Channels: It is important to educate the public on the different emergency notification systems and platforms and their intended purpose prior to an emergency event. During a wildfire event or periods of extreme fire weather, informing the public of potential power outages may prompt them to consider methods of receiving information that do not require power, such as weather radios. Weather radios are battery powered or have an emergency crank, so they can operate without electricity. Social media channels have shown to be an effective mechanism for disseminating information during an emergency if the information is from a reliable source.

Content of the Alert: Location-specific information, graphics that occur frequently, and repetitive messaging from a known source are all important for the threat to be perceived as real.

Resident Departure

Understanding the socio-demographic factors that influence individuals' decision-making can help agencies develop more targeted and effective evacuation outreach campaigns to reach diverse audiences. Analyzing census and demographic data can also help agencies identify areas with population groups that may be less likely to evacuate or may need assistance during an evacuation, and plans can then be developed to provide support to these groups.

Evacuee Exposure and Traffic Congestion

Vegetation management, roadside clearance, and parking limitations along winding, narrow roads are all preemptive measures that can be taken to improve egress/ingress routes and traffic flow in WUI environments. Improved signage along evacuation routes can aid evacuees and help improve traffic flow. Actions can be taken during periods of high fire danger (i.e., Red Flag days) to ensure roadways are clear and available for egress/ingress, including designating one-way travel directions on narrow two-lane roads and reducing parking at key intersections and roadways. Planning for strategic, active traffic management and allocating increased resources during an evacuation event has the potential to reduce the amount of time required to evacuate a community.

8. Citations

Bateman J. and Edwards B. (2017) Gender and evacuation: a closer look at why women are more likely to evacuate for hurricanes. *Natural Hazards and Earth System Sciences*, 89(6), 1461-1483, doi: https://link.springer.com/article/10.1007/s11069-017-3033-x.

Belleville G., Ouellet M.-C., Lebel J., Ghosh S., Morin C.M., Bouchard S., Guay S., Bergeron N., Campbell T., and MacMaste F.P. (2021) Psychological symptoms among evacuees from the 2016 Fort McMurray wildfires: a population-based survey one year later. *Public Health Nursing*, doi: 10.3389/fpubh.2021.655357.

Beloglazov A., Almashor M., Abebe E., Richter J., and Steer K.C.B. (2016) Simulation of wildfire evacuation with dynamic factors and model composition. *Simulation Modelling Practice and Theory*, 60, 144-159. Available at http://www.elsevier.com/locate/simpat.

Blanchi R., Leonard J., Haynes K., Opie K., James M., Kilinc M., Dimer de Oliveira F., and van den Honert R. (2012) Life and house loss database description and analysis. Final report prepared for the Attorney-General's Department for Bushfire CRC, CSIRO EP-129645, December.

Castro-Basurto K., Jijon-Veliz F., Medina W., and Velasquez W. (2021) Outside dynamic evacuation routes to escape a wildfire: a prototype app for forest firefighters. *Sustainability*, 13, 7295, doi: 10.3390/su13137295.

Chen Y., Shafi S.Y., and Chen Y.-f. (2020) Simulation pipeline for traffic evacuation in urban areas and emergency traffic management policy improvements through case studies. *Transportation Research Interdisciplinary Perspectives*, 7, 100210. Available at https://www.journals.elsevier.com/transportation-research-interdisciplinary-perspectives.

Cirillo C., Nejad M., Erdogan S., and Chavis C. (2020) E3: evaluating equity in evacuation: a practical tool and a case study. Final report prepared for the Urban Mobility and Equity Center, Morgan State University, Baltimore, MD, February.

Comfort L., Soga K., Stacey M., McElwee M., Ecosse C., Dressler J., and Zhao B. (2019) Collective action in communities exposed to recurring hazards, the Camp Fire, Butte County, California, November 8, 2018.

Comfort L.K., Mosse D., and Znati T. (2009) Managing risk in real time: integrating information technology into disaster risk reduction and response. *Commonwealth*, 15(1), 27-46, May.

Comfort L.K. and Zhang H. (2020) Operational networks: adaptation to extreme events in China. *Risk Analysis*, 40(5), 981-1000, doi: 10.1111/risa.13442.

Comfort L.K., Soga K., McElwee M., and Zhao B. (2021) Collective action in communities exposed to recurring hazards: the Camp Fire, Butte County, California,November 8, 2018. *International Journal on Advanced Science Engineering Information Technology*, 11(4).

Demuth J., et al. (2022) Longitudinal analysis of hurricanes Laura and Marco Part II: public risk perceptions and protective behaviors. *American Meteorological Society 102nd Annual Meeting, Houston, January 26, 2022*. doi: https://ams.confex.com/ams/102ANNUAL/meetingapp.cgi/Paper/398985.

Dye A.W., Kim J.B., McEvoy A., Fang. F., and Riley K.L. (2021) Evaluating rural Pacific Northwest towns for wildfire evacuation vulnerability. *Natural Hazards*, 35(3), 1393-1418, doi: https://doi.org/10.1007/s11069-021-04615-x.

Fehr and Peers (2021) Rancho Cucamonga Evacuation Assessment. Prepared for the city of Rancho Cucamonga, October 7.

Firescope California (2013) Wildland urban interface (WUI) Structure Defense (October 21).

Folk L.H., Kuligowski E.D., Gwynne S.M.V., and Gales J.A. (2019) A provisional conceptual model of human behavior in response to wildland-urban interface fires. *Fire Technology*, 55, 1619-1647.

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

Grajdura S., Borjigin S., and Niemeier D. (2022) Fast-moving dire wildfire evacuation simulation. *Transportation Research Part D*, 104, 103190.

Grajdura S. and Niemeier D. (2022) Inequities & injustices in large-scale California wildfire evacuations & post-evacuations. *Social Science Research Network*, doi: http://dx.doi.org/10.2139/ssrn.4022006.

Hall A., McLennan J., Marques M.D., and Bearman C. (2022) Conceptualising and measuring householder bushfire (wildfire) risk perception: the householder bushfire risk perception scale (HBRPS-4). *Intnernational Journal of Disaster Risk Reduction*, 67, 102667. Available at www.elsevier.com/locate/ijdrr.

Hardy K. and Comfort L.K. (2015) Dynamic decision process in complex, high-risk operations: The Yarnell Hill Fire, June 30, 2013. *Safety Science*, 71, 39-47.

Hasan S. and Rahman R. (2019) Assessing crash risks of evacation traffic: a simulation-based approach. Prepared for SAFER-SIM University Transport Center, December. Available at https://rosap.ntl.bts.gov/view/dot/56082.

Heath S.E., Kass P.H., Beck A.M., and Glickman L.T. (2001) Human and pet-related risk factors for household evacuation failure during a natural disaster. *Am. J. Epidemiol.*, 153(7), 659-665, doi: https://doi.org/10.1093/aje/153.7.659.

Herbert N., Gabrielle W.-P., Morss R.E., and Demuth J.L. Information seeking, uncertainty, and efficacy in the face of an evolving hurricane threat. *American Meteorological Society 102nd Annual Meeting,Houston, Jan. 26, 2022*, doi: https://ams.confex.com/ams/102ANNUAL/meetingapp.cgi/Paper/392786.

Hsiao, C.-C, Sun, M.-C, Chen, A.Y., Hsu, Y.-T., and Chen A. (2022) Location problems for shelter-in-place deployment: a case study of vertical evacuation upon dam-break floods. *International Journal of Disaster Risk Reduction*, 57, 102048.

Jensen S.J., Feldmann-Jensen S., and Woodworth B. (2019) Resilience under fire: protective action, attitudes, and behaviors evidenced in the 2018 Woolsey Fire. Prepared for the Natural Hazards Center Quick Response Grant Report Series by the Natural Hazards Center, University of Colorado, Boulder, CO. Available at https://hazards.colorado.edu/quick-response-report/resilience-under-fire.

Katzilieris K., Vlahogianni E.I., and Wang H. (2022) Evacuation behavior of affected individuals and households in response to the 2018 Attica wildfires: from empirical data to models. *Safety Science*, 153, 105799. Available at https://www.elsevier.com/locate/safety.

Kuligowski E. (2021) Evacuation decision-making and behavior in wildfires: past research, current challenges and a future research agenda. *Fire Safety Journal*, 120, 103129. Available at http://www.elsevier.com/locate/firesaf.

Kuligowski E.D., Walpole E.H., Lovreglio R., and McCaffrey S. (2020) Modelling evacuation decision-making in the 2016 Chimney Tops 2 fire in Gatlinburg, TN. *International Journal of Wildland Fire*, 29, 1120–1132, doi: 10.1071/WF20038.

Kuligowski E.D., Zhao X., Lovreglio R., Xu N., Yang K., Westbury A., Nilsson D., and Brown N. (2022) Modeling evacuation decisions in the 2019 Kincade fire in California. *Safety Science*, 146, 105541.

Larsen L.N.D., Howe P.D., Brunson M., Yocom L., and et al. (2021) Risk perceptions and mitigation behaviors of residents following a near-miss wildfire. *Landscape and Urban Planning*, 207, 104005.

Li L., Ma Z., and Cao T. (2021) Data-driven investigations of using social media to aid evacuations among Western United States wildfire season. *Fire Safety Journal*, 126, 103480.

Maranghides A., Link E., Mell W.R., Hawks S., Wilson M., Brewer W., Brown C., Vihnaneck B., and Walton W.D. (2021) A case study of the Camp Fire–fire progression timeline. Technical Note prepared for

National Institute of Standards and Technology, Boulder, Colorado, 2135, doi: 10.6028/NIST.TN.2135.

Marin Convention and Visitors Bureau (2021) 2021 Marin annual report. Available at https://adobeindd.com/view/publications/72a378c5-5613-4d2f-95e7-ea174a440901/udjd/publication-web-resources/pdf/Program_of_Work_2021.pdf.

Marin County Civil Grand Jury (2019) Wildfire preparedness: a new approach. Final report, April. Available at https://www.marincounty.org/depts/gj/reports-and-responses/reports-responses/2018-19/wildfire-preparedness-a-new-approach.

McCaffrey S., Rhodes A., and Stidham M. (2015) Wildfire evacuation its alternatives: perspectives from four United States communities. *International Journal of Wildland Fire*, 24, 170-178, doi: http://dx.doi.org/10.1071/WF13050.

McGuire L., Ford E., and Okoro C. (2007) Natural disasters and older US adults with disabilities: implications for evacuation. *Disasters*, 31(1), 49-56, doi: https://doi.org/10.1111/j.1467-7717.2007.00339.x.

McLennan J., Ryan B., Bearman C., and Toh K. (2019) Should we leave now? Behavioral factors in evacuation under wildfire threat. *Fire Technology*, 55, 487–516, doi: https://doi.org/10.1007/s10694-018-0753-8.

Mehta A.M., Murray S., McAndrew R., Jackson M., and Tippett V. (2022) Encouraging evacuation: The role of behavioral message inputs in bushfire warnings. *International Journal of Disaster Risk Reduction*, 67, 102673.

Na H.S. and Grace R. (2022) Influence of social networks and opportunities for social support on evacuation destination decision-making. *Safety Science*, 147, 105564.

Nara A. and Tsou M.-H. (2021) *Empowering human dynamics research with social media and geospatial data analytics*, Springer Cham, doi: 10.1007/978-3-030-83010-6.

NOAA October 2017 North Bay Fires: looking back to one of California's most destructive series of wildfires. Produced by National Oceanic and Atmospheric Administration (NOAA), National Weather Service (NWS), San Francisco Bay Area Weather Forecast Office (WFO MTR). Available at https://noaa.maps.arcgis.com/apps/Cascade/index.html?appid=790ba363d4e74c77a94d861a7dd533fe.

Palsa E., Bauer M., Evers C., Hamilton M., and Nielsen-Pincus M. (2022) Engagement in local and collaborative wildfire risk mitigation planning across the western U.S.—evaluating participation and diversity in Community Wildfire Protection Plans. *PLoS ONE*, 17(2), e0263757, doi: 10.1371/journal.pone.0263757.

Pishahang M., Droguett E., Ramos M., and Mosleh A. (2022) Wildfire egress model and simulation platform. Report prepared for PG&E, San Francisco, CA, GIRS-2022-03, doi: 10.34948/G4159S.

Ramsey M.L., Murphy M., and Diaz J. (2020) The Camp Fire public report: a summary of the Camp Fire investigation. Report prepared by Butte County District Attorney, Oroville, California.

Rosenkoetter M., Krassen E., Cobb B.K., Bunting S., and Weinrich M. (2007) Perceptions of older adults regarding evacuation in the event of a natural disaster. *Public Health Nursing*, 24(2), 160-168, doi: https://doi.org/10.1111/j.1525-1446.2007.00620.x.

Roy S., Vinayak P., and Stroh D.V. (2022) Modeling demographic relocation in response to climate risk factors and gentrification displacement pressures. *Transportation Research Record*, 2676(1), 688-703, doi: 10.1177/03611981211036367.

Senate committee on governance and finance (2019) SB 99 staff analysis, hearing date 4/24/19, bill purpose. April 24.

Seto D., Jones C., Trugman A.T., Varga K., Plantinga A.J., Carvalho L.M.V., Thompson C., Gellman J., and Daum K. (2022) Simulating potential impacts of fuel treatments on fire behavior and evacuation time of the 2018 Camp Fire in Northern California. *Fire*, 37(5), doi: https://doi.org/10.3390/fire5020037.

Sharma P. (2021) *Geospatial technology and smart cities ICT, geoscience modeling, GIS and remote sensing*, doi: 10.1007/978-3-030-71945-6.

Shi W., Wang H., Chen C., and Kong Z. (2021) Evolutionary game analysis of decision-making dynamics of local governments and residents during wildfires. *International Journal of Disaster Risk Reduction*, 53, 101991. Available at http://www.elsevier.com/locate/ijdrr.

Soga L., Comfort L., Zhao B., Lorusso P., and Soysal S. (2021) Holistic and adaptive are the keys to next generation wildfire emergency planning. doi: DOI:10.7922/G2WQ023S.

Stasiewicz A.M. and Paveglio T.B. (2021) Preparing for wildfire evacuation and alternatives: exploring influences on residents' intended evacuation behaviors and mitigations. *International Journal of Disaster Risk Reduction*, 58, 102177. Available at http://www.elsevier.com/locate/ijdrr.

The Press Democrat Staff (2017) Remembering the victims of the 2017 North Bay fires. *The Press Democrat*, December 27.

Thompson R., Garfin D., and Silver R. (2016) Evacuation from natural disasters: a systemic review of the literature. *Risk Analysis*, 37(4), 812-839, doi: https://doi.org/10.1111/risa.12654.

Toledo T., Marom I., Grimberg E., and Bekhor S. (2018) Analysis of evacuation behavior in a wildfire event. *International Journal of Disaster Risk Reduction*, 31, 1366-1373. Available at www.elsevier.com/locate/ijdrr.

United States Census Bureau (2021) Population estimates, July 1, 2021. Available at https://www.census.gov/quickfacts/marincountycalifornia. July 1.

United States Forest Service (2022) Wildfire evacuation risk for PNW communities. Available at https://usfs.maps.arcgis.com/apps/View/index.html?appid=8630fdb3e88f475fb5304415ce9e03c0&extent=-136.2333,39.1055,-102.4834,50.3252.

Vaiciulyte S., Hulse L.M., Veeraswamy A., and Galea E.R. (2021) Cross-cultural comparison of behavioural itinerary actions and times in wildfire evacuations. *Safety Science*, 135, 105122. Available at https://www.elsevier.com/locate/safety.

Vickery J., Errett N., and Bostrom A. (2022) The importance of inclusive risk communication: communicating extreme weather risk to those experiencing homelessness. Presentation given at the *American Meteorological Society 102nd Annual Meeting, Houston, TX, January 24*. 2A.2. Available at https://ams.confex.com/ams/102ANNUAL/meetingapp.cgi/Paper/393174.

Wahlqvist J., Ronchi E., Gwynne S.M.V., Kinateder M., Rein G., Mitchell H., Bénichou N., Ma C., Kimball A., and Kuligowski E. (2021) The simulation of wildland-urban interface fire evacuation: The WUI-NITY platform. 135, 105145, doi: https://doi.org/10.1016/j.ssci.2020.105145.

Wei, LuLiu C., and Bhaduri B.L. (2014) Agent-based large-scale emergency evacuation using real-time open government data. Technical report prepared by Oak Ridge National Laboratory. Available at https://rosap.ntl.bts.gov/view/dot/28288.

Wong S. and Shaheen S. (2019a) Current state of the sharing economy and evacuations: lessons from California. *University of California Institute of Transportation Studies*. Available at https://doi.org/10.7922/G2WW7FVK.

Wong S. and Shaheen S. (2019b) Leveraging the sharing economy to expand shelter and transportation resources in California evacuations. *University of California Institute of Transportation Studies*. Available at https://doi.org/10.7922/G2WD3XS4.

Wong S., Martin I., and Halpern J. (2020a) Kensington evacuation research project. Final report prepared by University of California, Berkeley, January.

Wong S., Broader J., Cohen A., and Shaheen S. (2021a) Double the trouble: a playbook for COVID-19 and evacuations. Available at https://escholarship.org/uc/item/3dm9q8db.

Wong S.D., Broader J.C., and Shaheen S.A. (2020b) Review of California wildfire evacuations from 2017 to 2019. *UC Office of the President: University of California Institute of Transportation Studies*, doi: http://dx.doi.org/10.7922/G29G5K2R. Available at https://escholarship.org/uc/item/5w85z07g.

Wong S.D., Broader J.C., and Shaheen S.A. (2020c) Can sharing economy platforms increase social equity for vulnerable populations in disaster response and relief? a case study of the 2017 and 2018 California wildfires. *Transportation Research Interdisciplinary Perspectives*, 5, (100131), May. Available at https://doi.org/10.1016/j.trip.2020.100131.

Wong S.D., Walker J.L., and Shaheen S.A. (2021b) Trust and compassion in willingness to share mobility and sheltering resources in evacuations: a case study of the 2017 and 2018 California wildfires. *International Journal of Disaster Risk Reduction*, 52, (101900). Available at https://doi.org/10.1016/j.ijdrr.2020.101900.

Wong S.D., Broader J.C., Walker J.L., and Shaheen S.A. (2022a) Understanding California wildfire evacuee behavior and joint choice making. *Transportation*, doi: 10.1007/s11116-022-10275-y, 2022/04/02. Available at https://doi.org/10.1007/s11116-022-10275-y.

Wong S.D., Chorus C.G., Shaheen S.A., and Walker J.L. (2022b) A revealed preference methodology to evaluate regret minimization with challenging choice sets: a wildfire evacuation case study. *Travel Behavior and Society*, 20, 331-347, July. Available at https://doi.org/10.1016/j.tbs.2020.04.003.

Xiang C., Kwan M.-P., and Qiang Li J.C. (2012) A model for evacuation risk assessment with consideration of pre- and post-disaster factors. *Computers, Environment and Urban Systems*, 35(3), 207-217, doi: https://doi.org/10.1016/j.compenvurbsys.2011.11.002.

Zhao B. and Wong S.D. (2021) Developing transportation response strategies for wildfire evacuations via an empirically supported traffic simulation of Berkeley, California. *Transportation Research Record*, 1-26, doi: 10.1177/03611981211030271.

Zhao X., Xu Y., Lovreglio R., Kuligowski E., Nilsson D., Cova T., Wu A., and Yan X. (2022) Estimating wildfire evacuation decision and departure timing using large-scale GPS data. *Transportation Research Part D: Transport and Environment*, 107, 103277.