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Integrating Traffic Network Analysis and Communication Network Analysis at a Regional Scale to Support More Efficient Evacuation in Response to a Wildfire Event

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RESEARCH REPORT

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Integrating Traffic Network Analysis and Communication Network Analysis at a Regional Scale to Support More Efficient Evacuation in Response to a Wildfire Event

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16. Abstract
As demonstrated by the Camp Fire evacuation, communications (city-to-city, city-to-residents) play important roles in coordinating traffic operations and safeguarding region-wide evacuation processes in wildfire events. This collaborative report across multiple domains (fire, communication and traffic), documents a series of simulations and findings of the wildfire evacuation process for resource-strapped towns in Northern California. It consists of: (1) meteorological and vegetation-status dependent fire spread simulation (cellular automata model); (2) agency-level and agency-to-residents communication simulation (system dynamics model); and (3) dynamic traffic assignment (spatial-queue model). Two case studies are conducted: one for the town of Paradise (and the surrounding areas) and another for the community of Bolinas. The data and models are based on site visits and interviews with local agencies and residents. The integrated simulation framework is used to assess the interdependencies among the natural environment, the evacuation traffic and the communication networks from an interdisciplinary point of view, to determine the performance requirements to ensure viable evacuation strategies under urgent, dynamic wildfire conditions. The case study simulations identify both potential traffic and communication bottlenecks. This research supports integrating fire, communication and traffic simulation into evacuation performance assessments.

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Disclaimer

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Abbreviations

CAWFE - Coupled Atmosphere-Wildland Fire Environment

CEFA - Wildland Fire Assessment System and the Program for Climate, Ecosystems and Fire Applications of the Desert Research Institute

CHP - California Highway Patrol

CRS - Coordinate Reference System

FAMWEB - National Fire and Aviation Management Web Applications

FDS - Fire Dynamics Simulator

GIS - Geographic Information System

ICS - Incident Command System

NCAR - National Center for Atmospheric Research

NIST - National Institute of Standards and Technology

OSM - OpenStreetMap

PBS - Public Broadcasting Service

PSPS - Public Safety Power Shutoffs

UCAR - University Corporation for Atmospheric Research

USFS - United States Forest Service

USGCRP - United States Global Change Research Program

WEA - Wireless Emergency Alerts

WFDS - Wildland-Urban Interface Fire Dynamics Simulator

WUI - Wildland Urban Interface

Executive Summary

Executive Summary

With increasing residential development into forested areas compounded by climate change (e.g., warmer temperature and droughts), wildfires in rural areas have become a perpetual crisis in California. For life-threatening wildfires, mass evacuation often becomes the only viable option to protect lives. Yet, looking back at recent events, there are significant challenges associated with the evacuation process, from multi-agency coordination to agency-resident communication and managing extraordinarily high amounts of traffic in a short period of time.

Previously, under the Quick Response Grant funded by the National Science Foundation and Natural Hazards Center at the University of Colorado Boulder, we identified a number of traffic bottlenecks encountered by the emergency response personnel during the 2018 Camp Fire evacuation near Paradise, CA. The incident happened on November 8, 2018 and was initially started by a faulty transmission tower in the forested area near Pulga, CA (Comfort et al., 2019). The fire quickly reached the more populous area, including the town of Paradise, and triggered the mass evacuation of tens of thousands of people. The breakdown of cell communication infrastructure greatly hindered communications and coordination between neighboring towns as well as the evacuees' access to valuable real-time information during the evacuation process (Comfort et al., 2019). This prompted us to extend the scope of our research on wildfire evacuations from the traffic system to also include the communication system.

This study of different evacuation scenarios in the event of a wildfire examines the mutual and combined impacts of three dynamic processes – fire, communication, and traffic – in performance assessment procedures. We constructed a series of dynamic models that holistically and realistically represent the evacuation process. Current evacuation models are typically based on existing traffic simulation models. Our framework is unique in that it also incorporates fire dynamics and communications process modeling. This framework and set of models constructed can be used by agencies and researchers to prepare and evaluate evacuations plans under different scenarios involving potential wildfires. In addition, special efforts were made to interview stakeholders and liaise with local agencies to establish realistic scenarios to use to test model performance as well as gather accurate information to estimate input parameters for our models.

The value of case studies

We applied this framework to two case studies in California: one for the Town of Paradise and the other for the much smaller unincorporated community of Bolinas. We used a semi-empirical FARSITE model from FlamMap to model the progress of the fire scenarios in the Bolinas case study. We used results previously obtained using the physics-based Coupled Atmosphere-Wildland Fire Environment (CAWFE) model (UCAR, 2020) for the Paradise case study. Our communications modeling component addresses the rate and spread of different forms of communications, as well as the impacts on their availability under conditions of fire-induced cell communications infrastructure damage. The model quantifies the impacts of different communication configurations, particularly in the Bolinas case study.

Even though both case studies were based on the same framework and set of models, the modeling details, scenarios tested, and the parameter inputs were adjusted based on knowledge collected from site visits. In the Paradise case, the scenarios tested were constructed based directly on the past Camp Fire event, but for Bolinas, the scenarios were based on hypothetical wildfire incidents in the future.

For the Paradise case study we developed alternative scenarios to reflect different numbers of vehicles being evacuated, different departure times, a random versus a phased evacuation, the probabilities of road closures on different roads on the evacuation routes, the use of contraflow strategies (allowing travel in the opposite direction on certain lanes to increase the capacity of the road to carry traffic away from the fire) on the main evacuation route, and the breakdown of the cell communications infrastructure. Based on our analysis of the various scenarios run using our model, we reach the following conclusions. Although these results would be different for different communities, they demonstrate the value of the framework for modeling evacuation outcomes.

Paradise, with a population of 26,682 (Maranghides et al., 2020), has only 4-5 roads that connect the town to the outside. If these key evacuation routes are closed due to fire-induced hazards, it is almost impossible to evacuate the whole town in time in the face of rapid progression of the fire. Therefore, it is critical to maintain normal operations on the key evacuation routes, for example, through removing dead trees, securing electric lines that might fall and block the roads, or having special personnel to quickly clear any obstacles. To reduce the number of vehicles participating in the evacuation, encouraging carpooling or having household members travel together requires fewer cars and could be a promising measure to increase evacuation efficiency and save lives. Practically, this strategy would involve education campaigns before the fire, recommending that residents pack essential personal belongings beforehand to save space in their vehicles.

As for traffic management during the evacuation, the contraflow measure is effective in helping evacuees to leave dangerous areas faster. However, it requires coordination between local officials and neighboring towns and across traffic operations agencies and law enforcement teams. Measures to guarantee smooth communication and orderly coordination should be planned and even rehearsed beforehand as part of wildfire preparedness efforts.

Another important consideration is the number of vehicles that will need to shelter-in-place because they do not have a safe path to reach their destination or have been stuck in gridlock for too long. Such metrics are hard to predict in a quantitative manner as they depend on many random factors, such as when and where a road might be closed due to the fire. Given the randomness of these metrics as well as the seriousness of the outcomes if shelters are unavailable, it might be beneficial to designate a few accessible locations in town as wildfire shelters (e.g., parking lots or fire-proof structures) and make them known to the residents as part of the evacuation preparedness plan. The capacity of these shelters can be determined together with the analysis of the road network to keep the evacuation traffic load at a manageable level, such as being able to evacuate or offer shelter locations to the residents of the town in two hours.

For the Bolinas case study, scenarios were constructed that represent different fire ignition locations, and different sizes and types of fires representing various fire threats. Various weather conditions were also tested, including changes in wind speeds, humidity, cloud cover, and temperatures. Delays in notifying the public regarding the fire danger and evacuation order due to gaps in communication (such as the loss of cell phone service) along with additional alternatives reflecting variations in the rate at which the population received notification from different media (fire/police radios, ham radios, social media services, emergency message services, cell phones, door-to-door notification, and visual cues) were also tested.

The most obvious challenge for evacuating the whole community of Bolinas in the event of a fire is that the city has only one lane leading from town for an evacuation route, however due to its lower population far fewer vehicles would need to be evacuated than would be the case in Paradise. The critical point is to maintain the safety and normal functionality of the evacuation routes, as it has zero redundancy for vehicles to leave using alternative routes. A larger danger lies in the close proximity of the evacuation route to flammable eucalyptus trees. If the fire develops rapidly within the community while the only evacuation route is blocked by burning or fallen trees (or abandoned vehicles, etc.), our simulations show a clear increase in the buildup of vehicles being trapped between the fire front and the blocked roads.

Another key difference between the two communities is that Bolinas has a large number of recreational visitors, who may not have the same access to local communication networks as the residents, especially since some cell phone services have poor coverage or are not available in the area. As a result, it is important to ensure robust communication channels are maintained between the fire department/law enforcement personnel and the residents and visitors and to offer training as part of preparedness exercises for the residents to enable them to make timely decisions in the event of life-threatening fires.

The Bolinas scenario demonstrates how the availability and efficiency of means to disseminate evacuation orders can greatly affect the evacuation process. Pre-fire communication campaigns may be developed to educate the public to make better decisions for when to evacuate, especially for those not able/planning to shelter at home.

Given the local geography, it is likely that multiple communities around Bolinas would also be engaged in simultaneous evacuation. Highway CA-1 out of Bolinas is winding and narrow and further bottlenecks may be encountered along the way, such as where the traffic from Stinson Beach merges onto CA-1. Similar to the Camp Fire evacuation, if a multi-town evacuation is expected, coordination between multiple communities (e.g., backup communication channels) should be carefully planned. A future study will include regional traffic evacuation modeling of the problem.

Lastly, given the unique geographical features and road topography of Bolinas, in the event of the loss of the only evacuation route, safe shelters within the community should be provided. The existing parking spaces near the fire department are not likely to be sufficient in case of serious interruptions to the evacuation route. Other safe and accessible locations from the fire need to be provided in the community.

Fire, communication, and traffic processes

Through these case studies and models that test multiple scenarios, we identified the following general connections between fire, communications, and traffic processes.

First, fire can impact communications processes through two mechanisms. On the one hand, fire can potentially cause damage to cell communications infrastructure or its power supply and increase the time and effort needed to notify the public of the danger by alternative means of communication. With a damaged or destroyed cell-based communications system, evacuees may not be able to recognize the danger or the need to evacuate soon enough. This may lead to the loss of hours of valuable time in the evacuation process. Moreover, the functioning of the cell-communications network also affects the availability and dissemination of the real-time traffic information to inform evacuees of the best evacuation routes. Such a loss of real-time information may have significant impacts on evacuation efficiency (Zhao and Wong, 2020). This is demonstrated by the scenarios developed for Bolinas where a regional fire causes a 50 or 100 percent reduction in cell communications capacity, leading to a drastic increase in total time (150-330 minutes) required to notify the public to evacuate.

On the other hand, the speed of the fire's progress can affect peoples' ability to visually perceive the fire danger for themselves particularly when they cannot be reached by other communications methods. This is also illustrated by the Bolinas case study, where the slow speed of the fire in one scenario allows people in town who still are some distance away from the fire to perceive the danger and urgency of the situation and permit a total of between 50-350 more vehicles out of a total of nearly 1,500 vehicles to reach safety.

Fire also affects the evacuation process directly by its impact on the traffic network. In both case studies, fire-induced road closures impacted the time it took to evacuate the community. This loss of time becomes especially critical when it increases the risk of being trapped within the fire zone. A key factor is the degree of redundancy in the evacuation network. Generally, if one residential road is closed, there are alternative routes for escaping. However, if there are fewer alternative routes out of town, or if a fast-moving fire reduces the number of available evacuation routes, the impact of individual road closures would be more significant, especially in terms of the time that vehicles could be exposed to the fire danger. If the fire causes trees to fall down and block the evacuation route, evacuation may become especially challenging. Furthermore, if fire-induced road closures are not cleared fast enough, the need for sheltering-in-place also increases.

Evacuation strategies

It is important to acknowledge the role played by fire and the communications dynamics in influencing the final outcomes of different evacuation strategies. The locations of the fire ignition points also can dramatically influence the choice of strategies. A fire starting farther away from the only evacuation route or routes will leave more time for evacuation. While fires starting closer to the town may quickly reach the only evacuation route or routes while also threatening more populous areas.

Evacuation strategies should focus on increasing the redundancy of evacuation routes or, where that is not practical, reducing the demands placed on the existing traffic network. In general, strategies addressing the former include: contraflowing, adjusting traffic signals, and reducing the probabilities of fire-induced road closures. Strategies to address the latter include encouraging car-pooling, phased evacuations, and offering safe shelters.

From our analysis of the two case studies, the most suitable strategies are context specific. For example, the Paradise road network is better connected within town, but there is still primarily only one road out of town. As a result, it becomes more important to identify ways to limit the number of vehicles attempting to use that road. Where evacuation routes are limited, communities should focus on reducing the number of vehicles used by each household for evacuation (e.g., through carpooling, conducting public outreach regarding the benefits of having fewer vehicles for evacuation) or implementing phased evacuations. While for the Bolinas case study, in addition to evacuating local residents, there was also the need to notify and evacuate visitors. Here there are potential choking points not only on the only way out of town, but also in other parts of the area. Given this, successful evacuation strategies should both increase the reliability of the communication system, efficiently address fire-induced road closures, or set up parking places for sheltering-in-place in case of a delayed evacuation.

The functioning of the communication infrastructure also affects the choices of evacuation strategies. To our knowledge, these interactions have not been well studied in the past research nor well considered in evacuation planning. For example, as demonstrated by the damaged communications network scenarios in the Bolinas case study, with broken communication channels, evacuees are mobilized more slowly, potentially leading to longer time spent in proximity to active fires. On the agency level, as seen in the Camp Fire evacuation scenarios, the loss of direct communications between agencies left certain strategies such as adjusting traffic signals or initiating contraflowing difficult to implement or coordinate.

The results of this study highlight the importance of considering various fire, communications, and traffic situations to make evacuation strategies more robust and comprehensive. This requires an in-depth understanding of the local environment, infrastructure, and organizational structures as well as the residents' likely behavior. Efficient simulation algorithms can greatly facilitate the assessment of the evacuation plan, as well as informing decision making at both the individual and the organizational level.

Challenges of current studies and future research directions

One of the limitations in this simulation and modeling study is the lack of behavioral data. At present, we can only assume the time it takes for households to evacuate once the order is given and received, and the number of vehicles that a household would use to evacuate, evacuees' routing preferences, and their choices of safe destinations. Some unknowns could be obtained by survey information, such as the expected number of vehicles per household for evacuation. Other behavior, particularly choice of evacuation route, is harder to predict realistically due to both the lack of a viable theory of individual routing decisions in emergency evacuations, and empirical data needed to validate any such assumptions. To produce a reasonably valid model despite the uncertainties, efforts are needed to tune and match these models with observations from site visits and documentary studies. In addition, models should be subject to random repetitions to assess the statistical significance of the findings under the uncertainties from the fire, communications, and traffic processes.

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Introduction

Wildfires and climate change

Fires are a natural part of the ecosystem, especially in the western United States. Fire renews plants, kills pests and gives birth to new generations of vegetation. But lately the number of fires has been increasing significantly, bringing not only the risk of damaging the ecosystem but also posing added threats to urbanized places and people. The Fourth National Climate Assessment (USGCRP, 2018, Ch. 25) reports that the land area burned by wildfires from 1984 to 2015 was double the area that would have been burned without global warming.

Fire risk depends on several factors, such as temperature, humidity, presence of fuels and type of vegetation (grass, shrubs, trees). All of these are affected by changes in the climate. Fires propagate easier and faster with hotter temperatures and a drier climate, making them more difficult to extinguish. In addition, such changes also lead to infestations of insects not native to the ecosystem (e.g., Mountain Pine Beetle, bark beetle) that could potentially attack and damage trees, increasing the amount of available fuel. For example, bark beetles were responsible for the death of seven percent of the trees in U.S. western forests from 1979 to 2012 (Hicke et al., 2016).

While the growth of trees and plants could naturally slow down global warming by storing carbon, fires not only decrease the number of trees and plants considerably, but they also release more carbon into the air during combustion.

How the climate and topography of California influence fires

California has always been a focus of attention for fires. The growing threat has been well highlighted by the disastrous fires of 2017 (Tubbs Fire, Thomas Fire, North Bay Fire), 2018 (Camp Fire, Mendocino Complex Fire) and 2020 with the August-September fire complex (CZU Complex, LNU Complex, Creek Fires). Fires have become more dangerous because increasingly extreme weather conditions caused by global warming have made the climate warmer and drier, lengthening the fire season. In recent decades, the number of acres burned by fires has increased every year. More than one million acres were destroyed in 2003, 2007, 2008, 2017, 2018 and 2020. Furthermore, the Camp Fire in 2018 was one of the most destructive fires in the country with the death of 85 people and more than 18,000 structures destroyed, most of which were in the town of Paradise.

In California, the fire danger depends on the seasons. A hot and dry summer season leads to progressive drying of vegetation that makes the fuel situation very dangerous. Further, California is subject to periods of severe drought. In particular, a period of deep drought began in 2011 that lasted until 2017, the worst ever recorded in California. The heavy rains of the last two years have improved the situation and now the state is back to normal. However, the drought resulted in an estimated 129 million dead trees in forested areas, and the ground is still very dry. All these dead trees provide an easy path for a fire to move and spread quickly.

In autumn, strong winds from the hinterland blowing towards the coast represent one of the biggest problems. These winds are called Diablo winds in northern California and Santa Ana winds in the south. They are facilitated by the particular terrain of California formed by high mountains and valleys that act as chimneys, making these winds extremely hot and dry. These strong offshore winds easily dry vegetation due to very low relative humidity, making fires extremely dangerous, especially if they occur before the beginning of the winter rainy season.

Lessons from recent California wildfire evacuations

Devastating damage caused by wildfires in California and around the world have taught many painful lessons. Compared to other hazards such as hurricanes, wildfires are difficult to predict and leave little time for evacuation. Since wildfires occur so frequently, they are no longer a low-probability event in certain parts of California (Governor Newsom's Strike Force Report, 2019). For many individuals, moving away from high-risk areas is often not possible due to the housing shortage. Instead, residents need to rely on preventive measures, from using fire-proof construction materials to creating defensible space around their homes. In addition, knowing the evacuation routes, making written plans, and preparing emergency kits can prove invaluable under chaotic short-notice evacuation scenarios.

At the agency level, the dynamics and scale of destruction from wildfires may quickly overwhelm emergency response capacity. Thus, careful planning ahead is essential. This includes, but is not limited to, making evacuation plans, conducting drills, enrolling residents in emergency alert systems, and enhancing public awareness of fire danger so they can make informed decisions. In addition, the reliability of evacuation plans should be carefully evaluated, particularly when they depend on vulnerable infrastructure, for example, having backup communication plans or generators in case the power supply to cell towers is cut off by the fire. Also, coordination and collaboration across different agencies have proven challenging in past events. Such coordination should be part of the emergency plan.

Purpose of this report

Current evacuation models are typically based on existing traffic simulation models. Our framework in this study is unique in that it also incorporates fire dynamics and communication process modeling. This framework and set of models can be used by agencies and researchers to prepare and evaluate improved evacuations plans under different scenarios involving potential wildfires. Our models are constructed based on two different case studies, one for Paradise, CA (based on the actual 2018 Camp Fire) and one for Bolinas, CA based on several hypothetical wildfires in the area. We use the models to estimate how long it would take to complete a full evacuation from the study areas under different scenarios for the fire's progress, including the generation of spot fires from embers thrown ahead of the main fire front. We also test our model by varying the amount of time it takes for residents to be notified of the fire danger and to receive the order to evacuate using different methods of communication. In addition, we consider multiple scenarios involving the impact of temporary road closures due to their proximity to the fire, or due to fallen trees or other debris blocking certain evacuation routes.

Structure of the report

This report is organized as follows. The Background section includes information on the development of the three individual models: (1) wildfire spread simulation, (2) communications process modeling and (3) evacuation simulation. In the course of this study, the research team also paid several site visits (or conducted video conference meetings) to the towns of Paradise and Bolinas. Building on knowledge gained from our review of the available modeling literature and the site visits, we developed a methodology to model three critic components in the evacuation process. We then created several scenarios to test the efficacy of the models. Given the diverse characteristics of each component — ***fire***,

communications, and ***traffic modeling*** — we analyze each separately. Part I, "Fire Spread Modeling" and Part II, "Communications Modeling" are standalone sections. In Part III, "Traffic Evacuation Modeling," the fire and communications model results are integrated into the traffic model. The evacuation processes are then studied for the two case sites. The report concludes with "Discussion" and "Summary" sections.

Background

This section reviews available studies on the key components of our integrated evacuation framework: (1) simulation of wildfire spread; (2) communication process between agencies, and from agency to residents; and (3) simulation of the wildfire evacuation process from a traffic perspective.

Wildfire Spread Modeling

Wildfires are complex events influenced by different environmental factors such as wind, relative humidity, fuel, temperature, and human interaction. Understanding the influence of these factors on fire is critical for evaluating fire behavior and progression. Wind is one of the main factors that affect the direction and speed of the fire, and its effects have been studied, for example, by Beer (1991) with laboratory experiments, field experiments, and analysis of existing wildfire spread models. Earlier works include those of Albini (1979) and Anderson (1983) who analyzed the relation between wind speed and the spread/size of wildfire. In particular, Albini developed a way to estimate the wind speed over various wildland fuel types, while Anderson studied how to predict the direction of wind-driven wildfire. Wind, together with other factors such as fuel status and topology, is one of the major input factors that are considered in the fire modeling in this study.

Wildfire simulations are typically conducted using one of three types of models: empirical models, semi-empirical models and physics-based models. The differences between the three types are explained by Vaccaro et al. (2017). Empirical models are of limited use outside situations similar to the sites and conditions studied. Therefore, they are not suitable for widespread use. Semi-empirical models are based on the physics of energy conservation but do not consider complex heat transfer mechanisms. Physics-based models are the most complex and are based on solving the conservation equations for mass, energy and momentum that are necessary for modeling the convective heat transfer process of a wildfire. Among these three models, the semi-empirical models are the most used in engineering applications due to their running efficiency, relative simplicity, as well as the availability of data inputs from online databases, such as LANDFIRE (LANDFIRE, n.a.). Given the available options, this study uses a semi-empirical model for fire spread.

One of the most widely used semi-empirical models is FARSITE (Finney, 1998), now included in the software FlamMap. FARSITE is based on the Rothermel model of fire spread (Rothermel, 1972) and uses a cellular automata model to simulate the fire front geometry, i.e., fire progression. It gives a graphic output of fire extent at different times, as well as other parameters involved in the process, such as wind speed, wind direction, flame intensity and so on. Among these outputs, the fire extent and the flame intensity results are used in the evacuation modeling in this study, influencing the departure times of the evacuees and the road closure status in the traffic simulations.

Physics-based simulation models can theoretically be adapted to every situation, as their underlying physical models are universally applicable and are not based on limited observation samples. However, in reality their use is limited by the difficulty in validating the results that are generated by complex combustion process. In addition, they take more time to complete compared to semi-empirical models. Bova (2016) compared the simulation results from FARSITE (a semi-empirical model) and the Wildland-Urban Interface Fire Dynamics Simulator (WFDS, a physics-based model). His work demonstrates that the two types of models are capable of producing similar but not identical, outputs, due to issues such as the numerical approximation as well as the spatial resolution. Even though similar results from the two models can be obtained from flat terrain and under uniform fuel conditions, the differences in the outputs of the two models are evident under more complex weather and topological conditions. However, given the level of maturity and the computational performance of the semi-empirical FARSITE model, it is still the preferred approach of fire simulation in this study, as the aim is to run multiple fire progression scenarios in a short time.

As an additional note, the WFDS software is developed by NIST (National Institute of Standards and Technology) and the United States Forest Service (USFS) as an extension of the Fire Dynamic Simulator (FDS) software. The code is still under validation but has been used by several studies. Mell (2007) used it to model grassland fires and tested it on two specific experimental cases to evaluate how accurate the model is in predicting fire development. In general, the use of physics-based models in wildfire simulations still needs to undergo much improvement.

Based on these considerations, the present study relies mainly on the semi-empirical FARSITE/FlamMap modeling software for fire simulation in the Bolinas case study. We also document our efforts in using the physics based WFDS model. For the Paradise case study, we used the fire progression simulation outputs from the Coupled Atmosphere-Wildland Fire Environment (CAWFE) model, a physics-based simulation conducted by researchers at the National Center for Atmospheric Research (NCAR) (UCAR, 2020). The reason to choose the FARSITE/FlamMap model for the Bolinas case study is due to its computational efficiency and flexibility in running multiple scenarios. For the Paradise case study, since only one fire scenario is considered, the existing simulation results from NCAR could be leveraged and integrated into the evacuation performance assessment.

Communication Processes in Wildfire Situations

Under life-threatening wildfire emergencies, maintaining smooth and effective communications can be especially challenging. Yet, communications are also crucial for coordinating activities, distributing information, and executing various evacuation strategies. This section summarizes information regarding communication issues in wildfire evacuations.

Communications in a wildfire evacuation are conducted on at least three levels. First, there are cross-agency communications, such as between fire, police and traffic departments in the same area, or between the agencies of multiple areas (i.e., the town being evacuated to the town that is receiving the evacuees). In California, the Incident Command System (ICS) was established in the 1970s as a standardized inter-agency command and control system to respond to wildfire hazards, which has now expanded to all types of hazards nationwide (FEMA, 2018). Cross agency communications are essential for coordinating the efforts of different organizations but may be difficult or disrupted during a wildfire due to the lack of functioning infrastructure (Wong et al., 2020). Second, communications also occur between agencies and residents, which can be unidirectional as, for instance, when the sheriff's office sends out evacuation warnings/orders, or bidirectional if agencies can also collect feedback or crowd-sourced information (i.e., volunteered geographic information) from the evacuees (Goodchild and Glennon, 2010; Zhong et al., 2016). Agency-resident communication is the pivotal mechanism for ensuring timely and accurate information is delivered to the evacuees. In addition, with the wide adoption of social media, there are direct lines of communications among the evacuees. These types of communications have the special advantages of being able to share first-hand information as well as wider user coverage/penetration compared to traditional media. However, the legitimacy and accuracy of unvalidated information on social media can often be questioned (Sutton et al., 2017).

The communication process in a wildfire incident occurs not only during the evacuation process, but also before and after the event. Pre-evacuation communications are usually in the form of training and public outreach; both formal programs and social connections can help residents living in fire-prone areas understand the fire risks and take mitigation actions (McCaffrey et al., 2011). The process is the most challenging during the event notification phase, given the lack of personnel and urgency of time. To improve the efficiency of the notification process, Doermann et al. (2020) developed tools to quickly compose accurate and understandable Wireless Emergency Alert (WEA) messages, which emergency personnel can use when disseminating evacuation warnings/orders. Also, studies have shown that certain communication mechanisms (e.g., reversed 911) are more effective than others in improving the compliance rate of evacuations (Strawderman et al., 2012). In recent years, the role of social media has become prominent in wildfire communications. In the study by Sutton et al. (2008), social media platforms were less well adopted, and were mainly regarded as a "backchannel" for official messages. However, in recent years, we are seeing more official communications made on social media platforms (e.g., the Camp Fire evacuation orders were sent to the county-wide emergency alert system and additionally posted on Twitter and Facebook in an effort to reach all county residents) as well as how social media platforms have enabled two-way interactions in providing instructions to evacuees and providing feedback to the organizers. While employing multiple platforms to reach evacuees is critical, it is also important to ensure that all communications with the public are quickly distributed and consistent across platforms. Once the main evacuation has been completed, agencies should continue to maintain a high media presence and attempt to control rumors to improve communication flow, as questionnaire interviews have shown that carefully executed post-event updates can be effective in reducing the stress and trauma associated with the evacuation experience (Stidham, 2008).

Communications challenges in wildfire situations have been well studied and documented in the literature. We categorize them into three aspects: technical difficulties, organizational challenges, and societal/behavior problems. On the technical side, as more and more messages spread through cell-based communication methods, the functional performance of cell communications infrastructure becomes a critical issue (Anderson et al, 2020). For emerging sources of information on the Internet, there are also concerns regarding server capabilities (Sutton et al., 2008). Due to these reasons, agencies should also consider alternative low-tech communication methods including door-to-door notifications, radios, static sirens, and mobile sirens (using emergency vehicles or drones) to prepare for potential power outages (Wong et al., 2020). Other issues listed in Wong et al. (2020) include poor mobile service in rural areas, the impact of the PG&E Public Safety Power Shutoff (PSPS) protocols on emergency communications, and concerns about the WEA reaching unnecessarily large geographic areas, leading to higher numbers of evacuees and creating more congestion in the evacuation. On the organizational level, it is sometimes difficult to establish multi-jurisdictional coordination between emergency operation centers (e.g., between the City of Santa Rosa, Sonoma County Office of Emergency Management, and the Sonoma County Sheriff's Office). Such problems would be evident in evacuation plans involving only a single town, while in actual evacuations, assistance from neighboring towns is often needed. On the societal and human behavior side, it is critical to understand the limitations of different forms of communications in terms of timeliness, accuracy and coverage (Strawderman et al., 2012). For example, visual information such as maps are useful in conveying information in a more understandable manner (Cao et al., 2016).

Based on the scope of this study, we focused on modeling a particular stage of communication, namely the dissemination of evacuation orders. This is the second step in our simulation framework, which is triggered by the fire model and subsequently influences the traffic simulation model by setting an upper bound on the evacuee departure time. Our communications modeling component addresses the rate and spread of different forms of communications, as well as the impacts on their availability under conditions of fire-induced cell communication infrastructure damage. The model quantifies the impacts of different communication configurations, particularly in the Bolinas case study. As summarized in the FEMA report on emergency management (2011), building the resilience and security needed to cope with the threats of natural disasters requires individual responsibility and self-preparedness, transformations in emergency management, as well as a collaborative community.

Wildfire Evacuation Traffic Simulation

Given the complexity and non-typical situation of wildfire evacuations, traffic simulations often become a useful tool in research studies and community planning for wildfire events. A basic question to ask is “how long would it take to evacuate the community?” Answers to this question are usually obtained by running dynamic microscopic traffic simulations that model the movement of each individual vehicle from the origin (usually house locations) to a safe destination (Cova and Johnson, 2002; Wholson and Marchive III, 2007; Beloglazov et al., 2016; Li et al., 2019; Chen et al., 2020). There are many existing traffic simulation programs that can provide such dynamic simulation functionalities, such as SUMO, PARAMICS, and they have been adopted in evacuation studies (Chen et al., 2020; Cova and Johnson, 2002). Compared to off-the-shelf software programs, custom made simulation codes that are based on fundamental traffic theories have also been developed and adapted in evacuation simulations (Wahlqvist et al., 2021). They have the advantage of greater flexibility, especially when coupled with other modules. When faced with limited resources by local agencies, de Araujo et al. (2014) show how to adapt existing static four-step models for evacuation planning and achieve successful outcomes in a real event.

Once a baseline for the evacuation time has been determined, traffic simulations or analytical methods (e.g., optimization with mathematical programming) can also be used to improve or optimize the evacuation process. Some typical measures that have been tested in the literature include contraflowing, phased evacuation, vehicle reduction, etc. (Chen and Zhan, 2008; Li et al., 2015; Chen et al., 2020). Since delays at traffic intersections are often the critical component that slows down the evacuation, Cova and Johnson (2003) proposed a novel idea called “lane-based routing,” which uses a mixed-integer programming solver to generate routing plans that prevent cross-conflict at intersections to minimize the delay. However, such solutions (e.g., redirecting traffic flow at many intersections) can be time and resource consuming to be implemented for a large road network in reality. Thus, the proposed improvements in this report will focus on more common scenarios and readily implementable approaches, such as phased evacuations and contraflowing.

Apart from the traffic evacuation time, Cova et al. (2005) proposed using wildfire spread simulations to understand the time available for evacuation before the fire reaches a community. Based on this idea, a spatial extent that corresponds to a time threshold can be set, e.g., a two-hour buffer, in what is called a “trigger model.” The evacuation order must be sent before the fire crosses this buffer to leave sufficient time for evacuation, while not evacuating unnecessarily early and causing over-evacuation or panic. However, Cova et al. did not include traffic simulations, so the time for evacuation is only an estimate. Wahlqvist et al. (2021) further builds on this idea and uses a computer game (developed with the Unity game engine) to resolve the buffer boundary iteratively, considering the dynamic interactions of fire and traffic, such as fire-induced road closures, on the boundaries of the trigger buffer. In their work, the game is a shortcut/user interface for users to conduct complex simulations (e.g., set the scenario variables). The complex simulations incorporate the behaviors of fire, pedestrians and vehicles. In this report, a communications module is included along the fire and vehicular movement modules, adding an extra layer of realism considering the communications bottlenecks in real evacuations (Comfort et al., 2019).

Most of the published studies are based on realistic networks and travel demands sourced from OpenStreetMap or local land use data. Chen and Zhan (2008) used theoretical models and abstract case studies that argued for the benefits and challenges of phased evacuations. In general, though, actual road network data are readily available from sources such as OpenStreetMap and the spatial extent of wildfire evacuations is generally small (i.e., within the county) compared to other natural disasters, such as hurricane evacuations. Therefore, using a realistic network will not incur excessive computational burdens. As a result, realistic networks are used for both case studies in this report for evacuation simulations, incorporating information including the geometry, speed limit, number of lanes, etc. of the roads in the study areas.

Apart from the simulation work, a rich body of literature also focuses on evacuation behavior, such as residents' decision whether to evacuate or stay and defend their properties (McCaffrey et al., 2018). A seminal work by Beloglazov et al. (2016) demonstrates that incorporating realistic dynamic factors (e.g., evacuation delays to different types of triggers) will produce results with greater statistical significance. However, the communications process, i.e., when and where the residents are notified, is usually modeled with less fidelity or complexity. For example, the work of Cova and Johnson (2002) considers a Poisson-distributed departure delay parameter that is the sum of the notification delay and preparation delay. The distribution parameters are decided based on expert judgements. In Beloglazov et al. (2016), both the decision delay (a constant value) and preparation delay (a random variable) are considered, as the values or distributional parameters depend on the urgency of the event that triggers a group to evacuate. In this report, rather than using a probabilistic distribution, the notification rate is derived from a communications model. The details of the communications model (e.g., rate of notification) are obtained through site investigations of the case study areas.

Overall, the concepts of using traffic simulations for evacuation studies are already mature. However, there are great knowledge gaps regarding the details of the simulations. In our work, we try to fill the gap by introducing coupled fire, communications and traffic simulations, which can account for the uncertainties in the evacuation process (e.g., road closures, notification delays and evacuation risks) more explicitly and robustly.

Summary

In this section, we summarized information on the key components needed to create an integrated wildfire evacuation model incorporating three aspects: fire dynamics, communications processes, and traffic activity. We describe the common types of models/tools used to model each aspect, and which approaches were chosen for our model. We also explained how dynamic models that are computationally feasible and can use readily available data are the most suitable choices for the simulations in the current study. In the next section, potential scenarios regarding the three processes are identified based on the site visit and interview findings.

Methodology

As introduced above, fire dynamics and communications processes are important components affecting wildfire evacuation outcomes. However, one or both of them is frequently neglected in simulation-based studies. To understand the roles that fire, communications, and traffic dynamics play in evacuation as well as to explore the most efficient methods of mobilizing the whole community to evacuate effectively, our study adopted the following approach:

- Constructing a framework made of dynamic models of fire propagation, communications network and transportation network in communities exposed to recurring hazards;
- Demonstrating the application of the above framework through two case studies (Paradise, CA and Bolinas, CA). To make the case studies as realistic and representative as possible, many scenarios and key variable inputs have been identified through site visits and interviews with the local agencies and residents in the case study areas.

The following section is divided into two parts. First, the framework consisting of dynamic fire, communications, and traffic simulation models is described, with a focus on how we established the linkages between these different types of models. Secondly, our findings based on the site visits for each case study are presented, with an explanation of how these findings were used to shape the case study scenarios and parameter inputs.

Simulation Framework

This study constructed a set of dynamic models of fire, communications, and transportation networks to simulate the wildfire evacuation process as shown in Figure 1. Specifically, the framework consists of three components leading to a series of outcome metrics. Starting from wildfire spread simulations (Box 1 in Figure 1), the progression of the fire front and footprint are simulated at different time steps using existing software.[1] After the fire outbreak is detected, the communications process is initiated. The communications process (Box 2 in Figure 1) simulates the dissemination of the evacuation order to the town residents (and visitors if applicable) through different channels, e.g., emergency alerts, social media announcements or door-to-door notifications, using system dynamics models. Different methods of communication have varied levels of efficiency and robustness under wildfire attacks. For example, emergency alerts sent to registered cell phone users can reach a large audience in a short time, but they depend on a functioning cell communications infrastructure to work properly. While it takes much longer to inform the community through door-to-door communication, this inefficient method is one of the few viable options if the cell communications infrastructure is damaged or if it is necessary to reach out to community members who lack access to the cell communication technology. More details regarding the system dynamics model of the communication process are given in Part II “Communications Modeling” of this report. The third simulation component in the framework is the traffic model (Box 3 in Figure 1). In this study, a spatial-queue-based mesoscopic traffic model is adopted to track the positions of each vehicle throughout the evacuation process. Using this model, the vehicle on a road is assumed to run at free-flow speed until it joins a queue of vehicles at the downstream end of the link. The model is termed “spatial queue,” because the queue is assumed to take up

[1] Wildfire spread simulation is conducted by us for the case of Bolinas using the FlamMap software at hourly time steps. For the Camp Fire case, an existing simulation by the NCAR CAWFE model is taken as the input, which provides the 5-minute footprint of the main fire front. More details will be given in Part I “Fire Spread Modeling” and related sections in Part III “Traffic Evacuation Modeling".

space on the road link. The length of the queue increases when new vehicles join it from behind and reduces if vehicles in the front leave and move across the intersection to the next road link. In a relatively low travel demand case, the length of the queue is small. However, if the demand from the upstream is too high, the queue will keep growing until backing up to the entrance of the road link. The traffic simulation is used to quantitatively represent the challenges for evacuees in reaching safe destinations due to traffic bottlenecks and congestion (more demand than what the road network can sustain). The traffic simulation is elaborated on in Part III "Traffic Evacuation Modeling" of this report.

The three simulation components are interconnected in a number of ways. First, the fire, communications, and traffic processes are synchronized in time. The initial sequence of events goes from fire ignition, to the issuance of the evacuation order, and then to the vehicle departures. Shortly after an initial fire outbreak, a mandatory evacuation order is given. However, due to the varied levels of efficiency and availability of different communication methods, it may take much longer for the residents (or visitors) in the evacuation zone to be informed. The communications model then simulates the increase in the number of the "informed" evacuees over time. Assuming the residents in the same household and visitors in the same group act together, when a household (or visitor group) is informed of the evacuation order, it will start the evacuation and join the existing traffic on the network after a short period of preparation (i.e., to pack belongings and fetch animals). Secondly, the fire footprint dynamically impacts the traffic simulation model in terms of both supply and demand. When the fire front reaches a road, we assume that there is a certain probability of the road being closed due to fire-induced hazards (e.g., falling trees or abandoned vehicles). This effectively reduces the capacity of the road network. Also, when fire gets close to a household (or visitor group), even though it may not have received the evacuation order (through telecommunication or face-to-face communication channels), the model still assumes they will leave immediately due to the perceived fire danger. This is called cognition-based evacuation and can increase the evacuation demand at the specific point in time. Details of these model interactions vary depending on the characteristics of each case study area and will be explained along with the case studies.

Results from the three simulation components in the framework are used together to derive a number of evacuation-related outcome metrics. These include a number of time series outcomes, such as the number of vehicles arriving at safe destinations within specified times (the arrival curve), the number of vehicles within the active fire footprint (the fire exposure curve), the number of vehicles that have left the evacuation zone, etc. Also, maps can be generated from the results showing where the movements of the vehicles actually back up (traffic bottlenecks). Summary statistics can also be derived, such as the time for all evacuees to leave the affected area (clearance time) or the average trip duration. These metrics can be used to compare the pros and cons of different fire, communications and traffic scenarios.

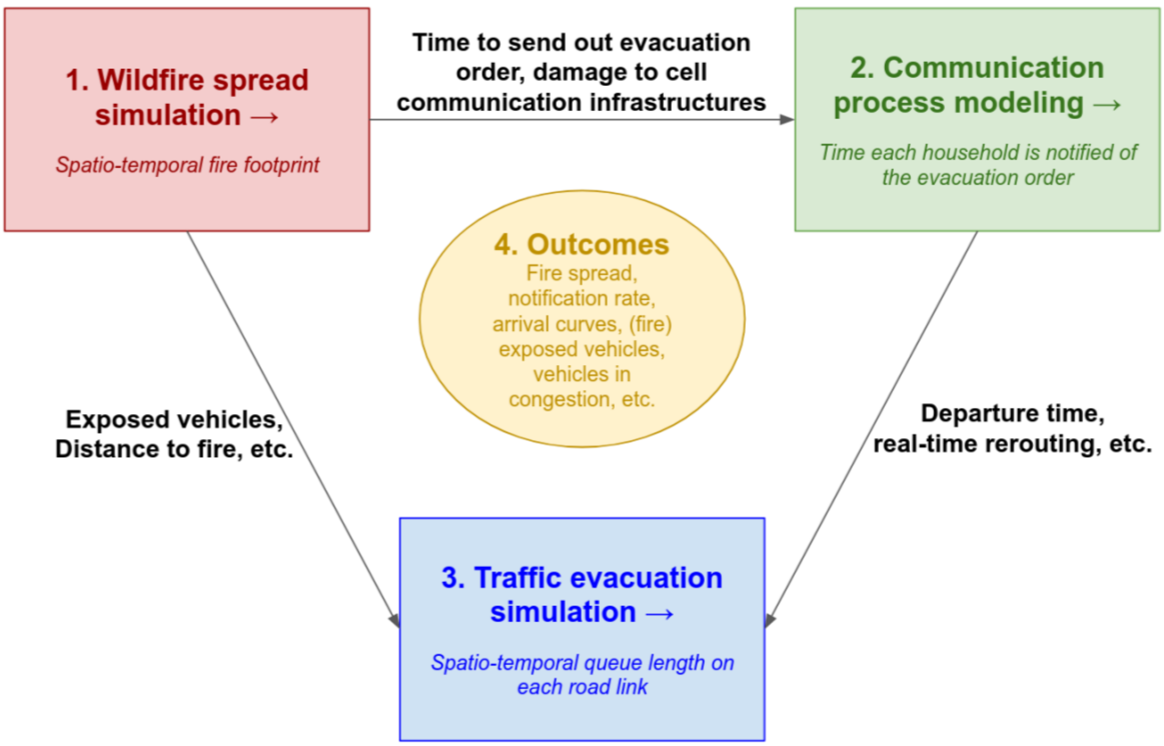


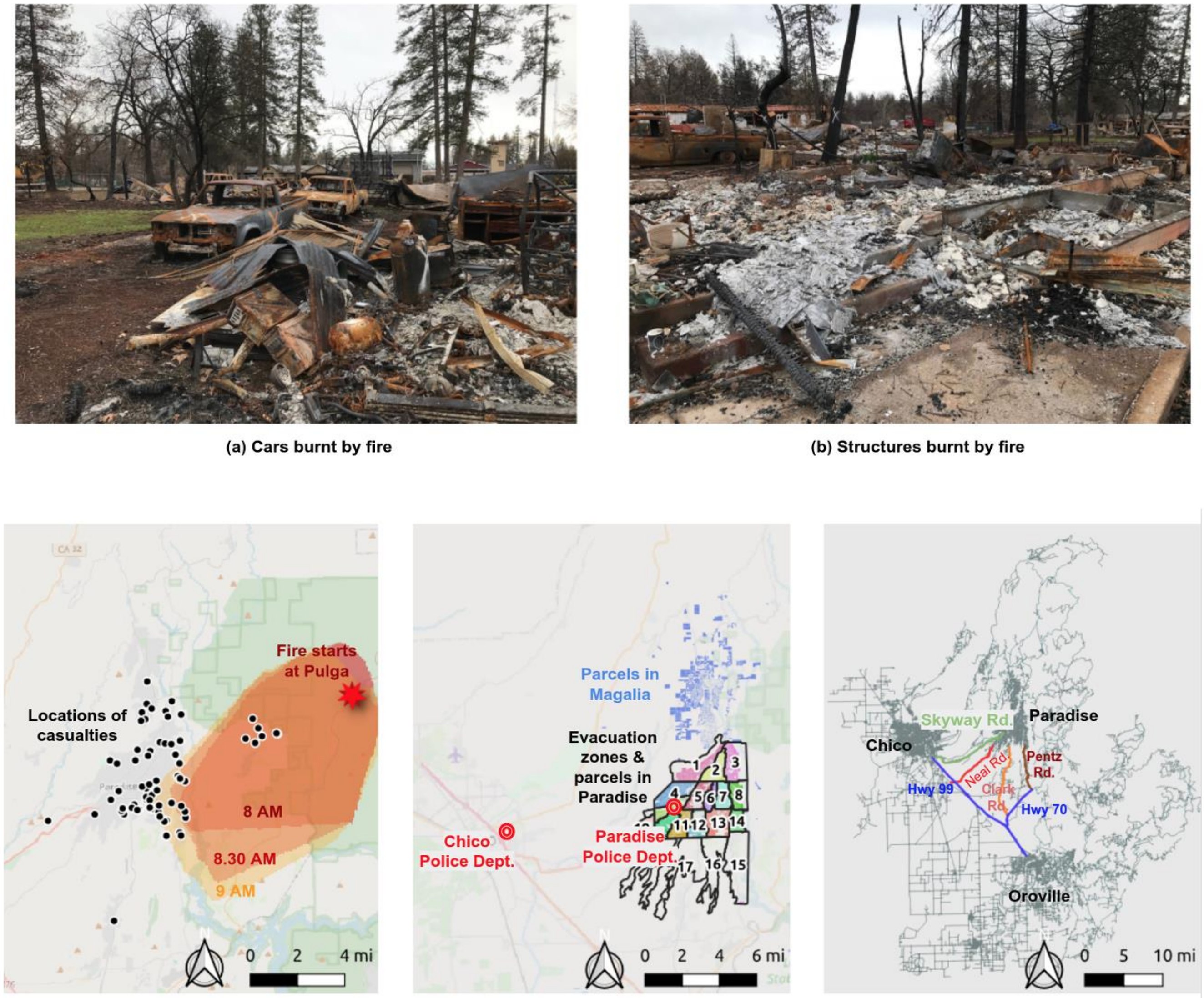
Figure 1. Framework

There are some limitations in implementing the framework. To begin with, though generally compatible, it is hard to unify the time units of the analyses across the models. The fire simulation results are given at 5-minute or 1-hour intervals, while those of the communications model are almost continuous in time, and the vehicle positions in the traffic simulation are updated every second. Due to the time lag of the fire progression simulation compared to the communications and the traffic model, some metrics which involve calculating the distance to the fire may be underestimated. In addition, both the fire and the traffic simulations take account of both space and time, while the system dynamics communication model only has a time dimension. This limits the modeling of cognition-based evacuation, which relies on the spatial distance between the evacuees and the fire front to trigger the decision to evacuate. As a result, in the communications model, the number of evacuees who leave because of visual cognition of the fire danger are estimated roughly. In the traffic simulation, cognition-based evacuation is determined more accurately by calculating the distance between the pre-departure evacuees and the fire front (they will depart if the fire front is too close). This may lead to slight discrepancies regarding the departure time and the percentages of evacuees falling into the cognition-based evacuation category. The third limitation is related to the modeling unit: communication is modeled at the group level (e.g., number of residents informed) while the traffic evacuation unit is vehicles. Multiple individuals in the same household may share one or more vehicles. To make the conversion from groups to vehicles, the individuals are first randomly assigned to a household (land parcel) or visitor group. It is assumed that, as long as one individual in the household (or visitor group) becomes aware of the evacuation order, the whole household (or visitor group) starts to prepare for departure. Lastly, many other realistic scenarios, such as varying the evacuation order compliance rate or altering the firefighters' roles, are not considered here as they are outside the focus of this study. However, these factors could be included in future studies with minor adjustments to the current framework.

In the next two sections, findings from the interviews and site visits to the two case study towns will be summarized. These findings informed the scenario development and the selection of key parameters for the case studies in this report.

The Paradise, CA Case Study

Under a previous quick response project supported by the National Science Foundation and Natural Hazards Center at University of Colorado Boulder, our research team made six field trips to the Camp Fire sites in Chico and Paradise, CA. Through a series of interviews with decision makers from the local area to the federal level, we collected firsthand information regarding fire hazards, communications challenges, and traffic bottlenecks (Comfort et al., 2019). In addition, we also collected and reviewed news and agency reports, planning documents, and social media posts related to the Camp Fire incident. The detailed documentation of the site visits can be found in the reference report (Comfort et al., 2019). Here, the main findings regarding the fire, communication and traffic aspects will be outlined, with focus on how these findings are used to establish the simulation scenarios and inform the choices of key parameter values.



(a) Cars burnt by fire

(b) Structures burnt by fire

(c) Fire spread

(d) Communication

(e) Traffic

Figure 2. Illustrations of findings from the Paradise site visits and desktop studies.

- ***Fire activity.*** The Camp Fire started in Pulga, a remote community to the east of Paradise at around 6.15 AM and was detected quickly thereafter. The location is shown as a red star on Figure 2(c) (CalFire, 2019). Due to the embers picked up by hot, dry winds, the fire quickly reached the boundary of the town of Paradise at around 8 AM. The yellow-orange shaded area shows the fire footprint at 8 AM, 8:30 AM and 9 AM, respectively (UCAR, 2020).

    - These findings inform the beginning of the communications process simulation. For our Paradise scenarios we assumed that the first message (between emergency personnel) was made over the fire/police radios at 6:16 AM, a minute after the estimated detection of the fire at 6:15 AM. We also assumed that these radio signals were picked up by ham radio owners (amateur radio operators not part of the emergency response team) at 6:17 AM.

- The important role that the ember fire played (as mentioned in Maranghides et al., 2021) is reflected in the final fire footprint adopted in the simulation. The fire simulation for the Paradise case study is obtained from external input, namely the dynamic fire progression simulation produced by researchers from NCAR using the CAWFE model (UCAR, 2020). However, the CAWFE model does not include spot fires triggered by embers that have flown far away from the main fire front. We added data on the random spot fires along the main fire progression direction. Both the main fire front from the CAWFE model and the random spot fire added by us were used to calculate vehicle fire exposure or the probability of road closures due to fire-induced hazards. More details on our modification of the CAWFE model are given in Section III-2.2, "Fire Spreading" in the Paradise case study.

- ***Communications***. The town of Paradise had an award-winning zoning system and evacuation plan (Figure 2(d)). The first evacuation order for Paradise was given at 8 AM to all of Pentz road in Paradise East to Highway 70 (Twitter by @ButteSherif, 2018). But this zoned evacuation plan had to be abandoned shortly due to the speed of the fire (NIST, 2020). The Code Red alerts went out only to landline telephones with publicly available numbers, reaching approximately 50 percent of the residents (Professional interview, Paradise, Feb. 12, 2019, see Comfort et al., 2019). The cell communications infrastructure was out of operation at 10:30 AM (Comfort et al., 2019), likely due to fire-induced power loss. This loss left residents largely without communication and forced operational agencies into relying completely on radios, which created confusion over the contraflow plan (i.e., people were confused whether contraflow was implemented on Skyway Road) as well as lack of traffic signal coordination at the entrance to Chico, which received the greatest number of evacuees.

    - The above findings were used to determine the start time of the evacuation process. The evacuation order is assumed to be sent out at 8 AM in the simulation through social media platforms, CodeRED alerts and cell phone messages. These communication methods are assumed to reach 50 percent of the town residents.

    - The difficulty in carrying out the planned phased evacuation is reflected in the simulation scenarios, where scenarios with or without phased evacuation are constructed and compared.

    - The loss of the cell communications infrastructure is embodied in the simulation scenarios through the loss of real-time traffic information (e.g., access to navigation services such as Google Maps or Waze). In the base scenario, the cell communications infrastructure is assumed to be damaged at 10:30 AM, about 2.5 hours after the start of the evacuation process. As a result, vehicles en route cannot perform frequent dynamic rerouting to avoid congestion further ahead. In the comparison scenario, the cell communications infrastructure is assumed to be functioning throughout the process, thus vehicles are always routed on the fastest path to their destinations.

    - The confusion over the contraflow on Skyway Road (the main evacuation route) is represented by another set of simulation scenarios, where the base case assumes no contraflow (two lanes going out of the evacuation zone), while alternative scenarios involve three or four lanes leaving the evacuation area.

- ***Traffic***. Between the two major evacuation destinations, most evacuees from Paradise went to Chico due to the higher number of amenities for shelter compared to Oroville (Figure 1(e)). Four major evacuation routes were used (Skyway Road, Clark Road, Neal Road and Pentz Road). The latter three were closed due to fire at different times. However, the traffic signal at the Chico end of Skyway Road was not adjusted, leaving long queues forming on the road. Within Paradise, the traffic congestion was also bad due to the high evacuation demand. About 200-300 residents were trapped due to gridlock and obstacles on the residential roads and were forced to shelter in place at a local, fire-resistant hardware store (Comfort et al., 2019).
    - These findings informed the destination choices for the evacuation simulation. Given that most evacuees went to Chico, the bigger city among the two nearby alternatives, 70 percent of the evacuees are assumed to choose Chico as the final destination, while the remaining are assumed to go to Oroville.
    - The known locations of road closures are incorporated into the simulation: the status of Pentz Road, Clark Road and Neal Road is turned from "open" to "closed" at 8:30 AM, 9 AM and 11 AM, respectively. Once the status is set to "closed," no more new vehicles can enter these road links.
    - The known bottleneck at the Chico end of the evacuation route is represented by placing a limit on the outflow capacity of Skyway Road. Assuming that the signal cycle is one minute, the output capacity is normal in the first 30 seconds but set to 0 in the second half of the cycle. This is expected to create a queue of vehicles backing up along Skyway Road.
    - Given our knowledge that around 200-300 residents were stranded in Paradise, the base values of several relevant parameters were adjusted to reflect such an outcome. Specifically, the probability of road closure upon fire arrival is set to 0.15 and the time that a vehicle waits before sheltering-in-place is set to 1 hour.
    - Background traffic traveling to or through the case study area (including trips within Chico and Oroville) was not considered. This assumption was made as the wildfire situation was broadcast almost in real time, thanks to information exchanged through social media and various news media, and instructions to avoid the affected area were given by the Sheriff's Office and Police Departments. Thus, it is reasonable to assume the travel demand to the affected area from the wider outside region was less than usual. McElwee (2021) found the impact of background traffic to the evacuation to be minimal (less than 10 percent).

Table 1 below summarizes the main findings from the interviews and site studies as well as how these findings are reflected in the simulation process. The system dynamics communication model and its results are discussed in detail in Part II "Communications Modeling." The spatial-queue based traffic model and the results are given in Part III "Traffic Evacuation Modeling." The fire spread modeling is sourced from external inputs and is only introduced briefly in Section III-2.2 as one of the inputs to the traffic simulation model.

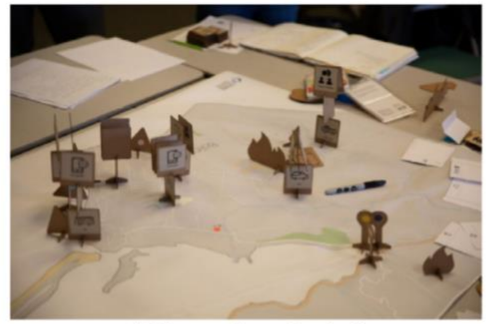
Table 1. Site visit findings and connections to the simulations for the Paradise case study.

Model components and type	Modeling considerations	Modeling assumptions
Fire model: external inputs (NCAR CAWFE simulations)	• Fire was detected at around 6:15 - 6:30 AM. • Ember fires traveled much faster than the main fire front and were a major issue in the Camp Fire evacuation.	• Spot fires triggered by random embers are added to the CAWFE simulation results.
Communications model: system dynamics model	• The first evacuation order to Paradise (east of Pentz Road) was given at around 8:30 AM, while the town of Pulga (not in the case study area) was ordered to evacuate at around 7:30 AM. • Phased evacuation was attempted initially but quickly abandoned due to the rapidity of the fire. • The cell communications infrastructure goes down at about 10:30 AM.	• The communication process starts at 6:15 AM, when the fire was initially detected. • The evacuation order is given at 8 AM, about two hours after the start of the fire, through cell phone-based communication methods. • Three vehicle departure times are considered, with or without phased evacuation. • Two routing scenarios are considered, where vehicles have access to the real-time traffic simulation throughout the evacuation process, or the real-time traffic information discontinues at 10:30 AM (as the cell communications infrastructure went down).
Traffic model: spatial-queue model	• Fire-induced road closures (e.g., falling trees, abandoned vehicles) were a big challenge in the evacuation. • Contraflow was attempted on the Skyway Road. • The traffic signal at the Chico end of the Skyway was not adapted to accommodate the evacuation traffic.	• Three road closure probability scenarios are considered. In general, better roadside fuel management and efficient removal of the hazard lead to lower likelihood of road closure and are better for maintaining a connected network for evacuation. • Three contraflow scenarios are considered, assuming 2 (no contraflow), 3 or 4 lanes on Skyway used for evacuation. • The outflow capacity of the Skyway road is reduced at the Chico end to reflect the effect of a series of unadjusted traffic signals at the location.

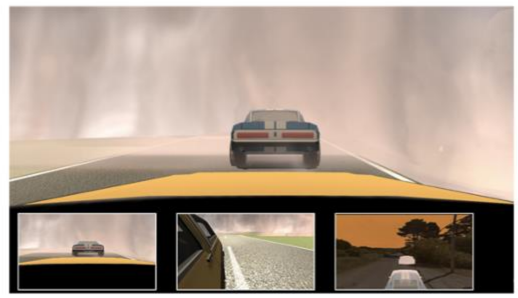
The Bolinas, CA Case Study

During this project, we also paid three site visits to Bolinas and held two additional video conference meetings during the COVID-19 lockdown. Like Paradise, Bolinas is also under fire threat and has foreseeable traffic problems in the event of a fire. Though it only has less than a tenth of the population as Paradise, the small community has a diverse demographic background. Discussions with partners from Bolinas mainly centered around preparedness in terms of fire risks, community cooperation, and evacuation scenarios. Below we summarize our findings from discussions with the Bolinas team and how these are considered in the simulation model.

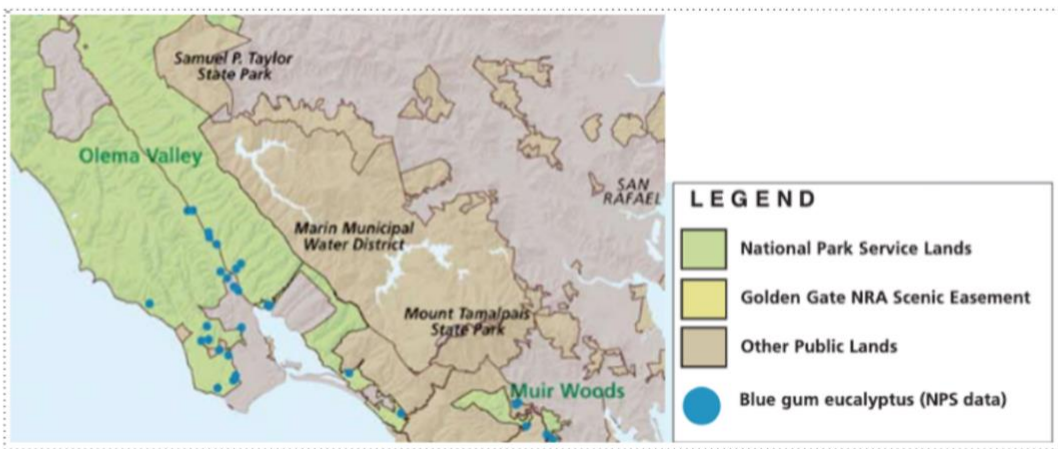
(a) Natural environment and road network in Bolinas



(b) Evacuation role-playing



(c) A digital version of the role-playing game



(d) Locations of Eucalyptus trees in National Parks near Bolinas
(adapted from National Park Service, 2006).

Figure 3. Illustrations of the Bolinas site visits.

- ***Natural environment and fire risk.*** Bolinas has a unique natural environment. It is surrounded by water on three sides and there is only one way out by land on the north side, as shown in Figure 2(a). Seasonal wind comes from the North and Northeast direction. The area immediately outside of the community is covered by grasslands and forests, posing fire risks. Apart from wildfires, Bolinas is also located on the San Andreas Fault, making it susceptible to earthquakes and tsunamis as well.

- For the scenario exercise, three locations within Bolinas were selected as potential fire ignition locations. Fires starting from these locations were simulated under a range of recorded or hypothetical weather conditions.
- Eucalyptus trees are a common fire hazard due to the flammable dead plant materials at their bases and their canopy that spreads embers (National Park Service, 2006). Figure 3(d) shows the locations of Eucalyptus trees on National Park land near Bolinas. Some of the trees are next to the only evacuation route and could potentially present a hazard during an evacuation.

- ***Demography and communication challenges***. According to the 2010 census, Bolinas has 1,600 residents. Small as it is, it consists of distinct population groups, from long-term residents to newcomers (including airbnb guests, vacationers, celebrities, etc.). In addition to the census population, a significant presence in the area is formed by day trip visitors (e.g., hikers and surfers). Their estimated numbers are around 300-500 on a good weekend. The diversity in demography poses issues in evacuation as different groups will potentially not share the same communication network. For example, tourists may have not signed up for the local alert system (Nixle) and short-term lodgers may not have access to informal notifications of evacuation warnings/orders from neighbors. During the COVID-19 pandemic, Bolinas became the first community in California to conduct COVID tests on all residents (including non-English speakers and the homeless groups). Knowledge gained from this community-level activity could also benefit communications in constructing further emergency scenarios.
    - Our current model identifies two target groups: local residents and visitors. In the event of fire, evacuees in these two groups would exhibit different traffic characteristics. For example, visitors would most likely be found around the tourist spots (hiking trails or beachfronts), while local residents, depending on the time and day, would be at home, school or in the downtown areas.
    - In addition, visitors may rely more on telecommunication methods such as social media to receive evacuation orders, while the local residents may have signed up for local emergency alert systems or have a neighbor to inform them of the evacuation order. Cell communication infrastructure damage is thus more likely to disproportionately affect visitors.

- ***Traffic system***. Apart from the fact that the community has only one evacuation route out of town, the Bolinas road network can be understood in three parts. The first part is the residential area (called the Big Mesa locally), which has a regularly gridded street pattern that consists of paved and unpaved two-lane roads (purple box in Figure 3(a)). The second part is the downtown area, which encompasses businesses such as cafes and restaurants (green area in Figure 3(a)). Visitors frequently park on-street on the downtown roads, which limits their capacity. Lastly, the residential roads and downtown roads are both joined to the single way out (yellow lines in Figure 3(a)). The merging point (blue area in Figure 3(a)) and other parts along the evacuation routes are lined with eucalyptus trees, which catch fire easily and may block the evacuation if they fall down. Based on our interviews, most residents would likely evacuate by automobile, though there have been discussions regarding the use of commute buses and school buses to ease the traffic. Given the limited egress capacity, access for emergency vehicles from the outside would likely be difficult.
    - Given the small size and simplicity of the Bolinas street network, we assumed that most people are fairly familiar with the local roads and that rerouting traffic in case of road closures could be easily

accomplished by the evacuees even without access to services like Google Maps. As a result, rerouting is assumed to be unaffected by the loss of cell communication services.

  - Assuming an uninterrupted flow capacity of 1,900 vehicles/hour per lane, the road network should be sufficient to support the evacuation of around 1,500 vehicles in less than one hour. However, if the fire progresses too fast or the main egress road is blocked due to the fire, vehicles still in the evacuation area would then be left in danger. The simulation assumes a shelter-in-place option for the vehicles trapped on the main road. Safe shelters to protect vehicles under a damaged network could become a good backup plan for places like Bolinas with low redundancy in the traffic network.

- ***Organizational resources***. The Bolinas Fire Department (red star in Figure 3(a)) is the first point of response in the event of a fire. It currently has three fire engines and three fire trucks, five full and part time crew members and twenty volunteer fire fighters of various qualifications. In addition, the community can get help from the Marin County Fire Department. Under multiple fires in the region, aerial resources (e.g., firefighting helicopters) will be prioritized to serve smaller wildfires. The Fire Department organized a fire drill in 2018, in which about 200 residents participated. The Fire Board, made up of local residents, meets regularly and sends out newsletters to the community regarding key planning decisions. This helps both the residents and the agency in terms of the fire evacuation planning and execution.

  - Given the limited resources of the local fire department, the key focus is likely to be on coordinating evacuation and ensuring safety in the event of a wildfire. On the traffic side, a critical activity is to clear blocked roads. The tightest part of the Bolinas network has only one lane of egress. This is reflected in the simulation through a “road closure hazard clearance time” variable. In the best case, the hazard can be cleared immediately without delaying the vehicles behind. In two comparative scenarios, the time to clear the blocked roads is set to one and three hours, respectively, to investigate the potential impacts.

Table 2. Site visit findings and connections to the simulations for the Bolinas case study.

Model components and type	Modeling considerations	Modeling assumptions
Fire model: Cellular Automata	• There are vegetation fuels near the community (on the North side) and along the evacuation routes; • The area experiences the hot and dry Diablo winds in the fire seasons.	• Three local fire ignition locations; • Fire simulation inputs are from a series of recorded or hypothesized weather conditions; • Fire may cross the key evacuation routes and cause road closures.
Communications model: System dynamics model	• Multiple demographic groups do not share the same communication network; • The cell communication infrastructure is susceptible to various types of damage in a wildfire event.	• Three levels of cell communication functionality loss corresponding to the three regional fire scenarios are assumed; • Two demographic groups, i.e., the local residents and the visitors, are included. The visitors have higher reliance on cell-based communication modes.
Traffic model: Spatial-queue model	• There is low redundancy in the evacuation routes, particularly after the evacuees have left the residential or downtown areas; • The evacuees from the community will merge onto California State Route 1 (CA 1); • There are no traffic signals in the area; • Two types of fire-induced road closures are assumed. The first is where the simulated flame length is long. The second is based on the locations of the flammable Eucalyptus trees in Bolinas.	• Vehicles are assumed to be familiar with the road network and can find the best available route throughout the evacuation; • Two locations along CA 1 are set as the safe destination. One location (going north) may not be available if a regional fire also occurs near it; • Time taken to clear blocked road is used as a scenario variable; • Availability of shelters in case of being trapped is used as another scenario variable.

During the Bolinas site visits mock evacuation drills were conducted through a tabletop role-playing board game (Figure 3(b)). A digital version of the game is under development (Figure 3(c)). Although the game settings would be significantly different from a real fire, the purpose was to collect knowledge regarding the behaviors and priorities of residents under a variety of scenarios, such as their modes of communication, modes of transportation, household-level activities (e.g., picking up a child or checking on a friend), evacuation or sheltering decisions under traffic disruptions, etc. Designs and findings from these role-playing games will be made available in a future separate report.

The Bolinas team also provided valuable feedback regarding the development of the fire, communications, and traffic simulations. These simulations will be presented in Part III of this report.

Part I. Fire Spread Modeling

I-1. Fire Modeling

For this study, we conducted a series of fire simulations based on the Bolinas case study in consultation with partners from the Bolinas Fire Board. The fire simulation is carried out using FARSITE software (Firelab, 2020b). The methodology, model inputs, and results are given in this section. Details of the software description are given in the Appendix A.1. For the Paradise Camp Fire case study, the fire spread was not simulated by our team. Instead, an existing simulation using the CAWFE software conducted by researchers at the National Center for Atmospheric Research is used (UCAR, 2020). Details regarding the reuse of the CAWFE results are given in Section III-2, “Camp Fire Case Study."

I-2. Methods of Fire Simulation

Fire is an exothermic chemical reaction of a combustible substance with a comburent, which aids combustion and results in heat, flame, gas, smoke, and light. Wildfire is a complex form of fire influenced by many environmental factors, including vegetation status, topological features, weather conditions such as the wind speed and direction, temperature, humidity level and so on. Changes in any one of these can directly affect the progression of the wildfire.

The ignition and evolution of wildfires are extremely hard to predict. Nevertheless, there have been numerous theories proposed to better describe or to model the process quantitatively. The evolution of a wildfire usually consists of four steps. In the initial growth phase, the intensity of the fire front is low. In the second “transition” phase, the intensity of the fire grows, and the front assumes bigger dimensions. In the third phase, the fire reaches its maximum intensity, and a huge amount of thermal energy is released from the fire front leading to the most damage. Spotting (generation of embers) also occurs in this stage. Spotting is the occurrence of new ignitions by the embers carried by wind further away from the main fire, which greatly increases the difficulty of fire suppression and may suddenly change the evolution of the fire. This phenomenon is linked to canopy fire (fire that involves the canopy of the trees) more than the surface fire (fire that spreads mainly on the ground). The higher the trees are, the further the embers could drift. Also, embers that are bigger in size are more likely to land and start new fires. Finally, there is the decay phase, where both the speed and the intensity of the fire decreases. The last phase can last a long time or stop suddenly as a result of changed weather conditions, topography, or the characteristics of the fuels (Sauberman, 2010).

Various types of theoretical, physics-based or numerical models have been proposed to model the propagation of wildfires. The main model used for this study is the semi-empirical FARSITE model included in the FlamMap software. The model inputs and results are given in the following text. In addition, a more computationally intensive physics-based Wildland-Urban Interface Fire Dynamics Simulator (WFDS) is also used to develop 3D fire effects for a realistic evacuation simulation (Figure 2(c)). Software details of the FARSITE model and the WFDS are given in Appendices A.1 and A.2.

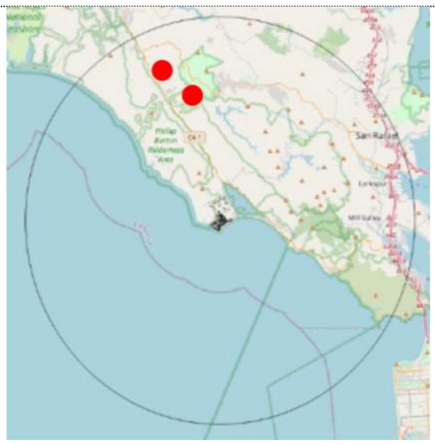
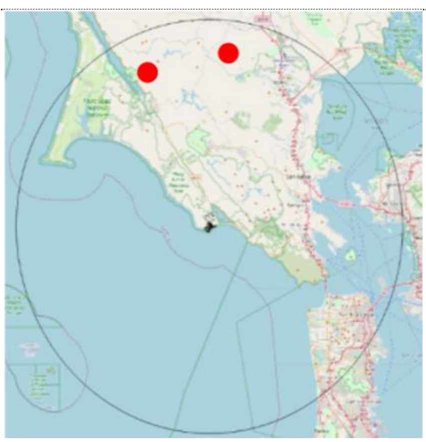
I-3. Fire Scenario Inputs

I-3.1 Fire locations

The fire simulation considers multiple outbreaks inside and outside of Bolinas. The regional fire scenarios include (1) a localized fire in Bolinas without a regional fire; (2) a localized fire plus a regional fire (within a 15-mile radius of Bolinas) that partially damages the cell communication infrastructures; and (3) a localized fire plus a larger regional fire further away in Marin County (within a 25-mile radius of Bolinas) that completely damages the cellular network. The reason to consider these three fire locations is to differentiate the potential disruptions that Bolinas may face due to outside impacts. For instance, a regional scale fire may damage critical communication infrastructures such as power grids, which may affect cell communication infrastructure functionality and the dissemination of the evacuation orders inside Bolinas.

For the localized fire simulation, three potential local fire ignition points were considered. After discussions with the Bolinas team, the three local ignition locations chosen were (1) an unpopulated grassland northwest of the residential area; (2) the grassland close to Mesa Road on the north side; and (3) the forest area close to Horseshoe Hill Road on its west. The locations of these areas are shown in the first row in Table 3. These high-risk locations are selected to represent a diverse range of environmental factor combinations, such as the fuel type (e.g., near forest, grassland or eucalyptus trees). In addition, these three ignition locations also represent different levels of threat to the evacuation road network. Location 1 is slightly farther away from key evacuation routes compared to the other two choices, and thus poses less risk of cutting off the only evacuation route. Comparing these scenarios in the traffic simulation will lead to enhanced understanding regarding the potential damage caused by fires starting at different locations within Bolinas.

Table 3. Fire scenarios

Ignition location	Fire scenario
	**Localized fire** This scenario simulates a localized fire inside Bolinas. Three ignition locations are considered. One is to the northwest of the residential area (the Big Mesa). The second location is close to the Mesa Road (a key evacuation route for the residential area) and the last location is right next to Olema Bolinas road, the main escape road. These locations were selected in consultation with the Bolinas team, considering both (1) the presence of fuel; and (2) varied levels of proximity, and potential impacts to the residential area or key evacuation routes.
	**Localized fire + small regional fire** This scenario considers a localized fire plus a regional fire within a 15-mile radius of Bolinas that propagates with increasing speed. Compared with the localized fire, the regional fire covers a wider area and burns for a longer time. Two ignition points are considered for the regional fire, including one that is closer to Highway 1 (the egress route for Bolinas and many nearby small communities), but more on the north side and farther away from Bolinas. The second ignition point is south of the first point, while at the same time farther away from Highway 1 but slightly closer to Bolinas. This regional fire is assumed to cause damage to the critical infrastructure and interrupts the cell communication system in the area.
	**Localized fire + large regional fire** This scenario represents a local fire in Bolinas plus a large fire that is within a 25-mile radius of Bolinas. The fire is driven by strong and dry winds from the east. This is the largest fire simulated in terms of the areas covered. The ignition point is around Petaluma and draws in all firefighting resources. The two ignition points for this huge fire are close to the regional highways (Highway 1 and Highway 101). This large fire is assumed to damage the cell communication system in the area completely.

I-3.2 Weather conditions

Weather conditions (wind speed, wind direction, humidity, cloud cover and temperature) provide important information needed to run the fire spread simulation program. Such information is obtained mainly from the historical records of the local weather stations. Figure 4 shows the locations of the weather stations near Bolinas.

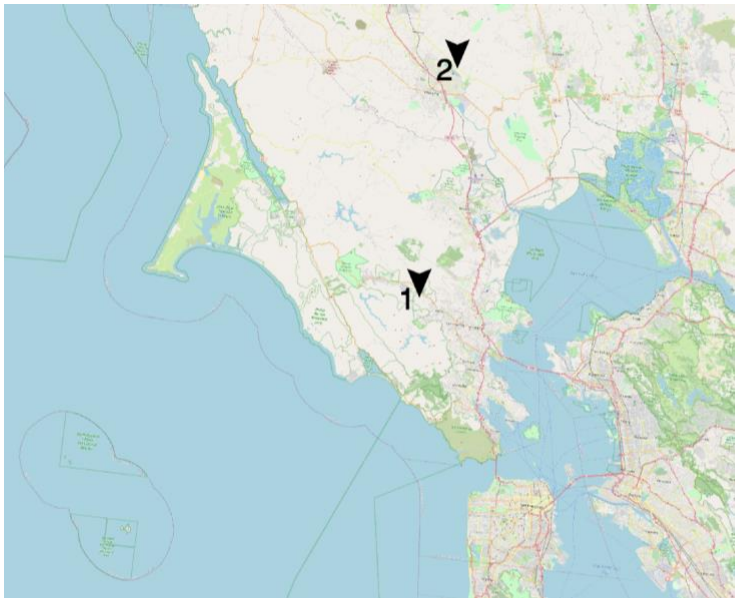


Figure 4. Locations of Bolinas vs weather stations. Station 1: Woodacre. Station 2: Santa Rosa (CEFA, n.a.).

Table 4 shows the weather condition inputs used for the FARSITE simulation. For each regional fire scenario and the multiple ignition points associated with the scenario (3 ignition locations for fire within Bolinas, 2 ignition locations for fire within 15 and 25 miles of Bolinas), five different weather conditions are considered. These include one hypothesized weather condition and four real weather conditions taken from the historical weather station records. The historical records consider some of the worst weather conditions that have occurred in the past, while the hypothetical cases are based on the researchers' understanding of the worst combination of weather conditions in the area, although the specific combinations have not been observed in the past. No hypothetical case is considered for the "large regional fire" scenario (the last row in Table 4), since it is not likely to happen under typical weather conditions.

To define the hypothesized weather conditions, data from the past 17 years were analyzed for the period from May to November. From these data the conditions considered the worst for fire propagation were chosen, such as wind direction from the north, medium wind speed, low relative humidity and medium temperature. Those features are not the most common for Bolinas but are all realistic and usually happen at some time in the year.

For Scenario 3 the aim is to simulate fire under the extreme condition of Diablo winds. Because this is an extremely variable phenomenon over the years, it is difficult to define conditions that repeat over the years as was done for Scenarios 1 and 2. For this reason, we chose not to consider hypothetical conditions but to use real weather scenarios that occurred in the past.

Table 4. Weather conditions.

Fire locations	Weather scenario 1	Weather scenario 2	Weather scenario 3	Weather scenario 4	Weather scenario 5
Fire in Bolinas only, or with medium regional fire	Hypothesized weather conditions 9:00 AM - 7:00 PM Relative Humidity: 15% Wind Speed: 15-18 mph Wind Direction: NNE Cloud Cover: 0% Temperature: 65 °F	Historical records Aug 13th, 2009 9:00 AM - 7:00 PM Relative Humidity: 35-40% Wind Speed: 10 - 14 mph Wind Direction: E Cloud Cover: 2% Temperature: 76 °F	Historical records Oct 3rd, 2009 9:00 AM - 7:00 PM Relative Humidity: 45 - 50 % Wind Speed: 18 - 20 mph Wind Direction: NNE Cloud Cover: 0% Temperature: 65 °F	Historical records Nov 17th, 2014 9:00 AM - 7:00 PM Relative Humidity: 45% Wind Speed: 11 - 14 mph Wind Direction: E Cloud Cover: 0% Temperature: 51 °F	Historical records May 3rd, 2015 9:00 AM - 7:00 PM Relative Humidity: 70 % Wind Speed: 8 - 10 mph Wind Direction: ESE Cloud Cover: 0% Temperature: 56 °F
Fire in Bolinas, with large regional fire	No hypothesized scenarios considered	Historical records Nov 20th, 2004 10:00 AM - 8:00 PM Relative Humidity: 20 % Max Wind Speed: 46 mph Wind Direction: SSE Temperature: 60 °F	Historical records Nov 22nd, 2013 10:00 AM - 8:00 PM Relative Humidity: 8 % Max Wind Speed: 47 mph Wind Direction: NNE Temperature: 65 °F	Historical records Oct 9th, 2017 10:00 AM - 8:00 PM Relative Humidity: 18 % Max Wind Speed: 68 mph Wind Direction: SSE Temperature: 70 °F	Historical records Oct 27th, 2019 10:00 AM - 8:00 PM Relative Humidity: 13 % Max Wind Speed: 63 mph Wind Direction: NE Temperature: 61 °F

The actual weather data can be downloaded from weather stations' records hosted on the National Fire and Aviation Management website (n.a.), however, some of the hypothetical scenarios were developed based on the researchers' experience. Specifically, data from the following two weather stations are used:

- The Woodacre station (2003-2010/ 2012-2019): for the localized fire scenario and medium-level regional fire scenario (1st and 2nd row in Table 4).
- The Santa Rosa station (1991- 2019): for the large regional fire scenario (3rd row in Table 4).

The data were then processed with the FireFamilyPlus software (FireLab, 2020a). The software was also used for creating fuel moisture input files apart from the humidity and wind inputs and supports querying historical meteorological events of specific places/stations.

Apart from the fire locations and weather data, there are other spatial and topographical data inputs required to run the FARSITE simulation. These are called themes and five basic themes are required for FARSITE: elevation, slope, aspect, fuel status, and canopy cover. Other potential themes include tree height, crown base height, crown bulk density, etc. These inputs were downloaded from various online databases and openly available datasets such as the LandFire database (LANDFIRE Program, n.a.).

I-3.3 Fire simulation results

The time-stamped fire footprint by hourly interval for the localized fire in Bolinas is shown in Table 5. For the hypothesized weather conditions as well as for the two historical weather events, the scale of the fire in terms of acreage burnt is the smallest for the fire starting from ignition location 1. This may be due to the specific vegetation and topology of the site. Also, since fire ignition location 1 is close to the residential area but far away from the evacuation route; it poses the least risk of potentially blocking the evacuation route. Fire ignition location 2 is in the middle of the residential area and the evacuation route, which may lead to the most dangerous results, as it quickly engulfs both within a short time from the start of the simulation. Comparatively, fire ignition location 3 for the localized fire is just next to Horseshoe Hill Lane and quickly moves towards the residential area driven by the wind coming from the northeast.

Results for the medium regional fire scenario are presented in Table 6. Under most weather conditions, the fire has the potential to develop over California State Route 1. Although not considered in the traffic simulation, this ignition has the potential to cause road blockages along the highway, delaying external response support and cutting off the northbound evacuation traffic from Bolinas.

For the large regional fire that is about 25 miles away from Bolinas, its development depends more on weather conditions (Table 7). The conditions chosen for this scenario are characteristic of the meteorological event that in California is called Diablo wind, extremely hot and dry. This scenario has been chosen to simulate a catastrophic fire situation. In fact, compared with scenario one and two, scenario three extends farther around the area with forests and trees, so the intensity of the flames is high. Diablo winds are a huge problem in case of fire because they can drive violent wildfire events. This scenario also includes a small fire occurring around Bolinas in order to consider the urgency to evacuate the city when a big fire is expanding, and most firefighter resources are involved outside the community. So, the fire near Bolinas becomes harder to contain due to the lack of resources and the priority given to the larger fire.

Table 5. Local fire

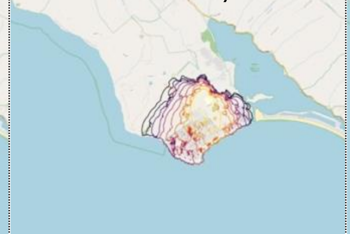
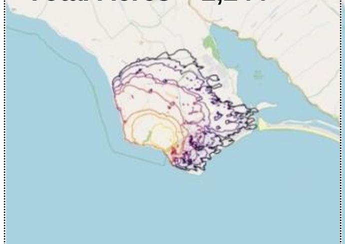
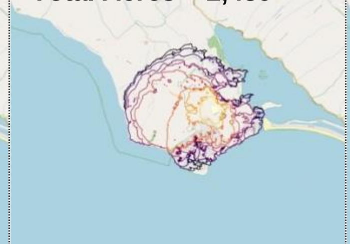
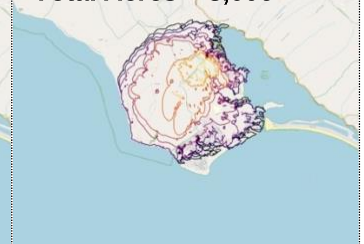
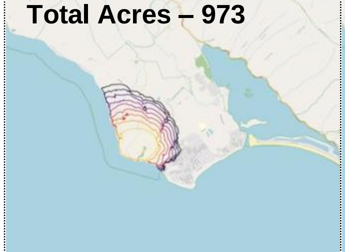
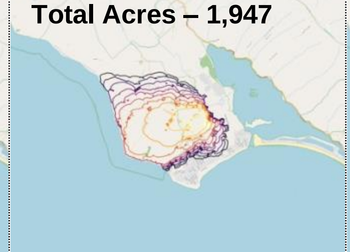
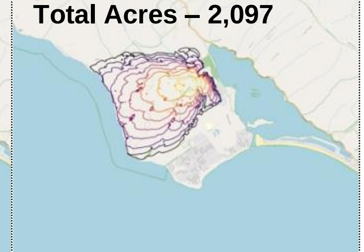
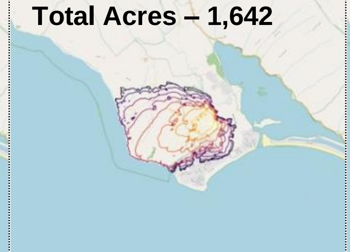
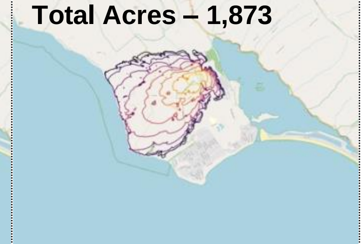
Localized fire	Ignition point 1	Ignition point 2	Ignition point 3
Hypothesized weather conditions 9:00 AM - 7:00 PM Relative Humidity: 15% Wind Speed: 15-18 mph Wind Direction: NNE Cloud Cover: 0% Temperature: 65 °F	Total Acres – 935 	Total Acres – 1,357 	Total Acres – 2,247 
Historical records Aug 13th, 2009 9:00 AM - 7:00 PM Relative Humidity: 35-40% Wind Speed: 10 - 14 mph Wind Direction: E Cloud Cover: 2% Temperature: 76 °F	Total Acres – 2,460 	Total Acres – 2,360 	Total Acres – 2,130 
Historical records Oct 3rd, 2009 9:00 AM - 7:00 PM Relative Humidity: 45-50% Wind Speed: 18 - 20 mph Wind Direction: NNE Cloud Cover: 0% Temperature: 65 °F	Total Acres – 2,244 	Total Acres – 2,439 	Total Acres – 3,006 
Historical records Nov 17th, 2014 9:00 AM - 7:00 PM Relative Humidity: 45% Wind Speed: 11 - 14 mph Wind Direction: E Cloud Cover: 0% Temperature: 51 °F	Total Acres – 973 	Total Acres – 1,947 	Total Acres – 2,097 
Historical records May 5th, 2015 9:00 AM - 7:00 PM Relative Humidity: 70% Wind Speed: 8 - 10 mph Wind Direction: ESE Cloud Cover: 0% Temperature: 56 °F	Total Acres – 766 	Total Acres – 1,642 	Total Acres – 1,873 

Table 6. Fire within 15 miles radius

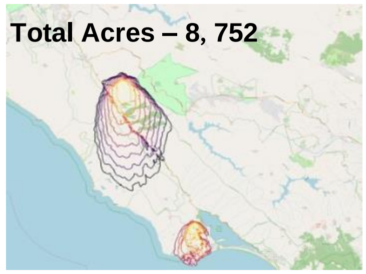
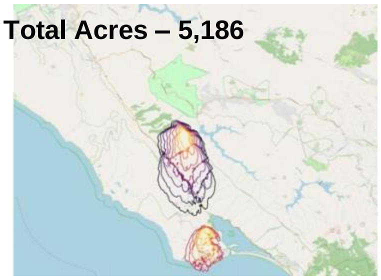
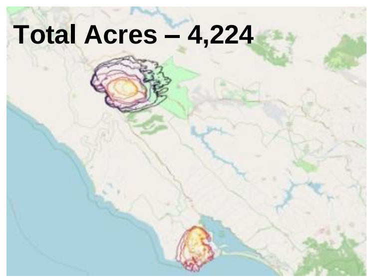
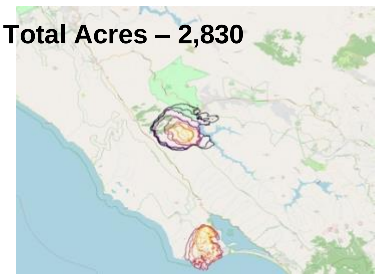
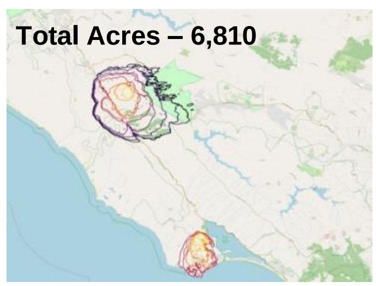
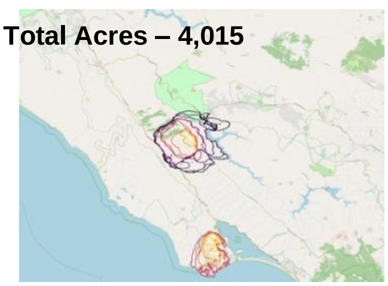
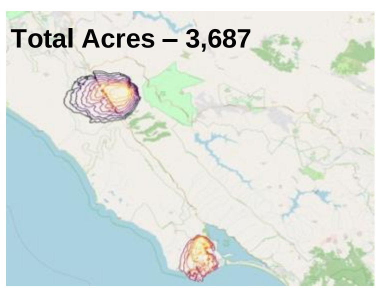
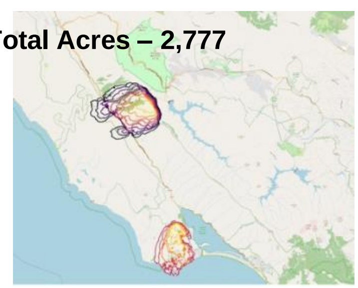
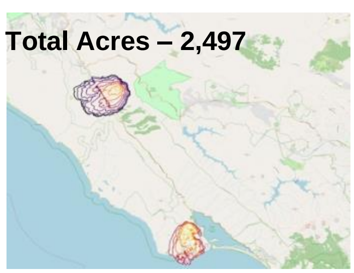
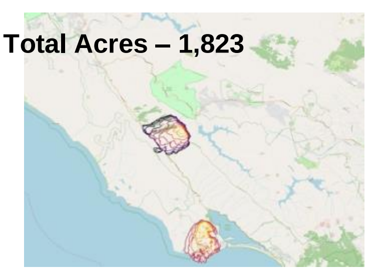
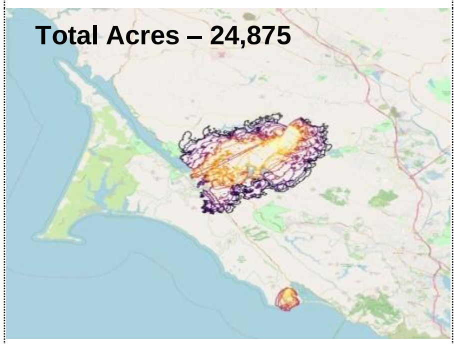
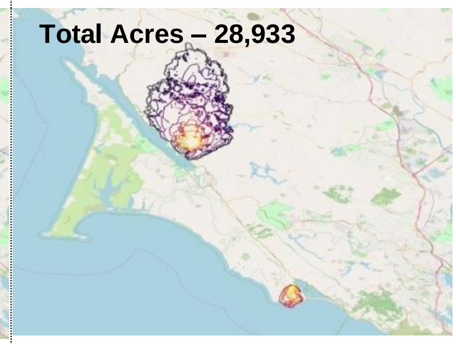
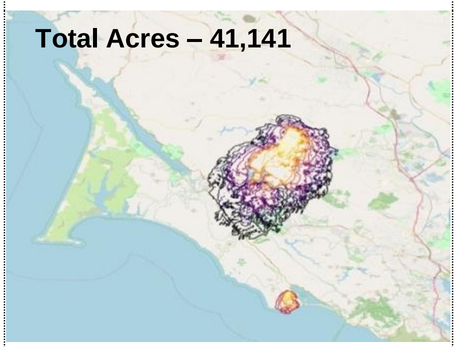
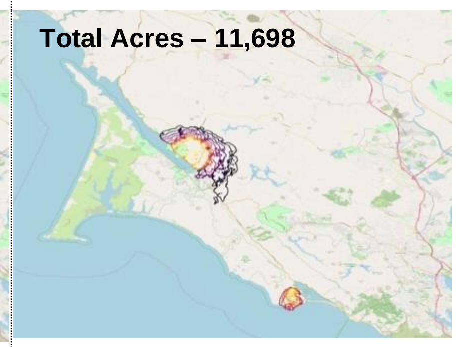
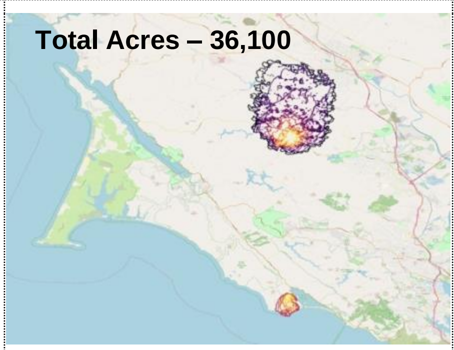
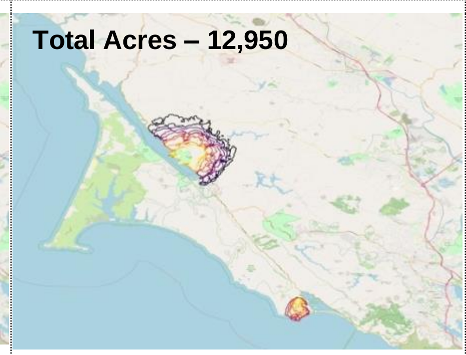
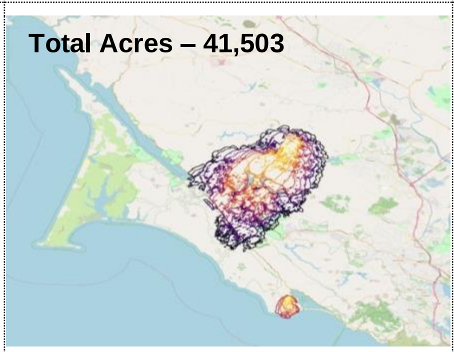
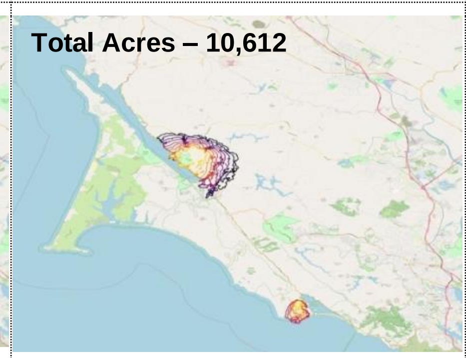
Medium Regional Fire	Ignition point 1	Ignition point 2
Hypothesized weather conditions 9:00 AM - 7:00 PM Relative Humidity: 15% Wind Speed: 15-18 mph Wind Direction: NNE Cloud Cover: 0% Hourly Precipitation: 0.00 Inch		
Historical records Aug 13th, 2009 9:00 AM - 7:00 PM Relative Humidity: 35-40% Wind Speed: 10 - 14 mph Wind Direction: E Cloud Cover: 2% Temperature: 76 °F		
Historical records Oct 3rd, 2009 9:00 AM - 7:00 PM Relative Humidity: 45 - 50 % Wind Speed: 18 - 20 mph Wind Direction: NNE Cloud Cover: 0% Temperature: 65 °F		
Historical records Nov 17th, 2014 9:00 AM - 7:00 PM Relative Humidity: 45% Wind Speed: 11 - 14 mph Wind Direction: E Cloud Cover: 0% Temperature: 51 °F		
Historical records May 5th, 2015 9:00 AM - 7:00 PM Relative Humidity: 70 % Wind Speed: 8 - 10 mph Wind Direction: ESE Cloud Cover: 0% Temperature: 56 °F		

Table 7. Fire within 25 miles radius

Large Regional Fire	Ignition point 1	Ignition point 2
Historical records Nov 20th, 2004 10:00 AM - 8:00 PM Relative Humidity: 20 % Max Wind Speed: 46 Mph Wind Direction: SSE Temperature: 60 °F		
Historical records Nov 22nd, 2013 10:00 AM - 8:00 PM Relative Humidity: 8 % Max Wind Speed: 47 Mph Wind Direction: NNE Temperature: 65 °F		
Historical records Oct 9th, 2017 10:00 AM - 8:00 PM Relative Humidity: 18 % Max Wind Speed: 68 Mph Wind Direction: SSE Temperature: 70 °F		
Historical records Oct 27th, 2019 10:00 AM - 8:00 PM Relative Humidity: 13 % Max Wind Speed: 63 Mph Wind Direction: NE Temperature: 61 °F		

I-4. Summary and Discussion

In Part I of this report, the fire simulation component of the study framework is explained in detail based on a case study in Bolinas. Three regional fire scenarios under various hypothetical or historical weather scenarios are studied. Occurrences of regional fires while a local fire is going on in Bolinas have the potential to damage key communication infrastructures (e.g., the power supply to the cell towers in Bolinas), thus creating different levels of disruption to communications for the Bolinas evacuation simulations. The changes in communications efficiency under different levels of cell infrastructure damage will be explained in Part II, Section II-3.2 “Communications Modeling: Bolinas, CA.” In addition, based on the time-stamped fire progression results, the traffic network is also under various threat levels. For local fires in Bolinas, depending on the start location and weather conditions, the fire may block the evacuation route or endanger the residential and commercial areas. These are considered in the traffic simulation to show the challenges of evacuating from a threat of wildfire. Regional fires may impact the operation of the highway and affect access for emergency crews from the outside or the egress of the evacuation traffic. These issues are not considered explicitly in the current traffic simulation, although some scenarios (e.g., time to clear closed roads in Bolinas) are indirectly related to the amount of emergency response resources available, which may come from outside the area. In such cases, highway closures due to extended periods of fire outside of Bolinas may negatively impact the emergency response resources available in Bolinas. The integration of the fire simulation results into the Bolinas evacuation simulation will be presented in Part III, Section III-3 “Traffic Evacuation Modeling: Bolinas, CA.”

Part II. Communications Modeling

II-1. Communication Process Modeling

This section explains how we model communication processes, i.e., providing the public with notification of the evacuation orders, using a system dynamics model. A system dynamics model is a highly abstract way to represent the status change of a complex system that ignores fine details such as individual properties (The AnyLogic Company, n.a.). Here, the complex system is formed by the emergency response personnel and the evacuees and the aim is to simulate the process whereby the evacuees gradually become aware of the evacuation order. The reason for adopting a system-dynamics model rather than a more detailed agent-based model is due to the limited available data regarding the communication process of each individual. In such a case, a system dynamics model allows us to gain a better understanding of the importance of communication methods. Specifically, the interest here lies in the speed that an evacuation order can spread within the community, which depends on the availability and functionality of the communication mechanisms that can be used under wildfire events. Based on previous site visits, interviews, and documentary reviews, seven main communication methods are identified, ranging from efficient fire and ham radios and cell phone alerts to slow door-to-door notifications and cognition-based signs of fire danger. Among them, the communication methods relying on cellular data to function (e.g., social media announcements or cell phone calls) may be interrupted during wildfire events.

II-2. Methods and Software Setup

The system dynamics model for this study is constructed using the AnyLogic software (The AnyLogic Company, 2020). Figure 5 below is a screenshot from the AnyLogic software and illustrates the modeling methodology. For each case study area and scenario, a total population is identified, represented by a source icon on the left. This population equals the total number of residents in Paradise, or the total number of residents and tourists in the Bolinas case study. Initially, all individuals in the initial populations are assumed to be uninformed and unaware of the fire danger. As the fire starts and spreads, the official evacuation orders are sent out to these populations through the following methods, ranked by the rate of efficacy of the communication mode (i.e., number of people notified per minute): fire radios, ham radios, social media platforms, CodeRED alerts, cell phone calls and lastly the door-to-door notification. In addition, for the group of people without access to any of the above mechanisms, they can still perceive the fire danger and make the decision to evacuate if they directly perceive the risk, e.g., the fire front gets close to their current locations. As time proceeds, the initially uninformed and unaware population groups gradually join the evacuation process (represented by the sink icon on the right of Figure 5). People may have access to more than one communication method. However, in the simulation we assume that they will be informed by one communication method (the fastest channel that delivers the information to them).

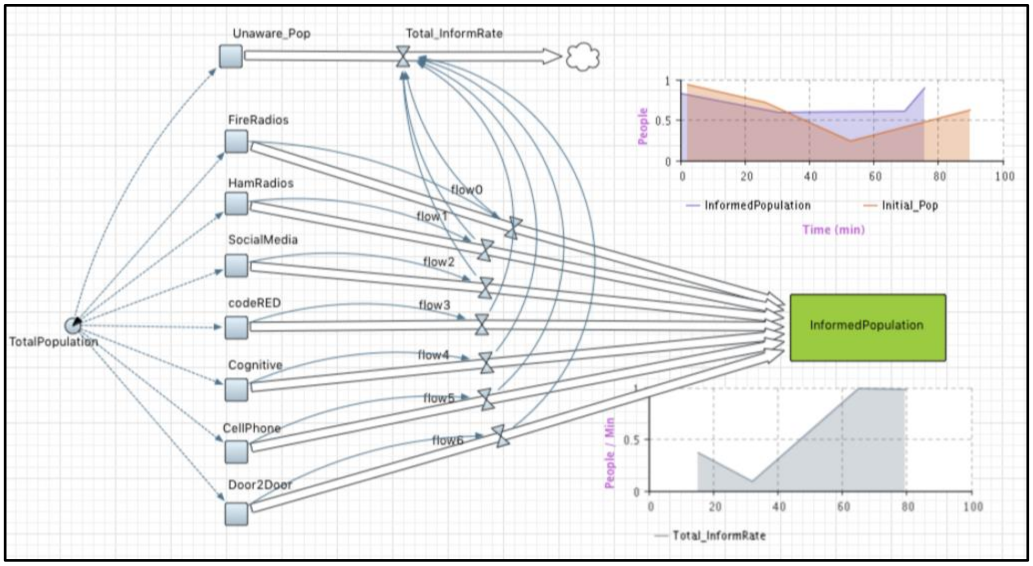


Figure 5. System dynamics model of the evacuation order notification process in AnyLogic.

Table 8 summarizes the characteristics of each communication method considered in the system dynamics simulation. The fire radios and ham radios are among the fastest channels for the evacuation order to be sent out, taking only one or two minutes after the official evacuation order is made. However, only the emergency response personnel and radio operators/enthusiasts may have access to them, thus limiting the number of recipients who can be reached. In comparison, cell phone-based communication methods such as the announcement of the evacuation order on social media platforms or sent through the CodeRED alert systems on landlines can reach a large number of people, but they can only deliver the information to people who are listed in the public telephone directory, or who have signed up for the CodeRED program on a mobile app, or who are following the public agencies' warnings or seeing reposts on social media. In addition, according to a previous study (Anderson et al., 2020), these methods are dependent on the functionality of the cell communication, which may not be totally reliable during wildfire events due to loss of power, damage to backhaul fibers (buried fiber cables that connect the core network to the cell sites) or damage to the structure itself.

In the unfortunate event of cell communication infrastructure damage, door-to-door notifications are adopted to inform the rest of the population. In the system dynamics model, the door-to-door communication is modeled as the slowest communication method; only able to inform 2.5 people per minute for the Bolinas study. For the Paradise study, we assumed that the door-to-door communications are used to inform 10 percent of the population in a time span of one hour, which is equivalent to an information spread rate of 44 people per minute.

Cognition-based notification of the wildfire risk is also considered. Unlike other methods, the cognition-based approach represents the situation when the fire gets too close, and the residents or visitors make their own decisions to evacuate even before receiving the official evacuation order. In the system dynamics model, due to the lack of spatial dimension to represent the distance between the evacuees and the fire front, an estimated rate of spread is assumed for the cognition-based communication: 10-30 people per minute are assumed to leave by visual cognition of the fire danger for the Bolinas study, and 15 percent of the population in 15 minutes for the Paradise study (178 people per minute). The cognition-based approach was modeled in greater detail in the traffic simulation part for the Bolinas study, using spatial information and considering the distance to the fire as a trigger of the cognition-based evacuation decision for every vehicle in the simulation model.

Table 8. Characteristics of communication methods.

Communication mechanism	Characteristics
Fire and police radios	Pros: fast, reaches the recipients almost immediately after the first report of the fire. Cons: only the emergency response personnel have fire radios.
Ham radios	Pros: fast, owners get informed almost as soon as the emergency personnel use fire radios. Cons: only very few people are estimated to have ham radios.
Social media platforms	Pros: relatively fast and can reach a large number of recipients. Cons: dependent on cell communication functionality and only available to social media users; information may not be reliable.
CodeRED/Nixle/AlertMarin alerts	Pros: relatively fast and can reach a large number of recipients. Cons: dependent on landlines for broad public dissemination, and on cell communication functionality and program signup rate for app-based dissemination.
Cell phone calls	Pros: medium speed and can reach a relatively large number of recipients. Cons: dependent on cell communication functionality and personal networks.
Door-to-door notifications	Slow, used only when other communication methods fail.
Cognition	Pros: allows evacuees to mobilize before receiving official evacuation orders if close to fire. Cons: Evacuees mobilized through this method (e.g., seeing the fire) may already be very close to the fire danger.

Additionally, it should be noted that the model presented in this study is simple; it is merely intended to present the logic of the information flow, with no feedback involved. Consequently, an equivalent model was also built in Excel for verification, calculation, and plotting. In a more advanced system dynamics model, the AnyLogic software would not be replaced by Excel calculations.

II-3. Case Studies

The communication process simulations were conducted for the two case study sites: Paradise and Bolinas. The respective modeling assumptions and results of each case study are presented in this section.

II-3.1 Camp Fire, Paradise, CA

As learned from the Camp Fire evacuation experience, communications (city-to-city, agency-to-residents) play important roles in coordinating traffic operations and safeguarding region-wide evacuation processes in wildfire events. For the communications network layer of the Camp Fire case study, using the information that we have obtained from our field study, we first developed a communications network map of the organizational actors, including key social subnets, or affinity groups, within the community of Paradise, and actual patterns of organizational or informal communication among them during the wildfire event, as illustrated in Figure 6.

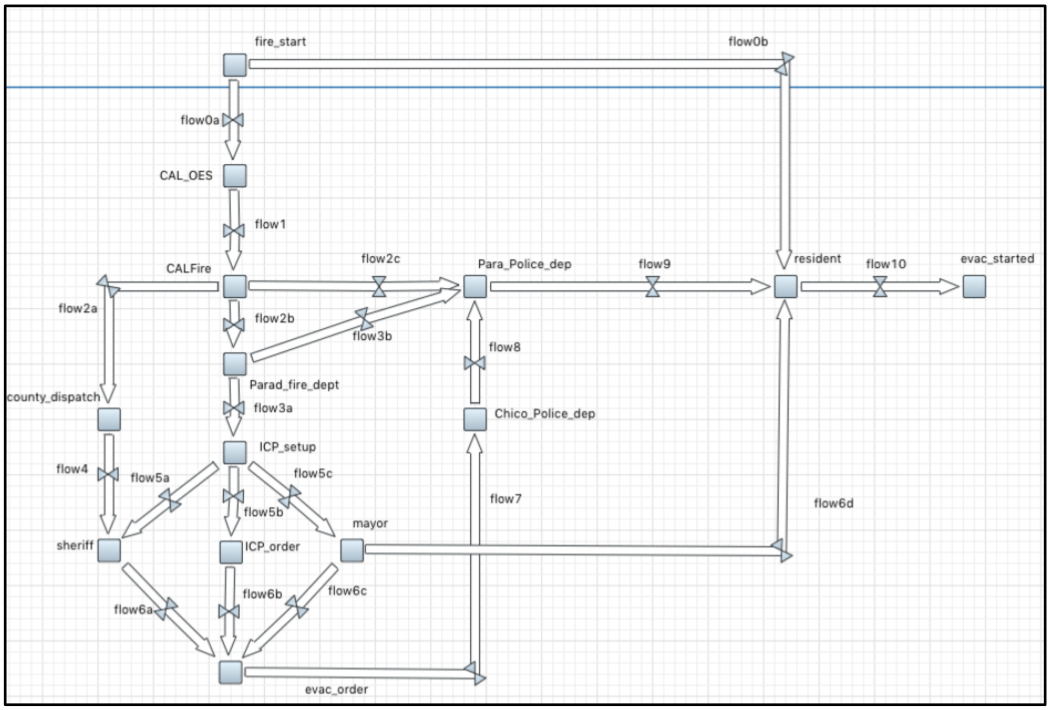


Figure 6. Maps of key players and information flow between them during the Camp Fire evacuation.

For the system dynamics model, the focus is on the information propagation between the agencies and the residents, as shown in the schematic diagram in Figure 6. The intermediate steps (e.g., from Cal OES to Cal Fire, the ICP, the Sheriff's Office and the Mayor's Office) are abstracted from an initial delay in start time due to gaps in the communications process. Table 9 below gives the start time, the proportions of population informed, and the information spread rate of different communication methods used for the Paradise simulation. The notification rate is given by the number of people informed per minute by each communication method. The notifications are not whole numbers, as they are calculated by dividing the "population informed by each communication method" and the "estimated time for each communication method to notify everyone in the same category." For example, we estimated that it would take five minutes to notify 20 percent of the population (26,682 in total) through CodeRED alerts, leading to 26,682 $\times$ 20% / (5 minutes) = 1,067 (people per second) as the notification rate of the CodeRED communication. The percentages of the population notified by each communication method is also shown in Figure 7.

Table 9. Inputs to the Paradise communication simulation model.

Communication mechanism	6:20 AM fire start time	Total time span (minute)	Percentage of population informed	Notification rate (people per minute)
Fire radios	6:36 AM	1	5%	2,668
Ham radios	6:37 AM	1	5%	2,668
Social media platforms	8:05 AM	1	20%	5,336
CodeRED alerts	8:44 AM	5	20%	1,067
Cell phone calls	8:20 AM	40	30%	200
Cognition	8:10 AM	15	10%	178
Door-to-door notifications	9:20 AM	60	10%	44

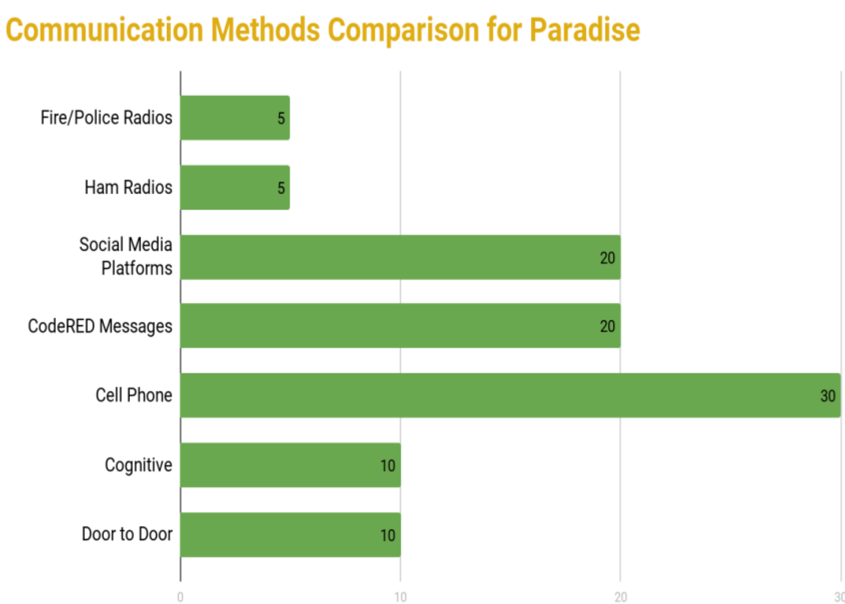


Figure 7. Percentages of the population notified by each communication method for the Paradise case study.

Based on the above assumptions and according to our AnyLogic simulation results, it would take 4 hours with 7 communication methods to inform all the people in Paradise after the start of the fire at around 6:20 AM. The change in the numbers of informed population over time is shown in Figure 8. Before 8:05 AM, only around 10 percent of the population are informed, who are mostly emergency personnel having access to fire or police radios, or residents owning ham radios that pick up the fire/police radio signals. The notification rate starts to pick up significantly after 8:05 AM, as cell-based communications (social media, CodeRED and cell phone calls) start to work. Cognition-based evacuation begins during this time as well, around 8:10-8:25 AM and representing 10 percent of the population — evacuees who made the decision to leave by seeing the fire rather than having received an official evacuation order. Lastly, after 9:20 AM, the final 10 percent of the population in Paradise who had not received any other form of the evacuation order are notified by door-to-door communication, shown as a rather flat line at the end of the curve in Figure 8.

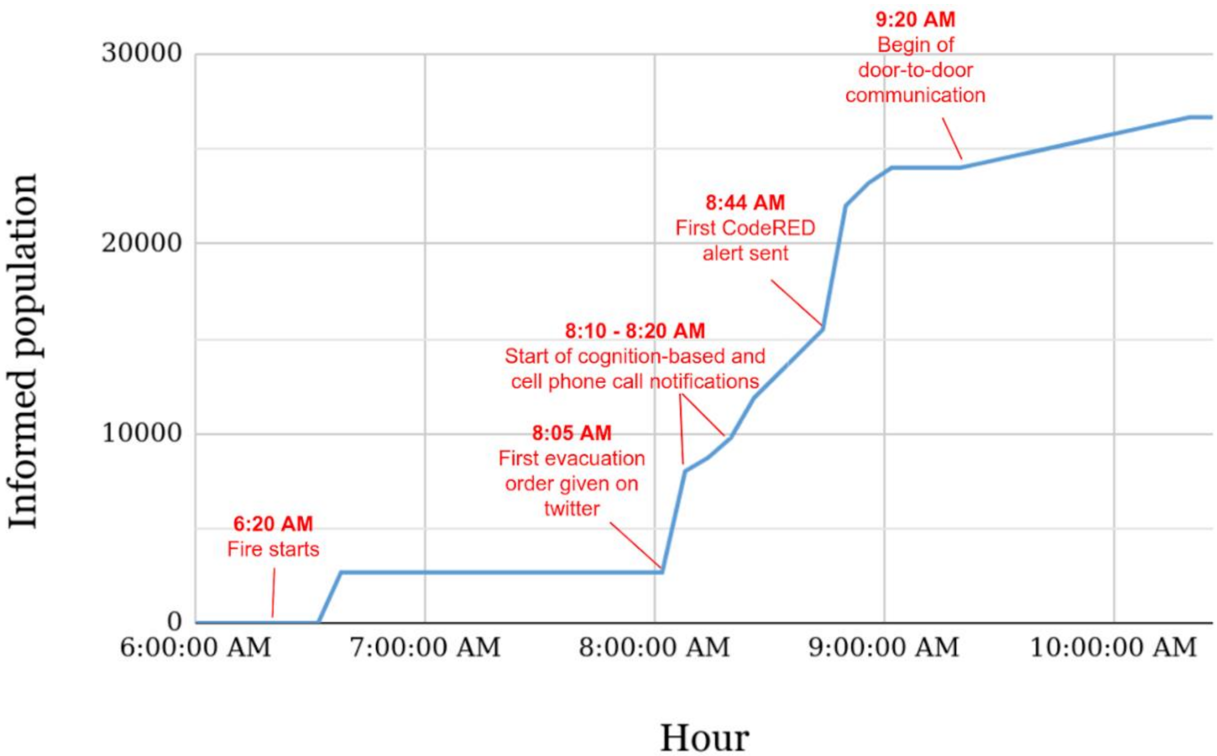


Figure 8. Changes of the numbers of the informed population in Paradise with time.

II-3.2 Bolinas, CA

A similar system dynamics simulation model was built for the second case study area, the community of Bolinas, CA. Since we were able to talk directly with the emergency personnel and local residents of Bolinas, a more involved set of scenarios was developed. Based on our discussions with the team, we understood that a 911 call reporting the fire would first be received by the Marin County Fire Department's dispatch center, or the CHP if the caller is on the highway. This information would then be sent to the Bolinas Fire Department to initiate local responses such as giving evacuation orders or combating the fire.

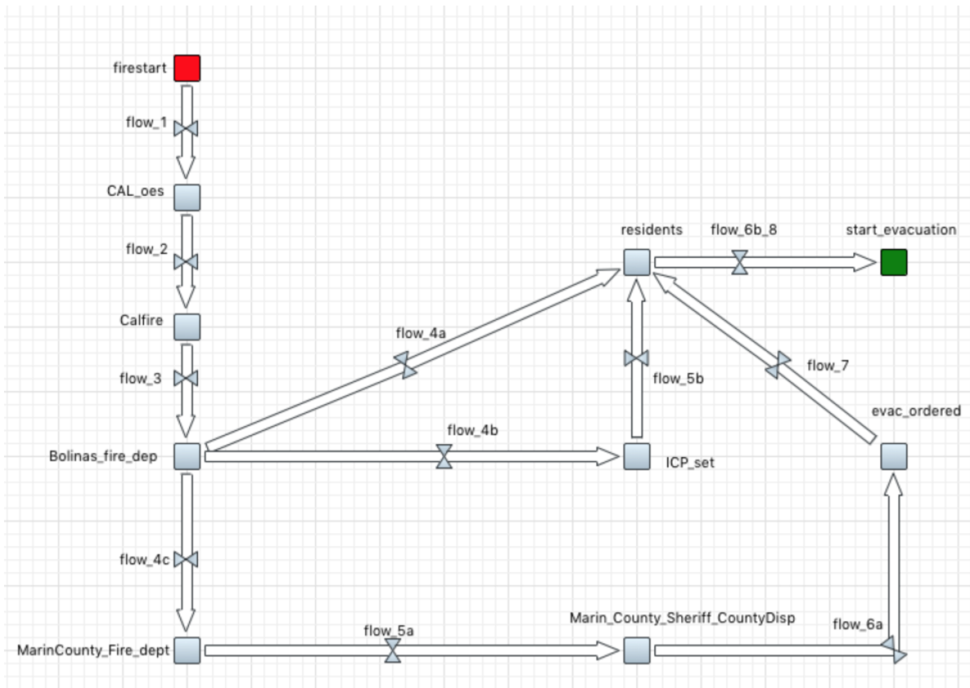


Figure 9. Organization Structure of Fire Communication among Organizations in Bolinas.

The overall setup of the Bolinas communication model is similar to the description given in Section II-2. Seven communication methods are considered in the model, from faster methods like fire and ham radios to the slowest means, door-to-door notifications. In the model, we assume the fire starts on a weekend morning at 9 AM, when local residents are at home and there are a good number of tourists with vehicles parked close to the beach and the beginning of the hiking trails. We also assume that it would take 15 minutes for the fire to be reported/detected after ignition. Emergency personnel in town become aware of the fire a minute later. Ham radio owners are likely to pick up the calls from the fire/police radios and are notified almost simultaneously. Next, an evacuation order is made and announced through social media and cell phone calls at 9:25 AM. Cognition-based notifications of the fire danger are assumed to take place early at 9:35 AM, when the fire becomes visible. CodeRED/Nixle/AlertMarin alerts are sent out to publicly listed landlines and mobile apps at 10 AM. Door-to-door communications would likely start after about one hour, as people may begin to inform their neighbors who do not use social media or have difficulties evacuating.

One of the main differences that distinguish the Bolinas simulation from that of Paradise is the consideration of three cell infrastructure damage sub-scenarios, where cell-based communication methods (social media, cell phone calls and mobile CodeRED/Nixle/AlertMarin alerts) are impacted both in terms of the percentages of population that can be reached as well as the notification rate. The level of damage to the communication system is loosely related to the three fire scenarios in Table 3, above, where a localized fire is assumed to have few or no negative impacts on the communication network, while the medium and large-scale regional fires are assumed to damage the communication infrastructure network partially and completely, respectively. Also, although not explicitly modeled in the system dynamics simulation, given the popularity of Bolinas as a tourist destination, the behavior of local residents and tourists will be modeled separately in the traffic simulation. Table 10 gives the detailed inputs for the Bolinas communication model under the three cell communication infrastructure damage scenarios. Under Scenario 1, the cell communication is assumed to be fully functioning. As a result, cell-based communication methods can be used to inform a large percentage of the population with high efficiency (highlighted in blue). If the cell communication infrastructure is partially damaged, as modeled in Scenario 2, we assume that half of the usual social media, CodeRED/Nixle/AlertMarin and cell phone message users will lose connection and the remaining half will receive notifications at half the rate (highlighted in orange). However, compared to door-to-door communication, the rates of notification of cell-based methods are still relatively fast. Lastly, in Scenario 3, we assume that the cell communication system is completely out-of-service. As a result, the evacuees who would normally be reached through social media platforms, CodeRED/Nixle/AlertMarin alerts or cell phone calls/messages have to rely on door-to-door notifications or cognition-based approaches to be informed of the fire danger (highlighted in red).

Table 10. Inputs to the Bolinas communication simulation model.

Communication models	Start time (min)	Communication Scenario 1 (No damage to the cell communication infrastructure)		Communication Scenario 2 (Partially damaged cell communication infrastructure)		Communication Scenario 3 (No cell communication)	
		% pop. informed	Notification rate (people per min)	% pop. informed	Notification rate (people per min)	% pop. informed	Notification rate (people per min)
Fire radios	16	5%	150	5%	150	5%	150
Ham radios	17	5%	150	5%	150	5%	150
Social media	25	**20%**	**300**	**10%**	**150**	**0%**	**0**
CodeRED/ Nixle/ AlertMarin	60	**25%**	**75**	**15%**	**45**	**0%**	**0**
Cell phone	25	**30%**	**22.5**	**15%**	**22.5**	**0%**	**0**
Door-to -door	65	5%	2.5	30%	2.5	60%	2.5
Cognition	35	10%	10	20%	20	30%	30

Figure 10 shows the breakdown of the population at risk by the primary means of communication used to receive the evacuation order under the three communication scenarios. As the degree of the cell communication infrastructure damage increases, a greater proportion of the population needs to rely on the slower cognitive or door-to-door type of communications.

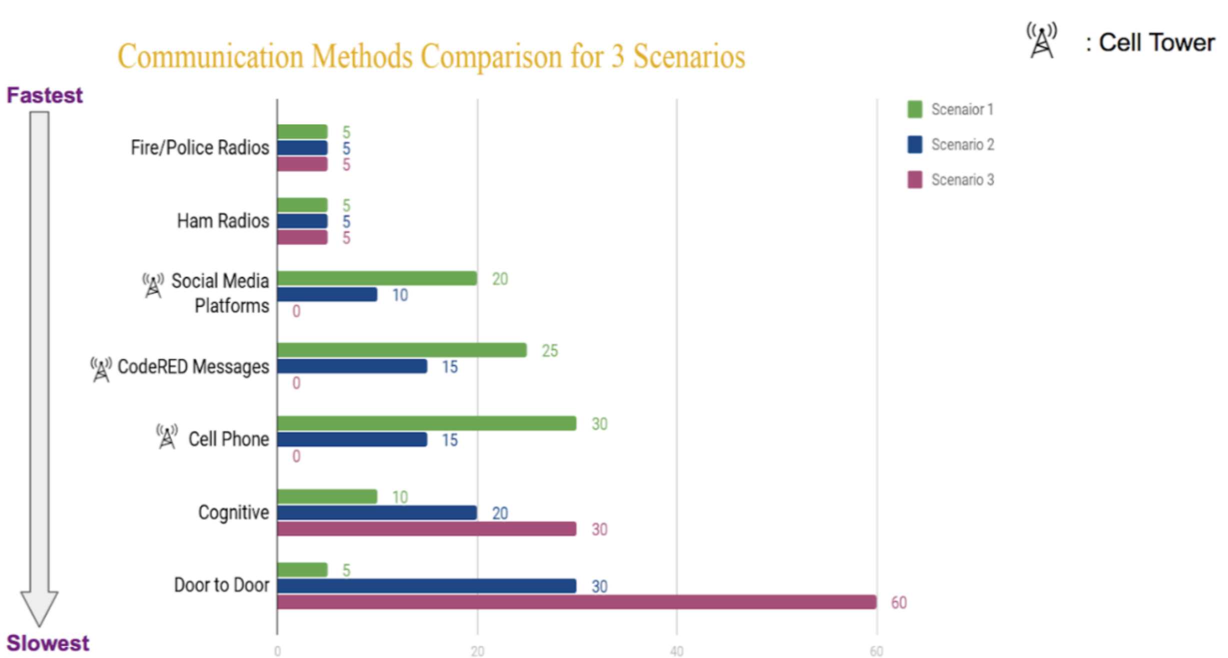


Figure 10. Percentages of the local residents and visitors notified by each communication method under different cell communication damage scenarios for the Bolinas case study.

The calculated time to notify all evacuees in Bolinas is given in Figure 11. With a fully functioning communication network, we estimate it would take less than two hours to inform all the residents, given our assumptions about the communication mechanisms and notification rates in Table 10. If the communication network is partially damaged, we estimate it would take about four hours to notify all individuals in the population. Lastly, with a completely damaged cell communication system,60 percent of the population would need to be notified through door-to-door communication, and the notification process would take 7 hours to complete.

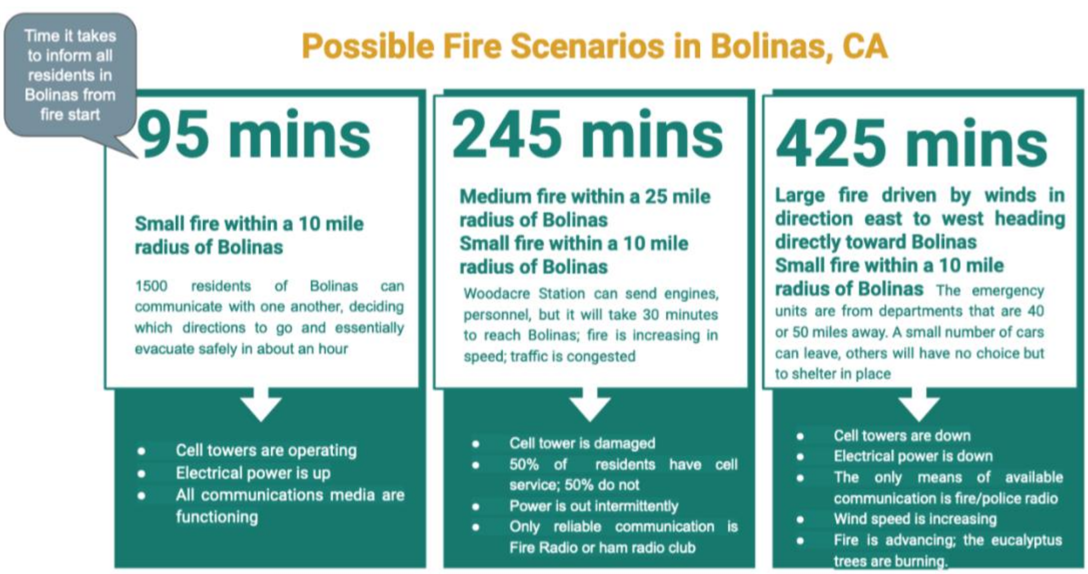


Figure 11. Possible Fire Scenarios in Bolinas.

II-4. Discussion

Given that many unpredictable human behaviors are involved, it is extraordinarily hard to accurately model the communication process. However, during this study, by talking with the Bolinas emergency personnel and residents as well as paying site visits to Bolinas, we gained additional insight into the mobilization of evacuation resources.

First, even though system dynamics models can create a reasonable abstraction of the notification process over time, the actual notification process is more complex. For example, emergency personnel may prioritize the notification of those close to the fire first to reduce anxiety. Also, each communication method may not have a definite start and end time as assumed in the simulation model.

Second, the events from the start of the fire to the issuance of the evacuation orders are largely ignored by the system dynamics model, which in reality can have great variability. Starting with the first discovery of the fire likely reported through a 911 call, that call will trigger the immediate response of the Bolinas Fire Department to dispatch an engine to the scene to do a "situation assessment" and report back to the Fire Department and the 911 Dispatch Center. If the fire is visible, it will likely generate further 911 calls to the local and regional Dispatch Centers. The Bolinas Fire Department's assessment would generate a call to CalFire for aerial suppression if needed, and further assessment of the progress of the fire would trigger the call for evacuation by the Marin County Sheriff's Office.

In addition, there would be significant community efforts in progress to improve communication bottlenecks, from discussions around the installation of sirens to identification of social networking groups (school parents, commercial, Airbnb, tourists). Additional practical issues include potential language barriers to communication with minority groups. As Bolinas became the first community in California to conduct COVID-19 tests on all of its residents, a great level of effort has been made to reach out to sub-communities at risk. This exercise was valuable in terms of understanding the challenges associated with reaching out to every community member in future emergency situations such as wildfires. As mentioned above in the Methodology Section (Figure 3), our research team is currently working on developing a role-playing evacuation process simulator that could engage residents and gain insights regarding their behaviors and choices in an emergency evacuation situation, such as their usual locations at different times of the week and the number of vehicles or modes of transport that they would use for evacuation. In a future study, we would like to include the lessons learned from such activities in our simulation models.

Even though it is impossible to account for all the complex and individual-specific factors, our system dynamics models nevertheless illustrate the potential delays to the evacuation process caused by communication challenges. Taking the worst-case scenario as an example, it would be quite unacceptable to take seven hours to notify all evacuees in Bolinas under an urgent evacuation situation where the loss of cell communication infrastructure leads to the heavy reliance on the slow and labor-intensive door-to-door communication methods. To prepare for such a worst-case scenario (damage to the cell communication infrastructure), alternative arrangements such as a more reliable communication methods or education to raise the awareness of fire danger (i.e., helping the residents to form a judgment of the fire risk in case the official order cannot be delivered) are highly recommended.

Part III. Traffic Evacuation Modeling

The third part of this report describes the traffic simulations conducted to evaluate the outcomes of different fires, communications, and traffic operation scenarios. First, the basics of the mesoscopic spatial-queue based traffic simulation model is introduced in Section III-1, covering the network loading component (node and link model), the treatment of the supply (road network) and the demand for travel (vehicle-level trips). The focus is then given to the two case studies (Paradise case study in Section III-2 and Bolinas case study in Section III-3). Although both of the cases are based on the same underlying traffic model introduced in Section III-1, site-specific adaptations are made to better reflect the characteristics and challenges associated with each case. Also, the connections with the fire and communication simulations are described in greater detail. A brief summary is then given in the end in Section III-4.

III-1. Traffic Modeling

III-1.1 The Supply Side: Network Representations

Traffic dynamics can be viewed as the outcome of supply-and-demand interactions between the road network and vehicles. On the supply side, the road network is represented by a node-and-list graph, where in general each intersection is represented by a graph node (or vertex) while the stretch of road between two intersections is represented by a link (or edge) between two nodes. The graph is directed, meaning for two-way roads, each direction is represented by a separate link. Node and link attributes are given in Table 11.

Figure 12 illustrates the change in link status in a wildfire. At the beginning, all links are “open” and vehicles can pass through them normally. At some point, when the fire arrives, the link status is changed to “burning,” indicating that an active fire is burning on the side of the road, but not necessarily making it impossible for vehicles to drive through. However, some of these “burning” links are assumed to be closed due, for instance, to falling trees or abandoned vehicles that made the road impassable. The status of these closed roads is now set to “burning_closed.” Since it is impossible to know where exactly road closures might happen, the links with the “burning_closed” status are selected randomly from those with status “burning,” with the probability being a control variable/sensitivity factor in the simulation. Next, after a certain amount of time (a fixed 30 minutes for the Camp Fire study but variable in the Bolinas study), the fire is assumed to be extinguished and the “burning_closed” roads will become open again, with the new status being “burnt_over.” Since the fuel has already been exhausted, the link that has the status “burnt_over” will not be subjected to fire-induced closure again. In addition, for a few special links (e.g., Pentz Road, Neal Road and Clark Road), their closure time is known to be much longer. As a result, their status is assigned to “closed” at the respective closure time (e.g., 8:30 for Pentz Road) and will not reopen again during the simulation time frame.

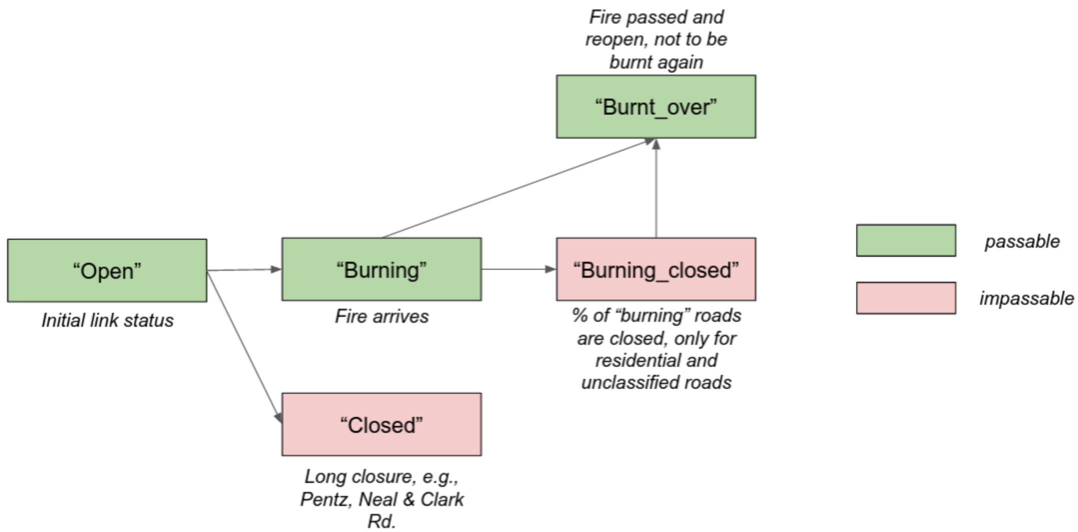


Figure 12. All possible link status.

The geospatial information of the road network is retrieved from OpenStreetMap (OSM), which denotes the coordinates of the nodes and links in latitude and longitude. To avoid having to calculate the distance between nodes on a 3D sphere (earth surface), all coordinates are projected to the local coordinate reference system (CRS). In both case studies (Butte County and Bolinas, CA), the NAD83/UTM Zone 10 (EPSG:26910) CRS was adopted. This assumption is reasonable given most distance calculations are highly localized. For example, distances are calculated to obtain the length of the road between two intersections or the distance between a vehicle and the fire boundary. They usually are on the scale of a few miles or less, making it acceptable to ignore the distortion caused by the curvature of the earth's surface.

Apart from the nodes and links from OSM, at each intersection, a virtual "node" and link is added pointing towards the "real" node. These virtual links have almost infinite capacity and zero length and can be used to hold pre-departure vehicles.

Table 11. Node and Link Attributes of the Road Network Used to Simulate Traffic Dynamics.

Attribute Name	Explanation	Example
Node Attributes		
node_id	Sequential index of the node in the graph network	0 or "vn0" for virtual nodes
osmid	Index used by the OSM for this node	"86605824" or None
x or lon	Northing of the intersection in projected CRS, or the longitude	-122.6499455
y or lat	Easting of the intersection in projected CRS, or the latitude	37.9023114
node_type	If the node is a real intersection or those added to assist vehicle loading at the initial start of each trip	"real" or "virtual"
incoming_links	Dictionary, first-level key is the id of the incoming link, second-level key is the id of the outgoing link, value equals the turning angle of this movement. Used to determine left turn, right turn and going straight ahead.	{1: {2: 180, 3: 90}}
outgoing_links	List of outgoing links from this node	[4, 5]
Link Attributes		
link_id	Sequential index of the link in the graph network	0 or "vn0_l" for virtual links used to load vehicles
start_nid	The node_id of the starting node of this link	24
end_nid	The node_id of the ending node of this link	96
geometry	Geometry of the link in the Well-known text (WKT) LineString format	"LINESTRING (-122.7088369 37.9005658,-122.7089076 37.9006585,-122.7089322 37.90069,-122.709149 37.9009552)"
angle	Link orientation compared to the east direction	10
link_type	Type of the link according to the OSM classification, or "v" for virtual network loading links	"motorway", "motorway_links", "trunk", "primary", "residential", "unclassified", "virtual", etc.
length	Length of the link calculated from its geometry in meters	51.2
fft	Free-flow travel time of the link, equals to length divided by the speed limit in miles per hour	25

Attribute Name	Explanation	Example
lanes	Number of lanes that this link has	1
capacity	Theoretical uninterrupted hourly flow capacity, equals to # lanes $\times$ 1,900	1,900
storage_capacity	Length of road lanes that can be used to hold vehicles, usually equals to # lanes $\times$ length. A minimum value of 18m (the length of the maximum vehicle spacing) is imposed to make sure short links can at least accommodate one vehicle.	1,900
remaining_inflow_capacity	Numbers of vehicles that can flow into this link per second, controlled by the link capacity, not integer	0.53
remaining_outflow_capacity	Numbers of vehicles that can flow out of this link per second, controlled by the link capacity, not integer	0.53
run_vehicles	List of tuples, where the first element is the index of each vehicle running on the link and the second element is the time for the vehicle to enter the link	[(1,0), (2, 100), (3, 150)]
queue_vehicles	List of vehicles queuing at the end of the link. List order indicates the order of entrance (and exits) of the vehicles	[4, 5, 6]
status	The fire and closure status of the link	"open": open as usual "burning": active fire close by "burning_closed": closed due to fire-induced hazards "burnt_over": fuel exhausted, fire has left and the road is open again "closed": closed due to other reasons
burnt_time	The time when fire reached the link, used to determine when the fire will leave and the road to be safe or can reopen again. In seconds.	1,800

III-1.2 The Demand Side: Trip Representations

Trips are modeled on the individual vehicle level, where each vehicle has a specific origin, destination, departure time, route and the model stores information such as its current position (link ID), etc. Trip information is derived from parcel-level land use maps for both case studies. The parcel map provides the locations of households. Assumptions are made regarding the number of vehicles per household for evacuation, and the closest road network nodes are then assigned to the household vehicles as the origins of the trips. Destinations are represented by network nodes sampled from the safe area (e.g., nodes inside the city of Chico and Oroville in the Camp Fire study, or one of two hypothesized destinations on

California State Route 1 in the Bolinas study). Details regarding the origin, destination and departure time choice can be found in the corresponding sections of each case study.

At the beginning of the simulation, each vehicle is assigned a route based on the free-flow travel time of the network links. This route is periodically updated to adjust to the changing traffic situation. The updating interval is five minutes for the Camp Fire study before the cell communication infrastructure is damaged (around 10:30 AM on November 8, 2018). For Bolinas, even in scenarios without cell communication infrastructure, it is assumed that people can still replan their route every five minutes or so, given the familiarity that the evacuees have towards the small road network. When congestion occurs, the new estimated link travel time equals the free-flow time plus the time for the queue to dissipate (queue length divided by the outflow capacity). For road links that are closed (status is "closed" or "burning closed"), the link travel time is set to an infinite large value to prevent vehicles from using them.

Each vehicle is initially labelled as "unloaded" at time 0. When it is time for each specific vehicle to depart, the vehicle is added to the list of running vehicles at the first link (a virtual loading link) and its status is changed to "enroute." At each rerouting time step (e.g., every five minutes), a new route is calculated. If no route can be found using network links that are still passable (i.e., not "closed" or "burnt closed"), the vehicle is forced to shelter-in-place. This is called "passive shelter" since the vehicle cannot finish its trip. On the contrary, we assumed that a vehicle may enter "voluntary shelter" if it has spent too long on one link (e.g., trapped in traffic gridlock on the link) or the new route is too long compared with the length of the original route. Finally, a vehicle that arrives at its destination is labeled "arrive." Vehicles that enter the shelter-in-place mode are no longer tracked in the simulation, since it is assumed that they will not re-enter the network until the main evacuation is over. All vehicle or trip-level information tracked by the simulation is given in Table 12.

Table 12. Trip or Vehicle Attributes.

Attribute Name	Explanation	Example
Trip Attributes		
agent_id	Sequential index for vehicular trips in the simulation	0
origin_nid	The node_nid of the starting intersection of each trip	1
destin_nid	The node_nid of the ending intersection of each trip	12
departure_time	Departure time of each trip, in seconds since the start of the simulation	3600
vehicle_length	Length of vehicles, which is used to determine the remaining link storage capacity and to simulate the spillback effect. In meters and usually 8 meters.	8
gps_reroute	Whether the driver follows GPS rerouting. If so, it periodically updates the routes.	Not used. Instead, assume partial rerouting when the cell communication goes down.
route	Dictionary, where the key value pair is the start and end node_id of each path segment	{1: 2, 2:3, 3:5, 5:10, 10:12}
current_link_start_nid	The start_nid of the current link of the vehicle	1
current_link_end_nid	The end_nid of the current link of the vehicle	2
current_link_enter_time	Time when the vehicle enters the current link. Used to determine whether the vehicle has joined the queue at the end of the link, in seconds	3,610
next_link	The link_id of the next link that the vehicle is going to enter	5
next_link_end_nid	The end_nid of the next link that the vehicle is going to enter	3
status	Status of the vehicle. Vehicles with status as "arrive," "shelter_active" or "shelter_passive" are removed from the iteration.	"unloaded": pre-departure vehicles "enroute": vehicles still in evacuation "arrive": vehicles arriving at destination "shelter_active": vehicles seeking shelters after encountering a road closure because the alternative route is too long; or any vehicles waiting too long on the same link (e.g., in congestion) "shelter_passive": vehicles do not have valid route to destination after road closures

III-1.3 Spatial-queue-based Link Model and Conflict-free Node Model

Traffic dynamics are simulated with a spatial-queue model. As shown in Table 11, each road link has at least the following attributes: inflow and outflow capacity, storage capacity (calculated based on the length and numbers of lanes) and free-flow travel time (calculated based on the length and speed limit). These attributes are used in the link dynamics model as shown in Figure 13. Specifically, when a vehicle enters the road link, it is labeled as a "running vehicle," indicating that the vehicle is still running on the road link (blue cars in Figure 13). It needs to spend a period of time equal to the free-flow travel time of the link before transiting into the queuing part of the link (red cars in Figure 13). The car at the front of the queue has a higher probability of moving through the node to the next link, but this depends on several factors, namely the outflow capacity of the current link, the inflow capacity of the next link, the availability of space on the next link as well as no conflicting vehicles moving through the intersection.

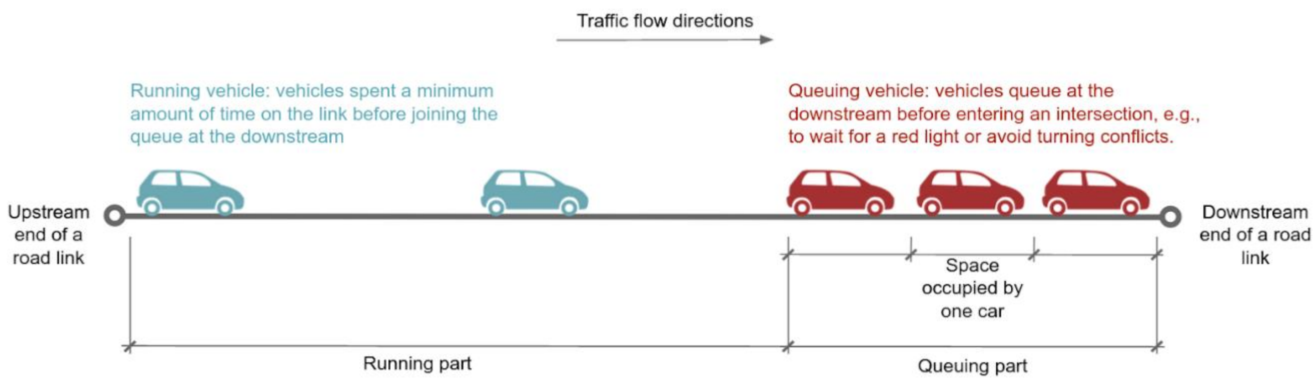


Figure 13. Spatial-queue based link model.

In an urban setting, the crossing of different traffic streams at an intersection is often the key bottleneck affecting traffic efficiency. If two perpendicular streams of traffic take turns to pass an intersection, the link output capacity is basically reduced to half (about 950 vehicles per hour). In these traffic simulations, delays at intersections are handled using a node model as illustrated in Figure 14, taking the vehicle on the south entrance of the intersection as an example. At each one-second simulation time step, if the vehicle goes straight or turns right, then the queuing vehicles from the opposite direction can also move (unless it is a left-turn vehicle). Vehicles in the perpendicular direction cannot move because they would conflict with the primary direction of movement. However, if the vehicle on the south entrance is turning left, then no vehicles in other directions can move, as left turns are considered protected. Through the iterations of each node and each link, vehicle positions are gradually updated to generate the traffic dynamics that would be observed in a real evacuation process, such as queues and spillbacks (vehicles in queue back up all the way till the upstream end of a road and block another road).

These node and link-level traffic models are implemented in our in-house traffic simulator. Compared with using existing general-purpose traffic simulation software, our own simulator gives us greater flexibility in implementing evacuation related scenarios and behaviors, such as fire-induced road closures or localized re-routing to avoid blocked roads. The computational performance is also sufficient (it finishes in minutes for the Bolinas case and less than an hour for the Paradise network), which allows extensive scenario testing to be conducted.

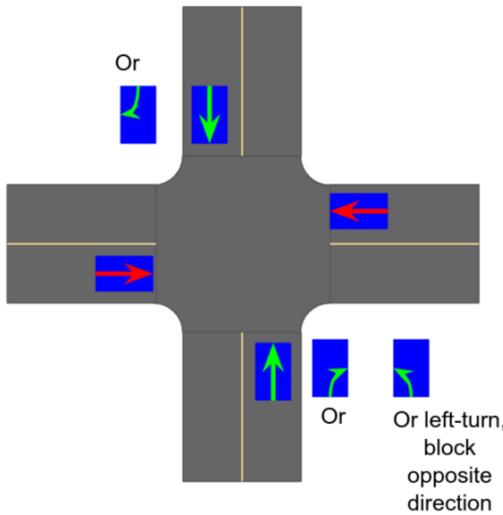


Figure 14. Node model that avoids the conflict movements of vehicles.

III-2. Camp Fire, Paradise, CA

The first case presented is based on the Camp Fire evacuation that occurred on November 8, 2018 in the town of Paradise, CA. The study predicted various evacuation outcomes under several alternative scenarios. The next subsections give an overview of the case study (Section III-2.1), the fire spread models used (Section III-2.2), the modifications of the road network downloaded from OSM that better reflects our understanding of the event (Section III-2.3), the scenarios tested (Section III-2.4), the simulation results in great detail (Section III-2.5), statistical results of random repetition tests (Section III-2.6) and key takeaways in the end (Section III-2.6).

III-2.1 Overview of the Case Study

As introduced in the Methodology section, three components are necessary to holistically represent the Camp Fire evacuation event from the start, consisting of the fire, communication, and traffic models. Information from our site visit is incorporated into the model as described in the methodology section.

Based on our site visit findings, the following scenarios were deemed worthy of further investigation:

- ***Vehicles per household.*** Traffic congestion inside Paradise was found to be a major safety issue and caused anxiety, given the fast-approaching fire. The narrow urban/suburban roads were handling traffic at much higher rates than their capacities, causing vehicles to become stuck in fully clogged local streets before entering the regional roads. As a result, alternative scenarios comparing the outcomes under different total numbers of vehicles were included in the study.

- ***Departure tim****e*. The town of Paradise had an award-winning zoning system and phased evacuation plan. The town had also organized drills before the fire that simulated a phased evacuation strategy. However, such operations were not possible during the Camp Fire incident due to the rapidity of the fire progression. Thus, we considered scenarios both with and without phased evacuation.

- ***Fire-induced road closures inside Paradis****e*. Traffic was reportedly blocked due to obstacles (falling trees, abandoned vehicles) on the road, which had to be cleared by bulldozer operators. To incorporate the negative impacts of fire-induced road closures, a factor was used to represent the probability of road closure when the simulated fire reaches the road. Furthermore, we assumed that such road closures will only happen on the narrower, “residential” or “unclassified” roads, according to OSM categorization.

- ***Contraflow on Skyway Road.*** According to our interviews, contraflow (requiring all traffic lanes to move in the same direction) was implemented on Skyway Road, the most heavily used evacuation route, but the operation was not effective due to the confusion caused by the lack of communication with traffic and rescue vehicles coming from the opposite direction. As a result, the efficacy of the contraflow operation was also included as a scenario variable.

- ***Real-time rerouting information.*** As the size of the study area is relatively large, we assumed that people need to rely on real-time traffic information for rerouting that avoids congestions or road closures. However, as the cell communication failed at around 10:30 AM, access to accurate traffic information became difficult. One scenario in our case study explores the potential benefit, had the cell communication infrastructure and real-time information-based rerouting remained uninterrupted.

Other key model considerations and assumptions involved:

- ***100% evacuation compliance***, i.e., shelter-at-home is not considered, given the ferocity of the fire.

- ***Known road closures.*** There were four main roads leading out of Paradise, including Pentz Road and Clark Road southward to the city of Oroville, as well as Neal Road and Skyway Road leading westward to the city of Chico. However, the fire coming from the east side soon engulfed Pentz Road (at about 8:30 AM) and Clark Road and Neal Road were also closed after some time (around 9 AM and 11 AM, respectively).

- ***Fire-induced random road closures.*** Roads closed due to fire-induced hazards were assumed to clear in 60 minutes. This may not represent all situations and could be incorporated as a further factor in future studies.

III-2.2 Integration of the External Fire Model Results

Many online images of the Camp Fire, such as the satellite view created by NASA (2018), do not reveal the dynamic progression of the fire front. Fortunately, there is existing research which simulates the fire spread, such as by CAWFE (UCAR, 2020). This video was downloaded and convex hulls around the fire were constructed in each frame to represent the fire extent. The fire boundary progresses every five minutes. Figure 15 shows the process of how fire spread inputs are constructed from the CAWFE simulation results. Figure 15(a) is one frame extracted from the CAWFE visualization. The difference between two consecutive frames (five minutes elapsed time) is extracted and shown in Figure 15(b). The differences are further processed with kernel smooth, dilation, and noise reduction functions to produce a cluster of points showing the locations of fire expansion, as shown in Figure 15(c). Based on pixel value, a convex hull is placed as a simplified way to denote the fire footprint boundary (Figure 15(d)). The convex hull is put back into the original frame to assess the validity of the figure processing (Figure 15(e)).

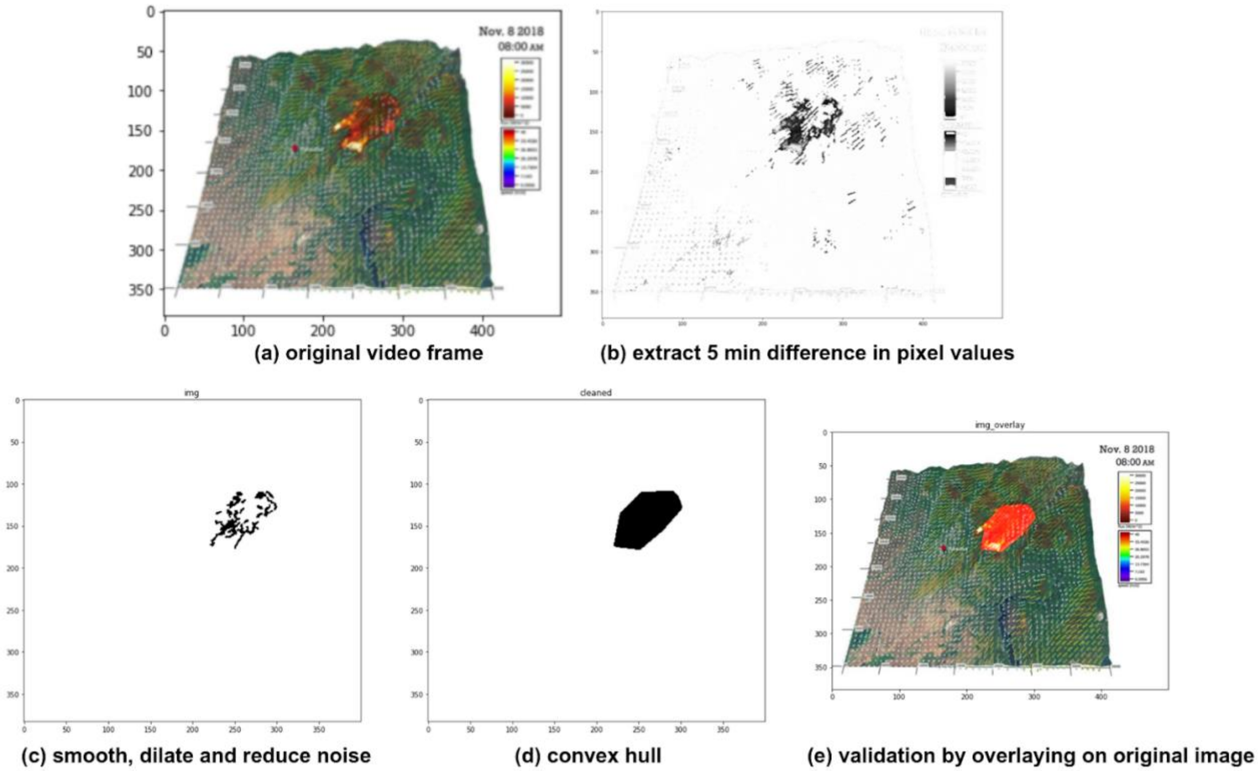


Figure 15. Extract of the fire footprint from CAWFE simulation results.

A possible limitation of this dataset is the lack of modeling ember fire, which can fly and land on roofs and vegetations earlier than the main fire. Embers were a major cause of damage and risk during the actual Camp Fire. Without considering their effect, the apparent speed of the fire would be much slower. Since the CAWFE model does not simulate isolated fires ignited by embers lofted away from the main fire frontier, this effect was constructed manually. At each five-minute fire visualization time step, a few embers are assumed to fly to a fan-shaped area, with greater distance towards the southwest direction. Each ember then ignites a spot fire, which in turn throws out embers in the next five-minute time step.

The above fire simulation results (including both the main fire from the CAWFE model and the random spot fires created in this study) were georeferenced and stored as a raster array. Such snapshots of fire progression were obtained at five-minute intervals from 8 AM to 1 PM, as shown in Figure 16. The spot fire starts ahead of the front of the main fire. Five random repetitions are conducted to generate different ember fires (spot fires in Figure 16) in order to reduce bias in the results from any one particular ember scenario. For each random repetition, the main fire spread remains the same, but the spot fire locations are different, leading to random variations in the simulated road closures and fire exposure risks.

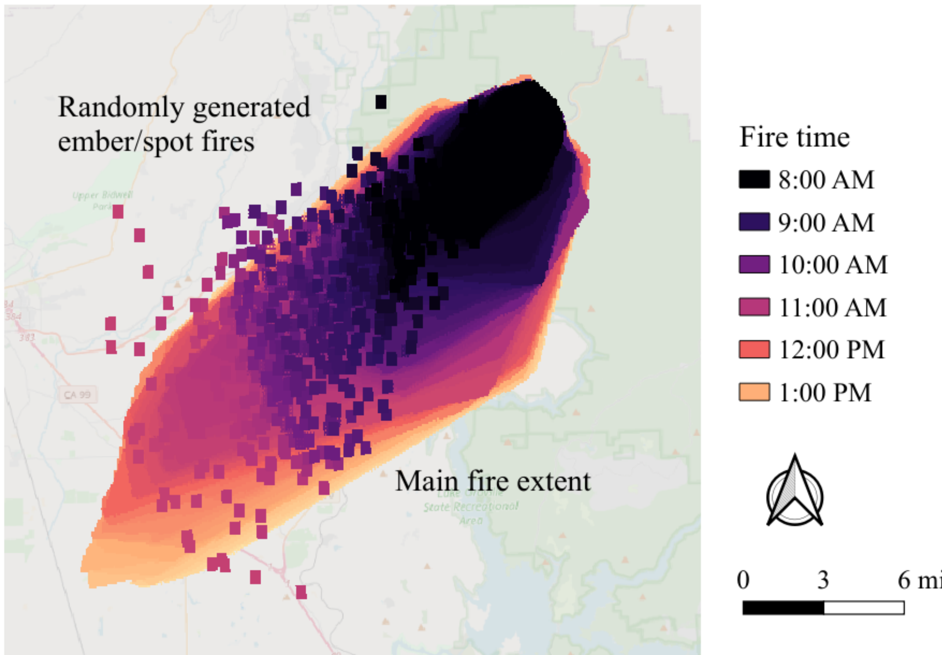


Figure 16. Georeferenced fire extent by hour. More detailed 5-minute results are used for traffic simulation.

III-2.3 Traffic Simulation Setup

The road network of the study area was obtained from OSM through the OSMnx software package. It consists of nodes and links (or vertices and edges), with corresponding attributes associated with each node and link as described in Section III-1. Figure 17 gives an alternative representation of the road network in the study area, colored by the link betweenness centrality, weighted by the free-flow travel time of each link. Betweenness is a network centrality metric that measures the importance of a link in a graph. Specifically, if a shortest path is found for each pair of nodes (street intersections) in the road network graph, link betweenness then measures the number of shortest paths that go through each road link. Higher betweenness centrality links generally correspond to better connected, more important, and more heavily used roads.

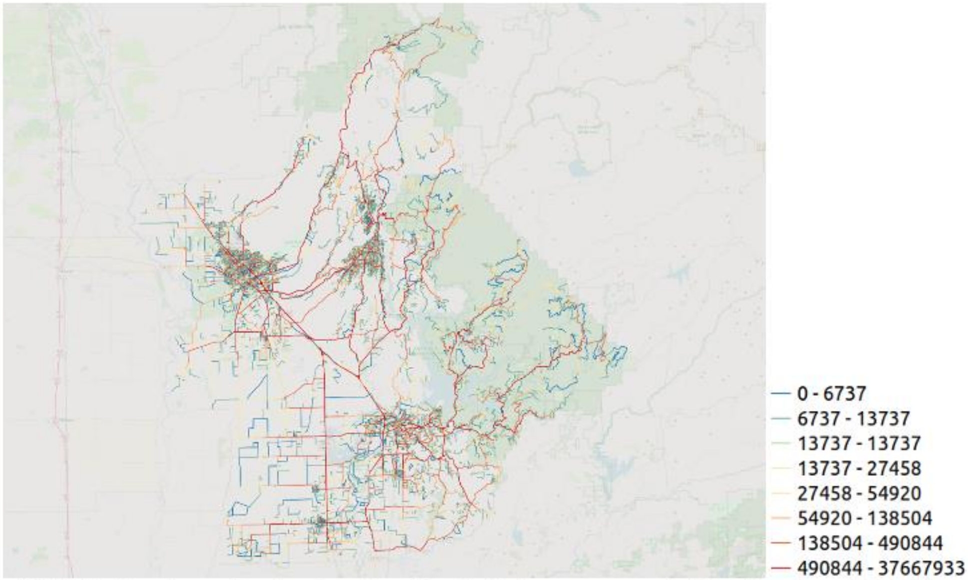


Figure 17. Butte County road network colored by the betweenness centrality of each road link.

The original road network required additional modifications to suit the simulation needs. Specifically, information about some special nodes and links replaced the original data. This information included:

- ***Signal nodes.*** Most of the nodes in the spatial-queue model are treated as non-controlled intersections. For all incoming links, queuing vehicles take self-organized turns to discharge the vehicle to the next link (if the flow capacity of the up/downstream links and downstream storage capacity permits). This strategy works reasonably well in the residential area. However, it is not good for intersections with signals (e.g., the one at the end of the Skyway), where clearly one phase (perpendicular to the Skyway) is underutilized due to the disproportionately low demand.
    - Intersection of Skyway Road and Bruce Road at the Chico end of Skyway. OSMid: 86418422; 331096653;
    - Intersection of Deer Creek Highway (CA 32) and Bruce Road at the Chico end of Deer Creek Highway. OSMid: 86558353.
- ***Priority nodes.*** As with the signalized nodes, most intersections in the simulation are modeled as uncontrolled. Vehicles queuing in different inflow links are released in random order. However, at the merging point of a highway and an inflow ramp, priority is given to vehicles on the ramp.
    - The intersection of the on-ramp and CA 99 at Chico. OSMid: 86375796.
- ***Prohibited turns.*** The usual nodes permit vehicle movements from every incoming link to any outgoing link. In certain cases, some movements are not permitted, e.g., U-turns. These are specified as prohibited turns.
    - No left turns are allowed at the on-ramp location from Skyway to CA 99. Vehicles going to CA 99 must use a right-turn on-ramp. OSMid: 86415031.

- ***Closed roads.*** Some roads are marked as impassable from the start of the simulation to prevent vehicles from using them.
    - Honey Run Road parallel to Skyway Road.

On the travel demand side, the parcel map of Paradise was obtained from the Butte County GIS Department and household parcels were mapped to the closest node. Also, a spatial interception was performed between the parcel map layer and the evacuation zone layer, enabling us to assign each parcel its own evacuation zone ID, as shown in Figure 18. Altogether, there are 12,324 residential parcels (households) in Paradise and Magalia. These are assumed to be the origin points for the individual evacuation routes. Each household may leave with one or more vehicles and vehicles belonging to the same household are assumed to leave together and have the same destination. In terms of the destinations, we assumed 70 percent of the evacuees would choose Chico and 30 percent would choose Oroville.

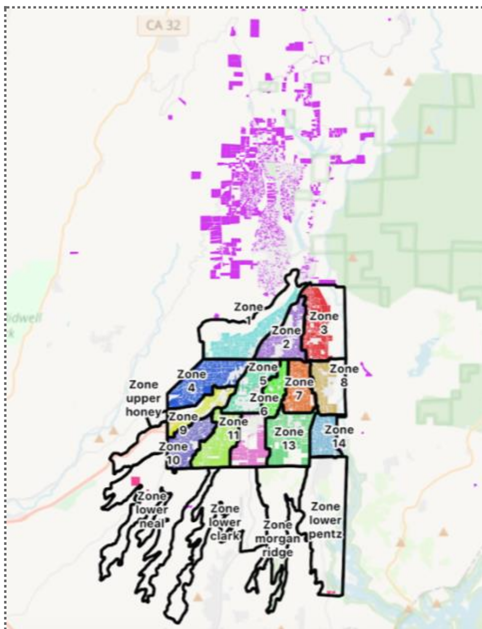


Figure 18. Residential parcels (i.e., households and origins of evacuation) associated with each evacuation zone in Paradise and Magalia, CA. Source: Butte County GIS Department. Note: Residential department has "LANDUSE" code 'RZ', 'RV' or 'RS'.

III-2.4 Scenarios Setup

As described in Section III-2.1, five different variable factors were considered in the Paradise case study, including (1) vehicles per household for evacuation; (2) departure time; (3) probabilities of road closures when fire reaches a link; (4) efficacy of contraflow on Skyway Road; and (5) availability of real-time information for rerouting. The details of each scenario are introduced in this section.

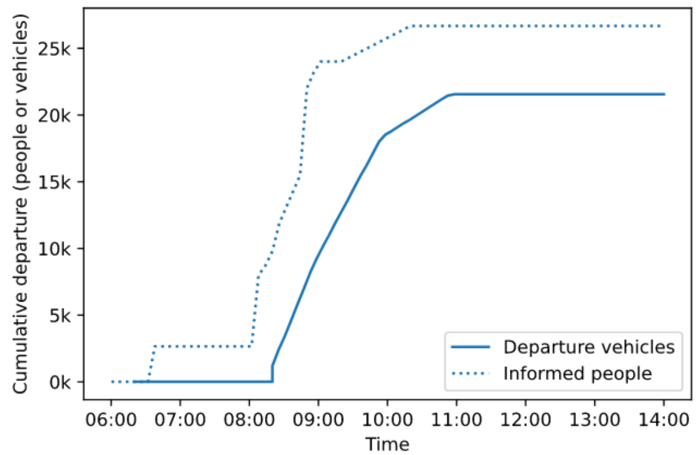
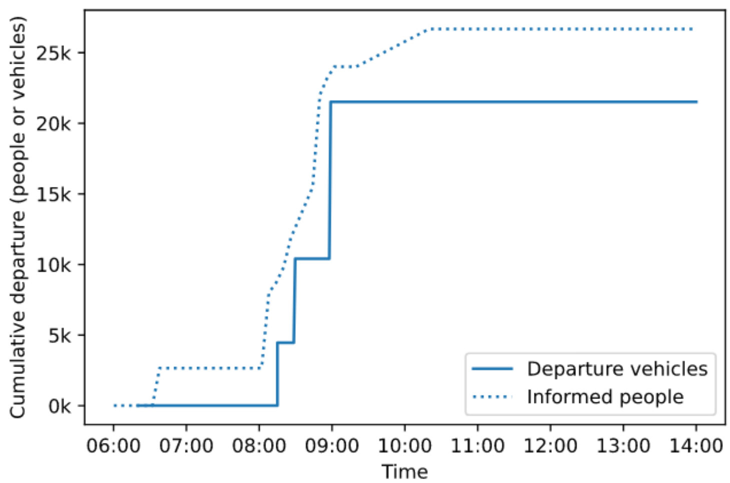
In an evacuation, a household may choose to leave with different numbers of cars. Having fewer cars would ease the demand exerted on the road network, while people may tend to take more cars to protect valuable personal belongings. As a result, the number of vehicles per household is designed as a factor in the simulation. The base case assumes that 55 percent of the households in Paradise will leave with two vehicles, while 30 percent will leave with one vehicle and 15 percent will leave with three vehicles (households are selected randomly). In the first alternative scenario, carpooling within the family is assumed and each household leaves with only one vehicle. In the second alternative scenario, each household takes two vehicles for the evacuation.

Table 13. Vehicles per household scenarios.

VPHH Scenario	% leave with 1 vehicle	% leave with 2 vehicles	% leave with 3 vehicles
Base	30%	55%	15%
alternative 1	100%	0	0
alternative 2	0	100%	0

Table 14 shows how quickly the population can be evacuated depending on whether evacuation times are random, or a phased evacuation is implemented. In both cases vehicles belonging to the same households are assumed to leave at the same time. In the base scenario, we assumed that 40 percent of the households start their evacuation within 20-60 minutes after the evacuation order is given at 8 AM. Another 45 percent leave within 1-2 hours while the remaining 15 percent leaves within 2-3 hours. In the first alternative scenario, all vehicles are assumed to leave simultaneously, potentially creating congestion in the initial period. In the second alternative scenario, a phased evacuation is implemented, where the town is evacuated in three phases from north to south, with one hour between each of the groups. In Section II-3.1, the communication process of the Camp Fire evacuation notification is modeled using the system dynamics model. The number of residents notified over time are plotted as dotted lines in the figures embedded in Table 14. The departure curve, i.e., the numbers of vehicles that have started evacuation, should be lower than the notification curve, as logically the evacuees can only leave if they have been notified of the fire risk, whether by receiving the evacuation order or cognitively perceiving the danger. In addition, the unit of the communication model is "group/person," while the unit of the departure curve and the traffic simulation is "vehicle." Households in the study area have about two people on average while the base case assumes 1.75 vehicles per household. As a result, the final value of the solid departure curve is lower than the dotted notification curve in Table 14.

Table 14. Vehicle departure time scenarios.

DEPARTURE TIME Scenario	Description	Plot
base	Random departure 40% of the total demand at 8:20-9:00 AM 45% of the total demand at 9:00-10:00 AM 15% of the total demand at 10:00-11:00 AM	
alternative 1	Phased evacuation Zones 3, 8, 4 leave at 8:15 AM Zones 2, 6, 7, 13 leave at 8:30 AM The rest of the zones leave at 9:00 AM	

The third factor considers the fire-induced road closure probability. This variable can greatly impact the traffic outcome as vehicles need to be rerouted onto alternative paths to their destination. If no alternative routes are available, vehicles are forced to shelter in place at the nearest safe location. For a few major roads, their actual closure status and times are known. These include:

- Pentz Road: closed at 8:30 AM
- Clark Road: closed at 9:00 AM
- Neal Road: closed at 11:00 AM

The closures of these main roads are modeled in a deterministic manner. Apart from these major roads, different probabilities are assumed for local road closures in the simulation. The base case assumes a 15 percent chance of road closure, which means that, when the simulated fire has reached the road link, there is a 15 percent chance that this road is closed temporarily due to fire-induced hazards (falling trees, abandoned vehicles, etc.), while there is also an 85 percent chance that the road will remain passable. The closed roads will reopen in 60 minutes to simulate the hazard being removed. These values are tuned together with other parameters in the simulation, so that altogether about 200-300 vehicles will seek shelter-in-place, as observed in our interviews (Comfort et al., 2019). As shown in Table 15, two alternative scenarios are considered, assuming no fire-induced road closure or 30 percent road closure once a fire gets to a link.

Table 15. Road closure scenarios.

ROAD CLOSURE Scenario	Probability of road closure
Base	15%
alternative 1	0%
alternative 2	30%

The fourth factor explores the efficacy of contraflow on Skyway Road, one key operation attempted during the Camp Fire event. This operation was not particularly successful in reality given the confusion and unfamiliarity of the evacuees with this special strategy, whereas our simulation compares the outcomes if the strategy would have been effective. This is achieved by setting the base case to no contraflow on Skyway Road (2 lanes westbound as usual). Two alternative scenarios each simulate the case where the directionality of one or two extra inbound lanes is turned for contraflow travel (Table 16). The traffic signal's green time at the end of Skyway Road is set to be equally split in both directions. As a result, contraflow also comes to an end at the signal locations and a queue is expected to appear upstream of the traffic signal location.

Table 16. Contraflow scenarios.

CONTRAFLOW Scenario	Contraflow on Skyway
Base	No contraflow; 2 westbound lanes in total.
alternative 1	One inbound lane used for contraflow; 3 westbound lanes in total.
alternative 2	Two inbound lanes used for contraflow 4 westbound lanes in total.

The last factor evaluates the benefit of having real-time traffic information for rerouting. Such information is usually available from service providers such as Google Maps or Waze, which in turn depend on a normal functioning cell communication infrastructure network. The base case is based on the fact that cell communication infrastructure in Paradise was out of service at about 10:30 AM. Before that, having access to real-time traffic information, the vehicles in the simulation are rerouted every five minutes to avoid congested areas. After 10:30 AM, the routing becomes a complex issue, and we made the following assumptions:

- Every 30 minutes, half of the remaining vehicles (randomly selected) choose a new shortest path, assuming that they have gathered some traffic information from other sources, though less efficient than smartphone navigation apps.
- When the next road that a vehicle is entering is closed due to fire-induced hazards, the vehicles perform a localized rerouting (to no more than three nodes ahead) to avoid the blocked link if such a detour exists.
- The Neal Road closure (11 AM) occurs after the cell communication infrastructure damage. Thus, we assumed that such information is not available immediately to the evacuees still in Paradise. Instead, we assumed that the vehicles learn about this closure after 10 minutes and replan their route if they were originally planning to take Neal Road.
- After the cell communication infrastructure damage but before the Neal Road closure, when vehicles reach the Skyway Road and Neal Road intersection, the simulation checks the number of vehicles within a visible range (300 meters). If there are fewer vehicles on Skyway Road than Neal Road, the vehicle will choose to go there as it is wider than Neal Road and mostly leads to the same area. This assumption is added because during the period between 10:30 AM and 11 AM, Skyway Road is congested downstream, but that congestion not visible to the vehicles that just enter the road from Paradise. Without real time information, the vehicle driver's best judgment would be to take the seemingly less congested road in the visible range.

In the alternative scenario, cell communication infrastructure is assumed to function well throughout the evacuation process. Thus, the vehicles' whole route to their destinations can be updated relatively frequently at five-minute intervals without complications, as shown in Table 17.

Table 17. Rerouting scenarios.

REROUTING Scenario	Description
Base	Loss of Internet at 10.30 AM. Rerouting every 30 minutes or reroute locally to avoid a closed link ahead.
alternative 1	No loss of Internet. Rerouting every 5 minutes throughout

III-2.5 Results

The simulated outcomes of the wildfire evacuation process are presented in this section. Specifically, the results are presented in the following format: we first examine the outcome of the base case in detail in Section III-2.5.1, using visuals and metrics such as the spatial and temporal changes in traffic congestion, rates of arrival, shelter-in-place counts and the usage efficiency of each node or link. Next, in Section III-2.5.2, we compare the base case and the alternative scenarios for each of five factors to see how different alternative values affect evacuation performance.

III-2.5.1 Base case

Below is a brief recap of the key settings specified for the base case:

- ***Vehicles per household.*** 30 percent of households use one vehicle; 55 percent use two vehicles; and 15 percent use three vehicles.
- ***Departure time.*** A total of 40 percent of households leave within 20-60 minutes after the evacuation order is given at 8 AM; 45 percent leave within 1-2 hours; the remaining 15 percent leave within 2-3 hours. No phased evacuation is assumed in the base case because in the real event on November 8th, 2018, the phased evacuation plan had to be dropped early due to the rapidity of the fire propagation.
- **Road closure.** When fire reaches a road, the base case assumes a 15 percent chance of fire-induced road closures. Closed roads are assumed to reopen after 60 minutes, the hypothetical time for the hazards to be cleared.
- ***Contraflow.*** No contraflow is assumed in the base case on Skyway Road, making the road two lanes in total going westbound.
- **Rerouting.** Before 10:30 AM, cell communication is working properly, so vehicles can replan their route every five minutes. After 10:30 AM, cell communication is down. Vehicles can reroute around a local obstacle if the detour is not too long or reroute in 30 minutes to simulate the effect of spreading information about congestion and road closures based on slower communication methods (e.g., word-to-mouth knowledge of the road closure).

The spatial and temporal simulation results for the base case are first presented for four outcomes: traffic distribution, arrival curve, danger indicator, and network usage efficiency. These metrics will then be used to compare alternative scenarios.

(1) Numbers of running and queuing vehicles at different time stamps

As introduced in the spatial queue-based traffic simulation (Section III-1.3), vehicles on any link have one of two statuses: if the time that a vehicle has spent on the road link is smaller than the free-flow travel time, the vehicle is considered "running" at full speed on the link. If the vehicle has spent more than the link free-flow travel time but still could not move on to the next link (e.g., due to downstream traffic spillback or flow capacity limitation), the vehicle is considered "queuing" at the end of the link. The queuing part has a spatial dimension, meaning that each link can only store a certain number of vehicles and no more than the storage capacity. Figure 19 shows the running and queuing status at different hours of the base case simulation. The blue lines represent the length of running vehicles on each road link, which is of less concern from the traffic perspective since the vehicles are running at full speed. The red lines represent the length of queues growing back from the downstream end of the links. The combined length of the red part and the blue part of the same link does not exceed the length of the link itself. The queuing lengths indicate the locations of the bottlenecks. Based on our site visit, there was a major bottleneck is at the Chico end of Skyway, where the traffic signal was not adjusted to accommodate the inflow of evacuees. In addition, there are significant queuing delays within the town of Paradise. They occur because the traffic from residential streets is merging towards a limited number of evacuation routes.

Taking a closer look at the temporal changes to the vehicle distribution, the queue density is the highest in the two hours plot, by which time the majority of the vehicles (85 percent) have been loaded onto the network. Pentz road is assumed to be closed at 30 minutes after the start of the evacuation order at 8 AM. As a result, there is almost no traffic on it in the figure for the first hour. Clark Road is closed one hour after the start of the simulation. Consequently, there are only a few lingering vehicles on it in the Hour 1 plot and no vehicles in the Hour 2 plot. Neal Road is closed after three hours. In the Hour 3 plot, there are quite a few vehicles running on Neal Road before the closure, but no vehicles on it in the Hour 4 plot. Due to the removal of Neal Road as an evacuation outlet, almost all vehicles have to be routed through Skyway Road. The traffic signal at the Chico end of Skyway Road is not adjusted to prioritize the evacuation traffic, thus creating long queues that spill back to Paradise in the Hour 4 plot.

When the parameters for the simulations are tuned, the route choice between Skyway Road and Neal Road before its assumed closure at 11 AM becomes a main concern. Since real observations regarding the queue length on both roads are limited (and would also be difficult to match accurately given the complex human behaviors involved), we rely on our understanding of the overall traffic situation and try to represent the evacuees' choices over these two roads as sensibly as possible with the tools that we can deploy in the simulation. Specifically, this involves:

- Before the cell communication infrastructure's failure at 10:30 AM vehicles are assumed to have access to real-time traffic information and in general prefer faster routes to their destinations. The link travel time is calculated by adding the free-flow time and the time to clear the queue, adjusted by the road class factor to reflect a general preference of using higher class factor roads under uncertainties.

$$link\ travel\ time = (free\ flow\ time) + \frac{queue\ length}{discharge\ rate} \times (road\ class\ factor)$$

- Here, the "discharge rate" is the output flow capacity of the link. The road class factor is estimated by the inverse of the speed limit; the higher the speed limit is, the more attractive the road is to the evacuees. Thus, under similar conditions, our simulation assumes that the evacuees would prefer to use Skyway Road.

- During the 10:30 - 11:00 AM time period, the cell communication is no longer functioning, but Neal Road is still passable. In this case, vehicles cannot timely update their route, thus many evacuees will stick to their planned route before the cell communication went out or replan their route at a lower frequency (as discussed in the general routing assumptions in the beginning of this subsection). However, this condition led to the unrealistic result that many people chose Neal Road over Skyway Road, even though the former had more traffic within a visible distance. To correct for this outcome, a separate simulation logic is applied at the Neal Road and Skyway Road intersection: as cell communication goes out, vehicles at the bifurcation point of Neal Road and Skyway Road do not know which one is more congested downstream, thus they would take the road that has less vehicles within a visible distance (1-3 links ahead, about 300 meters). This "myopic" routing behavior is illustrated in Figure 20 and would be more suitable than the widely used "shortest path" routing, especially under limited to no traffic information situations.

- In addition, news of the Neal Road closure is assumed to spread to the rest of the vehicles that plan to use it in 10 minutes. Thus, 10 minutes after the Neal Road closure, these vehicles will replan their route to avoid the closure.

Most of the queues cleared after six hours (2 PM), except on Skyway Road. However, at this time, the remaining vehicles were already far from Paradise, making them temporarily safe in the evacuation.

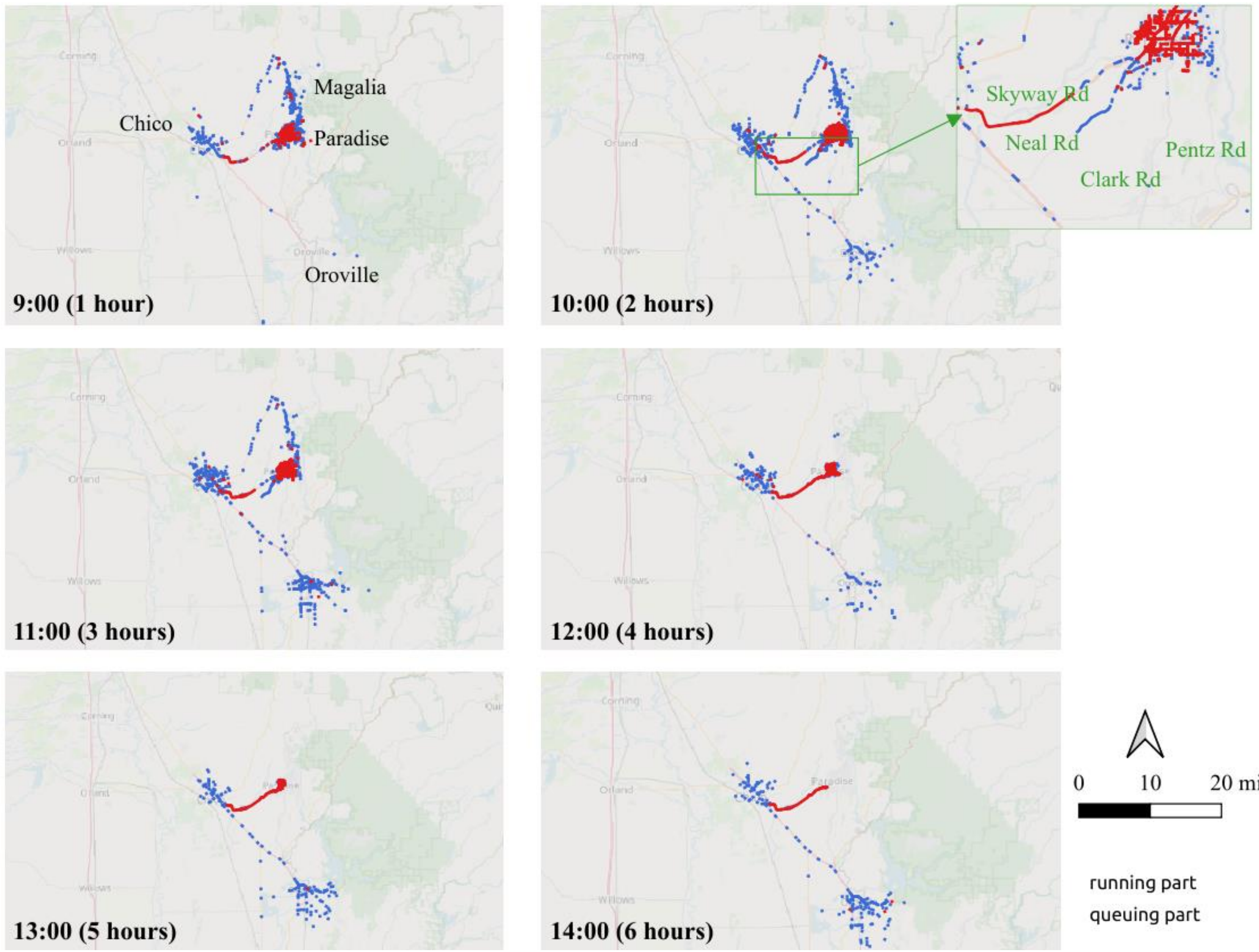


Figure 19. Running and queuing parts of the road links at different times.

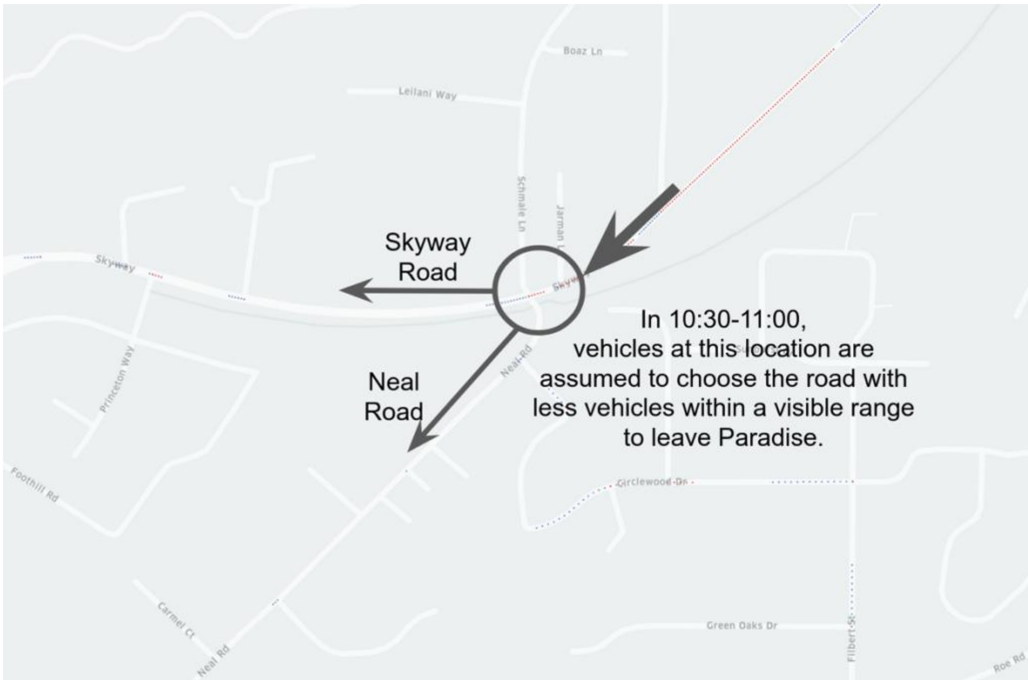


Figure 20. Illustrations of the "myopic" route choice at the Skyway Road and the Neal Road intersection, between 10.30 AM and 11.00 AM.

(2) Arrival: numbers of vehicles out of the evacuation zone and arrive at destination

Figure 21 shows the evacuation performance from a temporal perspective from five random repetitions. These repetitions are conducted to reflect the impacts of the random process (e.g., demand, ember locations) on the results. Overall, it can be seen that, under different random conditions, the simulation results for the arrival rate and the rate of leaving Paradise do not change much. The dotted line shows the number of vehicles that have left the Paradise boundary. This rate indicates the number of vehicles that are temporarily safe. The solid line instead indicates the number of vehicles that have arrived at their chosen destinations. In all five random simulations, 70 percent of evacuees choose Chico and 30 percent choose Oroville as their destinations. From this plot, it can be seen that most vehicles are out of the evacuation area after about six hours. It takes another 2.5 hours for all evacuees to arrive at their destinations. The arrival curve is flat in the first hour, since most vehicles have not started their journey or have just started to leave. The arrival rate picks up from 1.5 hours to three hours, when more than half of the evacuees have arrived. After Hour 3, the arrival rate again drops, likely due to the closure of Neal Road. The rate of the arrival in the last four hours is about 2,000 vehicles per hour, almost equivalent to the capacity of Skyway Road alone (two lanes going westward) with a traffic signal operating at the Chico end.

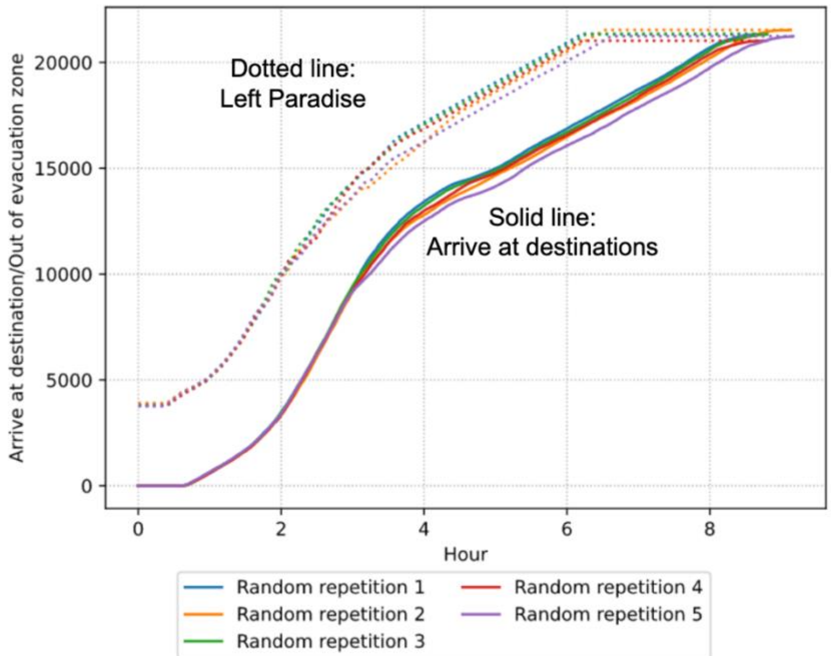


Figure 21. Rate of evacuation: leave the evacuation area, Paradise, and arrive at destination.

(3) Danger indicators: numbers of vehicles in stand-still traffic, exposed to fire and forced to shelter-in-place

Figure 22 shows the numbers of vehicles in adverse traffic conditions through a set of danger indicators. Figure 22(a) shows the vehicles in gridlock. Gridlock here is defined as vehicles spending more than half an hour or 10 times the free-flow time of the current link, whichever is the largest. Given that the length of the links in the study area are usually short, the half-an-hour criteria usually dominates. Intuitively, this would mean vehicles stalled and not able to move on to the next link for over 30 minutes. Before 1.5 hours, the number of vehicles in gridlock is relatively small, as many vehicles have not been loaded onto the network. There are some queues forming inside Paradise as seen in Figure 19(a). However, vehicles in the queue are usually able to move on after less than 30 minutes. The gridlock vehicle counts increase sharply around two hours, as 90 percent of the vehicles are loaded onto the network by that time. This metric starts to fall at around three hours, as the traffic density inside the town of Paradise starts to reduce as more vehicles have left.

Spatially, in terms of congested locations, the simulation shows that the congested areas (where vehicles in gridlock locate) often are in zones 1, 2 and 4 (Figure 23). This is not the same as the queuing length plots in Figure 19. This figure shows the locations of a subset of queues, where vehicles have remained on the same link for one hour, or 10 times longer than in the free-flow conditions, whichever is the longest. This finding is validated by information that we have collected online. For example, one twitter user tweeted about the difficult situations at Skyway Road and Wagstaff Road (Figure 24), though it was not clear if the problems were caused by traffic congestion or some unpredicted accidents. Further investigation shows that the residential parcel density in these zones is between medium and high (200-400 households per square miles). The residential parcel density in zones 5, 6 and 7 is also among the highest. However, these residents benefited from more and wider streets to access the evacuation routes.

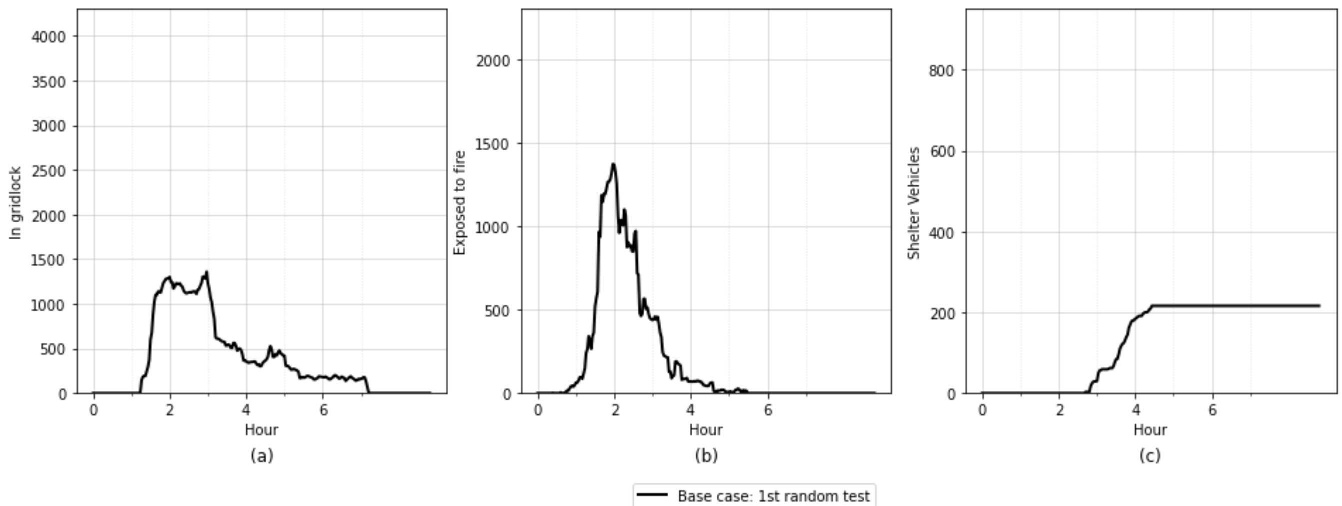


Figure 22. Vehicles in adverse traffic conditions. (a) In gridlock; (b) exposed to fire; (c) forced to shelter-in-place.

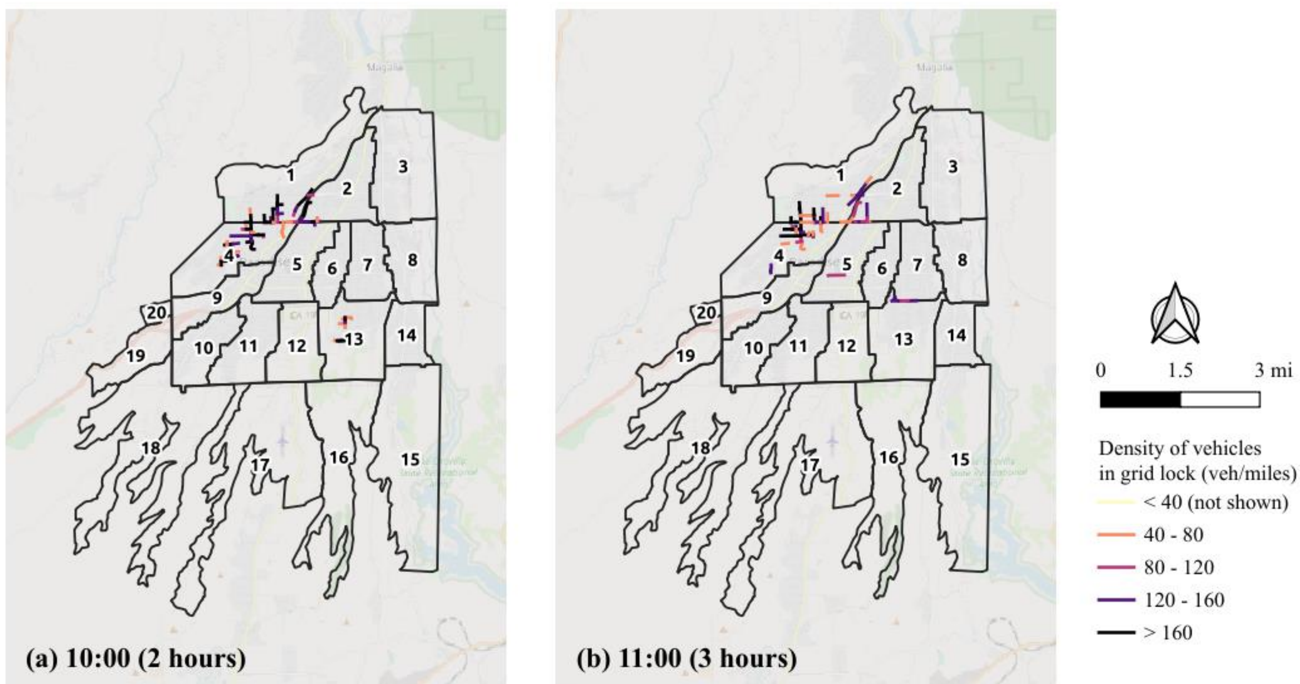


Figure 23. Locations of gridlocks where the stalled vehicle density is the highest. (a) Hour 2 (10 AM); (b) Hour 3 (11 AM).

Figure 24. Tweets regarding traffic on the Northside of the Skyway Road.

Figure 22(b) displays the numbers of vehicles exposed to fire. This is obtained from the simulation in two steps. First, all links with a midpoint within the current fire burning area are identified. Secondly, all vehicles on such links are assumed to be exposed to fire. We use the midpoint of the link at which a vehicle is currently to represent its location, because the spatial-queue-based traffic model does not give exact vehicle locations on a link, while interpolating vehicle locations based on its position in the queue can be time consuming. This is mostly reasonable, given that most of the links are not long and the fire input data (raster data) does not have a high level of resolution. We assumed that a road link will only be "burning" for one hour, after which the fuels will be exhausted, and the road will be safe again. The exposed vehicles peak at two hours (10:00 AM), when the vehicle accumulation within Paradise is the most severe (Figure 19). Another assumption related to the impact of fire on road accessibility is that fire will only pose risks to vehicles on residential roads. Big roads such as Skyway Road are assumed to be wide enough for vehicles to pass with fire next to it, except from those major roads that closed at some point due to fire (Pentz Road, Clark Road and Neal Road, see assumptions in Section III-2.1). As a result, after three hours, most vehicles have moved to Skyway Road and beyond (Figure 19), and the number of vehicles exposed to fire starts to fall flat.

The last subplot in Figure 22 shows the number of vehicles that choose to shelter in place. While in reality, some people may choose not to evacuate and defend their properties, this behavior is not considered in the simulation. Rather, vehicles are assumed to be sheltering-in-place if any of the following conditions apply: (1) a vehicle has remained on the same link for 2.5 hours; (2) the road ahead is closed, and the alternative route would be too long (meaning the alternative would take twice the time of the original route); or (3) there is simply no route left. The simulation results in 216 shelter-in-place vehicles, where most vehicles enter shelter-in-place mode due to queuing for more than 2.5 hours. A closer look at Figure 22(c) reveals the majority of shelter-in-place vehicles leaves the simulation between three and four hours (11.00-12.00 AM). Our simulation results suggested that, from 11:00 – 11:20 AM, about 60 vehicles sheltered-in-place due to the alternative path being too long, mostly due to the closure of Neal Road. After between 11:20 AM – 12:00 PM, about 150 vehicles are sheltering-in-place due to waiting for too long in the queue (more than 2.5 hours). This means that these vehicles started queuing at the same place at around 8:50 – 9:30 AM, almost as soon as they started to evacuate. From a simulation point of view, the network is overly congested when it simply cannot transfer the evacuees to their next link. In reality, the evacuees' behavior is more complex, and may involve seeking safe locations to shelter (e.g., parking lots) rather than waiting and sheltering at the same place.

The shelter-in-place count is very hard to calibrate due to its sensitivity to a variety of factors, including the probability and duration of road closures if fire arrives. The higher the road closure probability is and the longer the duration is, the more vehicles will be forced to shelter-in-place. Other factors that influence the shelter-in-place counts include fire progression, ember location, road closure probability and duration, tolerance to detours, etc. If any of the factors change, the shelter vehicle curve will change as well. In the simulation presented here, the parameters are carefully adjusted to lead to about 200-300 vehicles that need to shelter-in-place. However, from this we concluded that it is not reliable to use simulations to predict the numbers of vehicles that need to shelter in the middle of the evacuation trip, given its great range of variability under slightly different parameter settings. In future research, statistical analysis would need to be conducted to analyze the significance of differences among alternative scenarios in terms of reducing the need to shelter-in-place along the trip.

(4) Network usage: node transfer efficiency and cumulative link volume

Figure 25 shows the network usage in the simulation. The map has two layers, where the point geometry shows the vehicle transfer efficiency at each road intersection, and the linestring geometry (lines between two nodes) shows the vehicles that have passed each road link. Both layers are colored with the same scale (showing the numbers of vehicles that have passed the intersection/link throughout the simulation). Intersections and links that serve less than 1,000 vehicles are not plotted in the figure. The most heavily used link is Skyway Road, followed by CA 99 (especially for the parts inside Chico), Neal Road and CA 149 going towards Oroville. The busiest intersections are those along Skyway Road, particularly at the merging intersections inside Paradise and merging/diverging intersections inside Chico. Neal Road is heavily used; before its closure at Hour 3, it serves as one evacuation route circumventing congested Skyway Road. Based on our base case simulation, Skyway Road serves the evacuation of nearly two-thirds of the vehicles (about 14,000 out of 21,625). Neal Road serves about 4,700 vehicles before its closure and about 2,400 vehicles evacuated through CA 32 coming from the Magalia side.

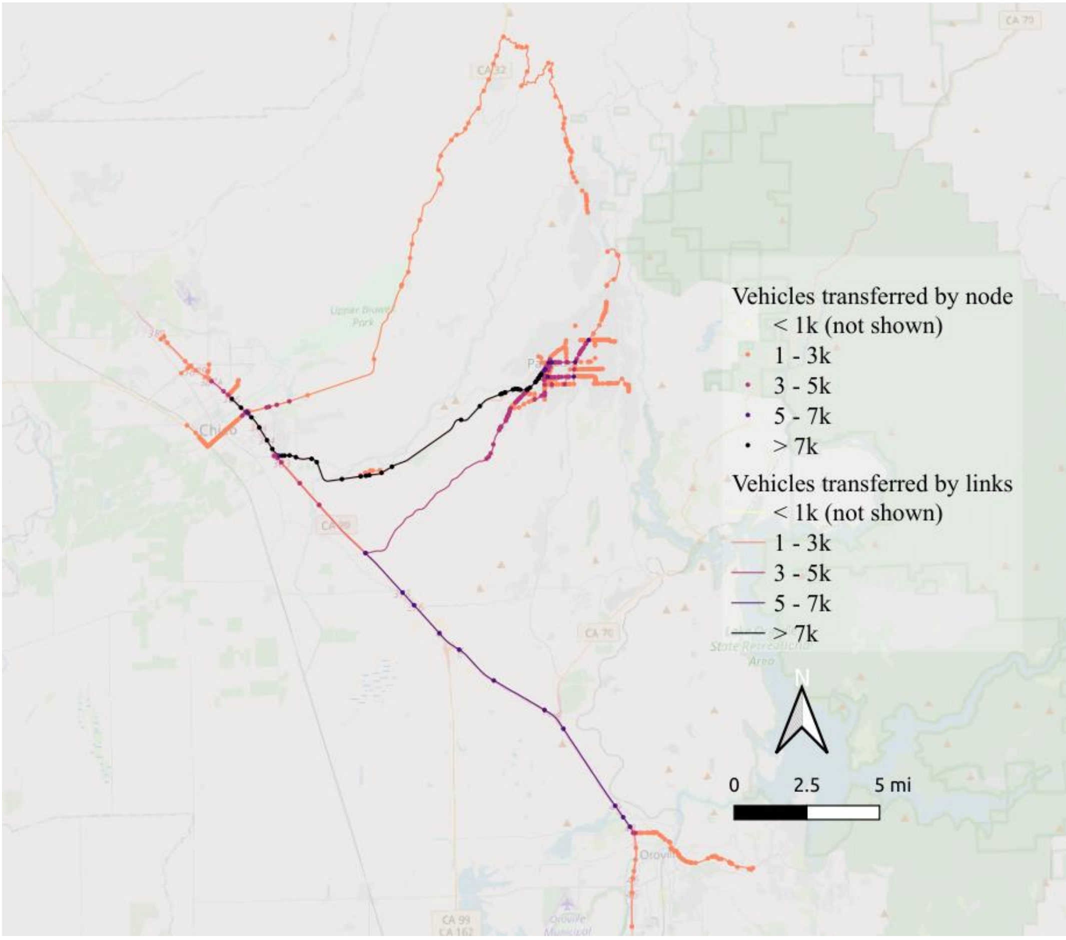


Figure 25. Network usage, color coded according to vehicles transferred by each node and link.

III-2.5.2 Alternative scenarios

The traffic evacuation efficiency of alternative scenarios is given below. For each scenario, time series plots of the following metrics are compared to the base case:

- Rate of vehicles leaving the evacuation zone and the rate of arrival;
- Number of vehicles in gridlock (i.e., vehicles spending more than half an hour or 10 times the free-flow time on the current link, whichever is the longest);
- Number of vehicles exposed to fire; and
- Number of vehicles forced to shelter-in-place due to road closures ahead (i.e., no alternative routes; alternative routes are longer than twice the length of the original routes; or having waited at the same link for more than 2.5 hours).

(1) The effect of vehicles per household

Figure 26 shows the effect of having different numbers of vehicles per household on the efficiency of evacuation. The base case (black curve) assumes that 30 percent of the households use one vehicle, 55 percent use two vehicles and the remaining 15 percent use three vehicles. On average, each household uses 1.75 vehicles. In the two alternative cases, the blue curve shows the scenario where each household only uses one vehicle for evacuation. This scenario turns out to be extremely effective in reducing all four metrics: 92 percent of the vehicles (11,283 out of 12,324 in total) left Paradise in three hours (Figure 26(a), dotted blue line). Almost no vehicle is caught in a long gridlock situation (blue line in Figure 26(b)) and around 400 vehicles are exposed to fire at its peak (vehicles present on the link when the fire arrives or is burning close to the link, blue line in Figure 26(c)). There is also a noticeable reduction in vehicles having to seek shelter-in-place (Figure 26(d)) compared to the black base curve line, thanks to the vehicle reduction associated with this scenario. Altogether, there are 21 vehicles that need to shelter-in-place, exclusively due to that alternative path being too long with links closed due to fire-hazards (solid blue line in Figure 26(d), overlapped with the solid orange line). No vehicles shelter because they are forced to wait for too long on a link (more than three hours, dotted blue line in Figure 26(d)).

In comparison, the orange curves show the alternative scenario when all households evacuate with two vehicles. This alternative adversely affects almost all evacuation performance metrics because of the increase in the travel demand from 21,527 vehicles in total in the base case to 24,648 vehicles. Specifically, the number of vehicles that leave Paradise or arrive at the destination increases, as shown by the higher orange curve than the black base curve in Figure 26(a), but not more than the total increase in the number of vehicles, as the number of vehicles that need to seek shelter also rises, particularly due to being in heavier traffic congestion and trapped on the same link for more than three hours (dashed orange line in Figure 26(d)). As expected, using two vehicles per household leaves more vehicles in congestion, which more than doubles the number in the base case (orange line in Figure 26(b)). However, in terms of vehicles exposed to fire, the impact of using two vehicles per household is small, due to the fact that the congested road sections (Zone 1, 2 and 4), located on the northwest side of the town, are further away from the fire front (Figure 27). This spatio-temporal arrangement of the fire and traffic allows time for the congestion to dissipate or for vehicles to seek shelter.

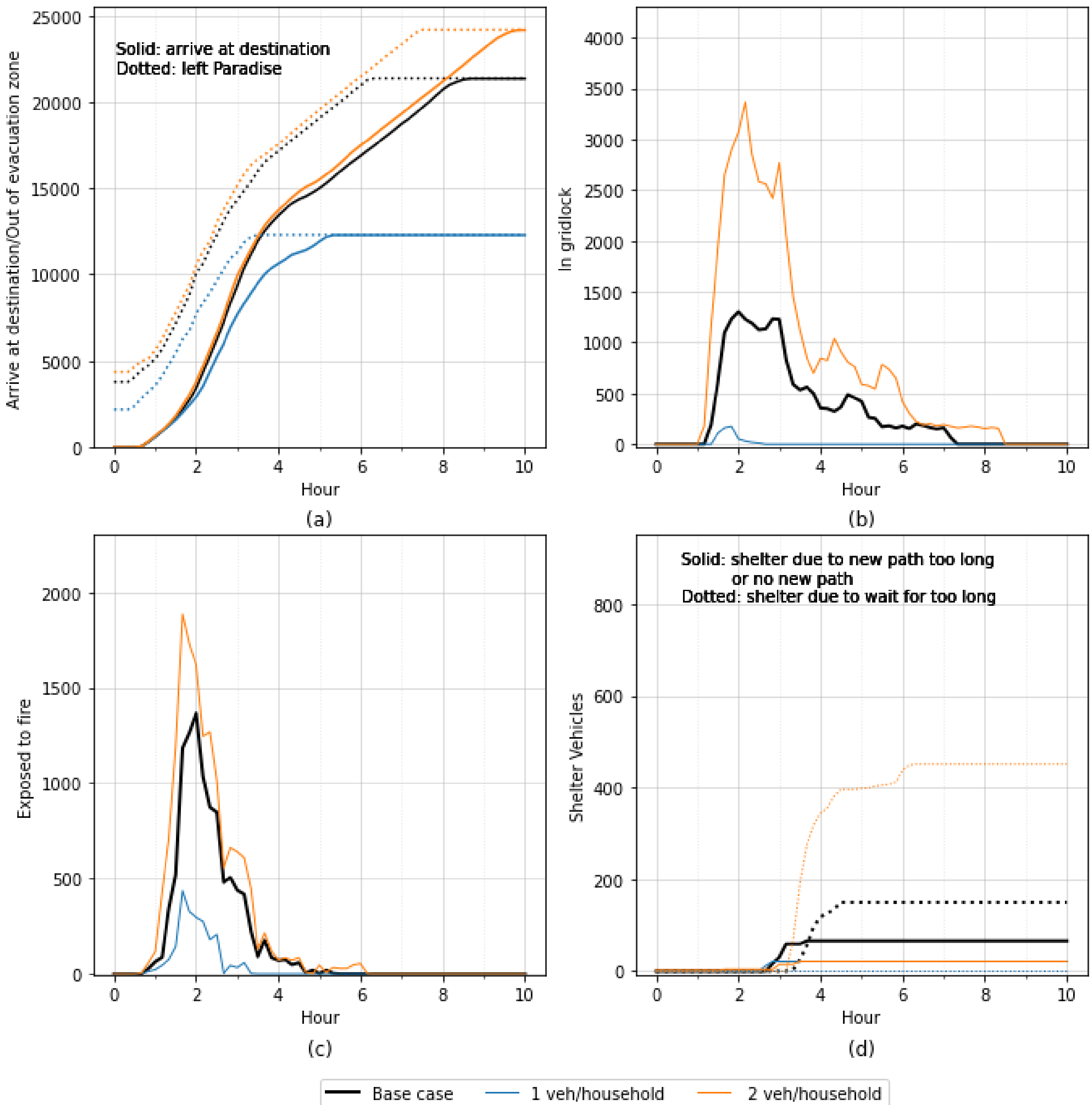


Figure 26. The effects of vehicles per household on evacuation efficiency. (a) Arrival and out of the evacuation zone counts; (b) number of vehicles in gridlock; (c) number of vehicles exposed to fire; and (d) number of vehicles forced to shelter-in-place.

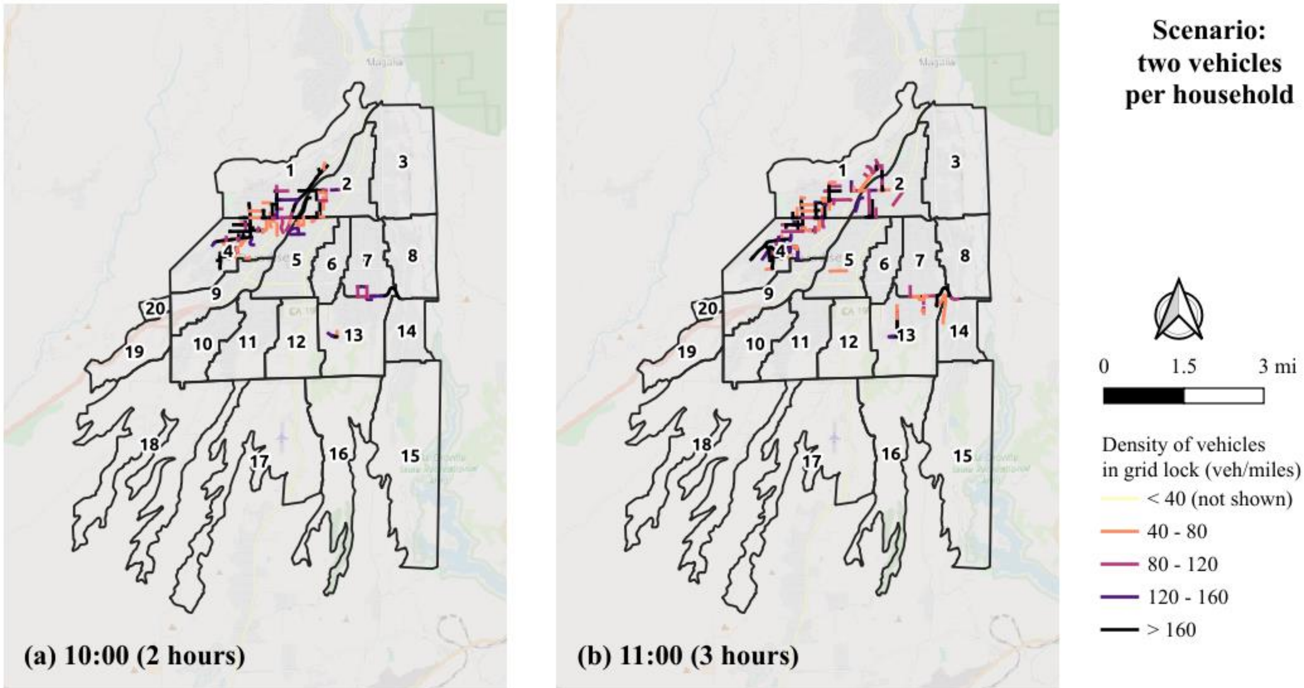


Figure 27. Locations of vehicles in gridlock (two vehicles per household). (a) Hour 2 (10 AM); (b) Hour 3 (11 AM). Notes: Compared with the base case (Figure 23), there are significantly more links in gridlock with two vehicles per household used for evacuation.

(2) The effect of departure time

The effect of vehicle departure time on evacuation efficiency is shown in Figure 28. The base case assumes that 40 percent of all vehicles will leave between 20-60 minutes after the start of the evacuation, 45 percent between 1-2 hours, and 15 percent of vehicles between 2-3 hours afterward (8 AM). The red curve shows the phased evacuation scenario, where the three eastern-most zones (Zone 3, 4, 8,) are evacuated at 8:15 AM. The middle zones (Zone 2, 6, 7, 13) are evacuated after another 15 minutes while the remaining zones leave at 9 AM. From the departure curves shown in Table 14 in Section III-2.4, "Scenario setup," it can be seen that the phased evacuation assumed in the scenario corresponds to a steeper departure curve compared to the base case. According to the results shown in Figure 28, the phased evacuation indeed brings about a higher rate of arrival initially that reduces the total network clearance time by more than one hour (red lines in Figure 28(a)). However, due to the more clustered departure, the maximum number of vehicles in gridlock (having spent at least 30 minutes or 10 times the free flow time on the same link) at one point almost tripled compared to the base case (red line in Figure 28(b)). The number of vehicles exposed to fire also increased (red line in Figure 28(c)), but the increase may not be statistically significant based on random repetitions. In terms of vehicles needing to shelter-in-place, this particular set of results suggested that, under phased evacuation, there would be a higher number of vehicles that would need to shelter-in-place due to the alternative path being too long following fire-induced road closures, while fewer vehicles shelter in place because they have been stalled on the network. But as discussed above, the shelter-in-place metric is particularly sensitive and has a wide range of variability. Thus, it is not suitable to draw conclusions without conducting more random repetitions.

Figure 28 shows that a phased evacuation plan does not always bring about the desired outcome. On the positive side, it prompts early arrival, but it also increases time spent in congestion. In future work, it may be possible to use optimization techniques to find a better phasing strategy. Since the fire arrived at the community at such a fast pace, it is likely that phased evacuation, no matter what the evacuation order is, may not be very helpful.

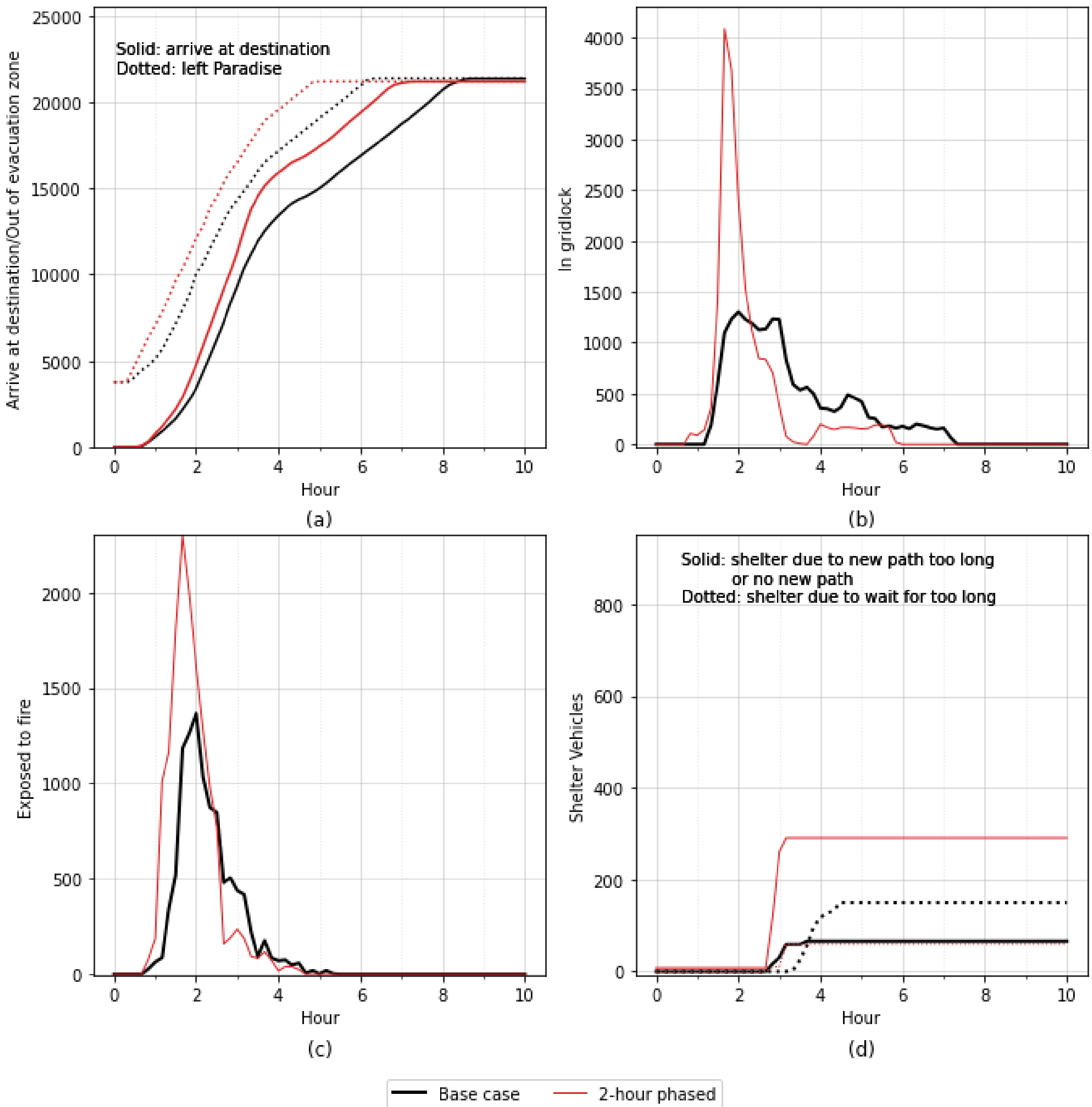


Figure 28. The effects of departure time on evacuation efficiency. (a) Arrival and out of the evacuation zone counts; (b) number of vehicles in gridlock; (c) number of vehicles exposed to fire; and (d) number of vehicles forced to shelter-in-place.

(3) The effect of road closure probability

The base case scenario assumed that there is a 15 percent chance that a residential road is temporarily closed if fire reaches it. This assumption was made to simulate closures due to the dangerous flame length or trees falling down, etc.

After one hour, when the fuel has been exhausted and the obstacles cleared, the road will be open again. In reality, the closure time may be shorter or longer and the chances of road closure may also be different than the conditions assumed in the base case. Figure 29 shows the effect of different road closure probabilities. The purple curves correspond to the favorable case when roads do not close when fire reaches them (except from Pentz Road, Clark Road and Neal Road, when closures are known to have happened during the day of the Camp Fire). The arrival time has almost no change (Figure 29(a)), while the gridlock situation and the number of vehicles exposed to fire have small variations from the base case (Figure 29(b) and (c)). This is expected, because lowering the fire-induced road closure probability from 15 percent to 0 percent on residential roads does not change the overall supply (egress capacity) and demand (vehicle counts and departure time) of the traffic simulation dramatically. The most obvious effect is on the number of sheltering vehicles. This alternative case effectively keeps all residential streets clear, which leads to a more robustly connected road network for vehicles to always find a route to their destination within a reasonable time. As a result, there is no vehicle that needs to shelter-in-place.

In another comparison scenario, with a 30 percent chance the roads are closed when fire reaches them, the evacuation efficiency metrics are shown by the light blue curves in Figure 29. There are nearly 1000 vehicles (five percent of all evacuation vehicles) that cannot find a route (or a detour that is within two times the duration of the original route) and are forced to shelter-in-place, which is the worst among all scenarios studied. This is expected since the high likelihood of road closure when fire arrives causes significant disruptions to the connectivity of the network. Due to the large number of vehicles that cannot complete the evacuation, all other metrics are affected. The total number of vehicles that arrived at the destination at the end of the simulation is 96 percent of the base case. The number of vehicles in long gridlock or exposed to fire is reduced after Hour 3 compared to the base case, as many vehicles that would otherwise cause congestion now would choose to shelter-in-place.

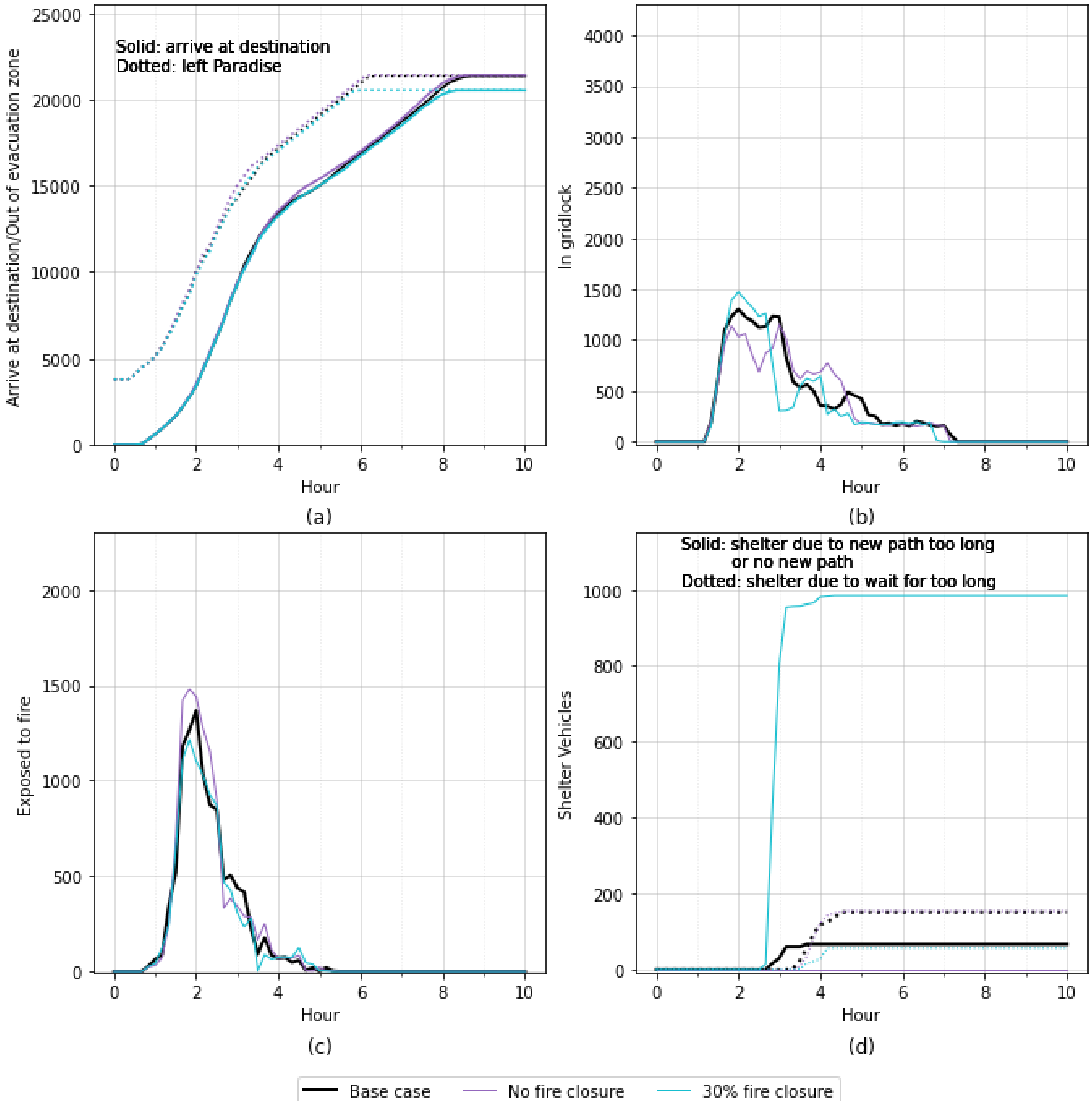


Figure 29. Effects of fire-induced road closure probability on evacuation efficiency. (a) Arrival and out of evacuation zone counts; (b) number of vehicles in gridlock; (c) number of vehicles exposed to fire; and (d) number of vehicles forced to shelter-in-place.

(4) The effect of contraflow on Skyway Road

One strategy attempted during the Camp Fire evacuation was instituting contraflow on Skyway Road. However, according to our site visits, this strategy did not achieve the desired effect due to communication and coordination difficulties. In our simulation, the base case scenario assumes no contraflow on Skyway Road. In the two comparison scenarios, an extra one or two lanes on Skyway Road are assumed to be used going westward, resulting in a total of three or four outbound lanes. In Figure 30, these two comparison scenarios are represented by the pink and gray curves, respectively. Figure 30(a) shows that adding lanes on Skyway Road is helpful for vehicles to leave Paradise earlier, by about one hour for each extra lane. In addition, in both alternative contraflow cases, the arrival curves do not differ significantly from the base case. This indicates that there are bottlenecks downstream, for example, at the end point of the contraflow operation. Such an outcome is in accordance with our understanding of the contraflow operation; it can help the traffic leave a dangerous area, but it may not be directly beneficial for assisting vehicles to arrive at their final destination, especially when the contraflow lanes end early, and vehicles need to merge back to the original outbound lanes before reaching their destination.

As traffic can get out of the evacuation zones earlier with contraflow, the number of vehicles in gridlock is not reduced. As can be seen in Figure 30(b), at around 3-5 hours after the start of evacuation, with two extra lanes of contraflow (or slightly delayed with one extra lane of contraflow), the number of vehicles in gridlock remains at a high level despite being almost zero in the base case. Further investigations of the congestion map indicate that the queues are almost exclusively on Skyway Road. Even though the inflow capacity to Skyway Road is increased due to the extra lanes being added to the outbound direction, the outflow is still limited by the downstream end, where the contraflow traffic needs to merge into the usual lane. This results in an accumulation of vehicles on Skyway Road. This is, however, potentially beneficial because it allows vehicles to queue in places away from the fire. As shown in Figure 30(c), having vehicles queuing on Skyway Road can reduce the number of vehicles exposed to fire.

In terms of the number of vehicles that need to shelter-in-place, the results of this particular simulation indicate that with three lanes going westbound, there are more vehicles that need to shelter-in-place, exclusively due to the detours being too long. With four lanes of road on Skyway Road leaving Paradise, less than 10 vehicles choose to shelter-in-place. As discussed previously, the shelter-in-place count is an extremely sensitive outcome and insights from this strategy need to be investigated further, using statistical analysis.

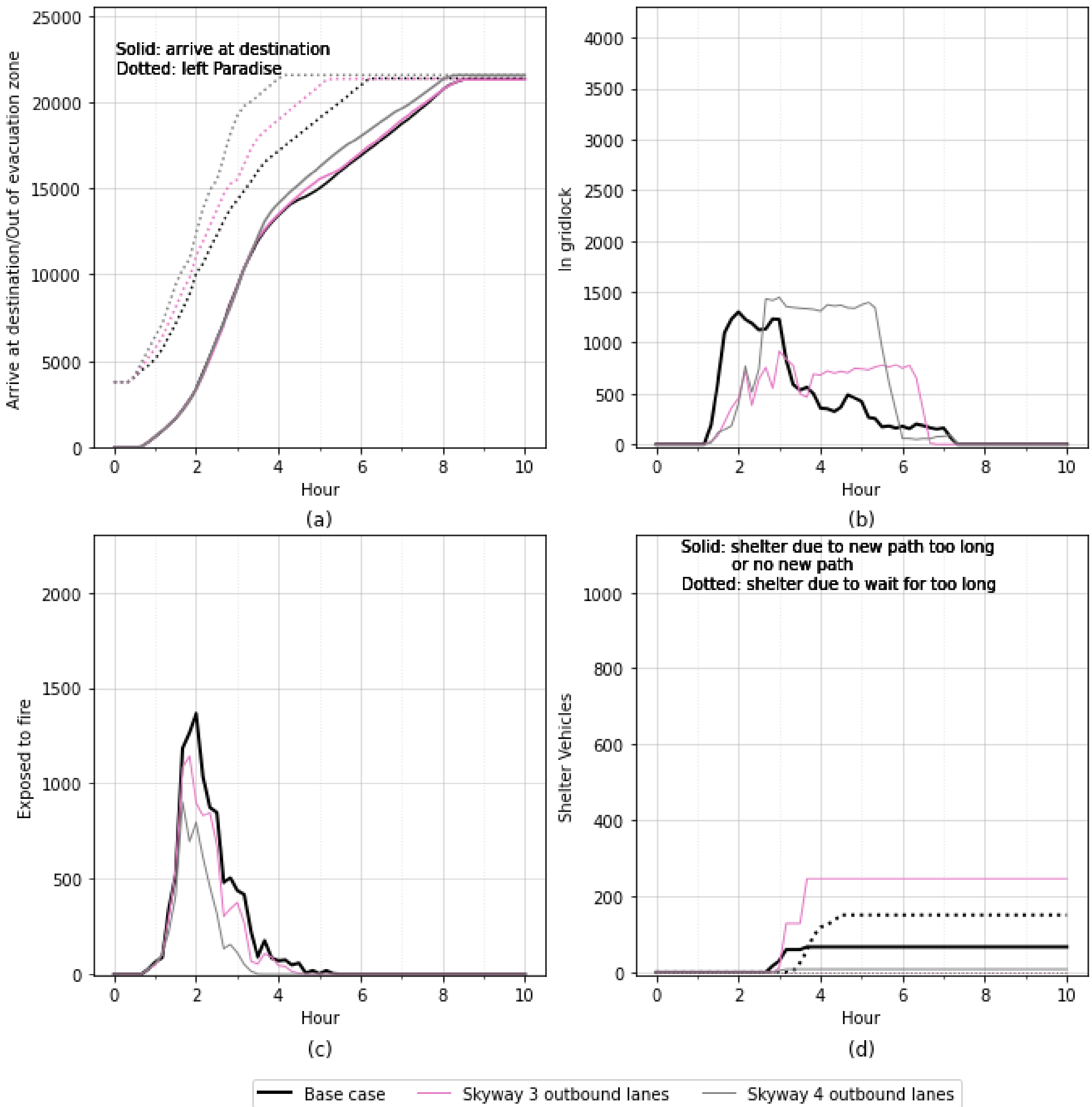


Figure 30. The effects of contraflow on Skyway on evacuation efficiency. (a) Arrival and out of the evacuation zone counts; (b) number of vehicles in gridlock; (c) number of vehicles exposed to fire; and (d) number of vehicles forced to shelter-in-place.

(5) The effect of cell communication functionality: real-time traffic information after 10:30 AM

The last alternative scenario examines the impact of losing cell communication infrastructure on evacuation efficiency. In the real Camp Fire evacuation, cell communication went down at about 10:30 AM. In the simulation, rerouting depends on the normal functioning of cell communication. With cell communication functioning normally, vehicles can replan their route every five minutes to avoid congestion. Without cell communication, access to traffic conditions information becomes more difficult and we assumed that rerouting only happens every half hour. The rerouting is not completely suspended to account for other methods to access road congestion and closure information (e.g., word of mouth). In Figure 31, the black curve is the base case with cell communication service being lost at 2.5 hours after the start of the evacuation, while the yellow curve shows the outcomes in the case of normally functioning cell communication throughout the simulation. Based on Figure 31(a), maintaining the connection to real-time traffic information can improve arrival times as well as time out of the evacuation zone by a small amount. This connection also helps to reduce the number of vehicles in gridlock, especially after 2.5 hours, as shown in Figure 31(b), since vehicles can continuously scan for the best route. Having access to real-time traffic information through cell communication does not seem to improve vehicle fire exposure significantly. Finally, real-time traffic information is of great importance in reducing the number of shelter-in-place vehicles under the unexpected closure of a major route. In Figure 31(d), under the base case scenario, when Neal Road is closed at Hour 3, about 150 vehicles cannot find an alternative route through partial rerouting (looking ahead for three intersections to circumvent a closure ahead). But with continuous access to real-time traffic information, this number reduces to 24.

Apart from providing access to real-time routing information, cell communication's functionality also impacts the coordination between agencies as well as communication between agencies and evacuees. These functions are not directly represented in our current framework, although some impacts, such as the coordination of contraflow, are investigated in other scenarios.

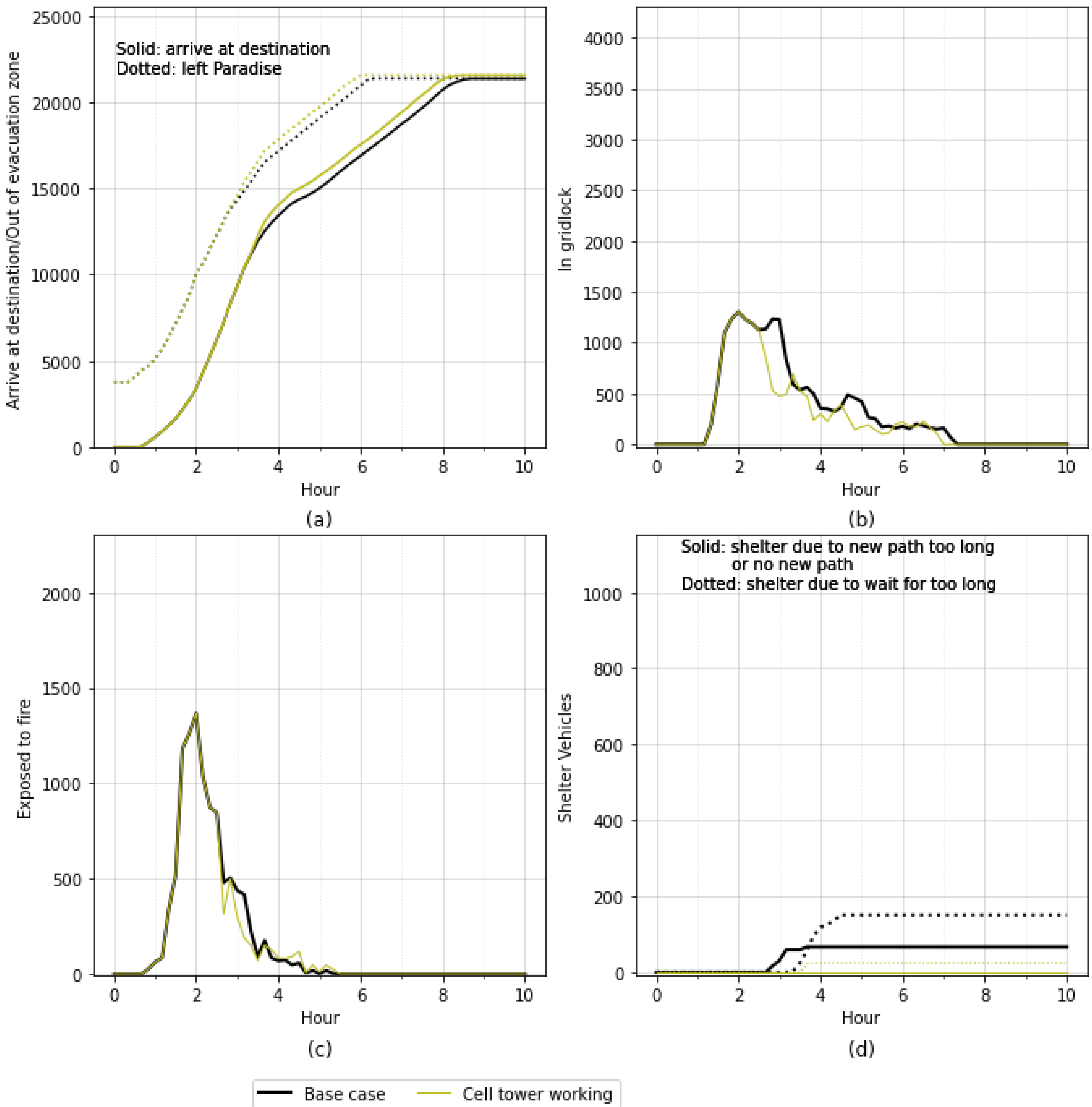


Figure 31. The effects of cell communication operation on evacuation efficiency. (a) Arrival and out of the evacuation zone counts; (b) number of vehicles in gridlock; (c) number of vehicles exposed to fire; and (d) number of vehicles forced to shelter-in-place.

III-2.6 Statistical analysis

As the simulations performed in this study are inherently random, we conducted additional random repetitions with different random seeds to validate the conclusions. Random seed is a user-input number used in computer programs to initialize the generation of "random" numbers (e.g., random sampling from a list, generating a random number from a known distribution). By setting a different random seed each time, different outcomes of the demand/departure time, ember location and traffic movements can be generated. Due to the running time of the simulations, only five random repetitions were conducted. Table 18 presents the mean values of each metric under different scenarios, as well as t-test results of the difference with the base case. The null hypothesis of the t-test is that there is no significant difference between the mean values of each metric under the base case and the alternative scenarios. If the p-value of the t-test is smaller than 0.01, we reject the null hypothesis. In Table 18, the metrics which are statistically significant from the base case mean are colored in blue or red. Blue represents that the alternative scenario demonstrates statistically significant improvements over the base case, while red represents that the alternative scenario leads to statistically significant worse results compared to the base value.

Based on the statistics shown in Table 18, it can be seen that reducing the traffic load from the base case (1.75 vehicles per household on average) to one vehicle per household can significantly reduce evacuation time, and gridlock, as well as fire exposure risks. However, it does not significantly reduce the number of vehicles that need to shelter. In fact, almost no metric can lead to statistically significant changes to the sheltering count metrics, potentially indicating the large variances associated with such metrics from simulation experiments.

Increasing the number of vehicles in the base case to two vehicles per household leads to a statistically significant increase in the arrival time as well as the gridlock metric. However, it does not have a significant impact on the fire exposure metrics, potentially due to the congestion mainly occurring in the northwest section of the town and along the evacuation routes, while the vehicles can still leave the fire front on the east side of the town in time.

The phased evacuation scenario in our study can greatly reduce evacuation times (the time for evacuees to leave Paradise and reach their destination), but it also leads to an increase in the number of vehicles in gridlock. As discussed in the alternative scenarios, the phased evacuation situation that has been specified in this study results in a more concentrated departure in the first hour after the fire reaches the town, which expectedly leads to more serious congestion. The phased evacuation scenario does not seem to cause statistically significant differences in other metrics (fire exposure risks and the shelter counts).

The probability of fire-induced road closures does not seem to affect any metrics in a statistically significant manner. However, this does not mean it is unimportant. The statistical results indicate that there is relatively large uncertainty regarding the outcomes depending on where the closures occur. Road closures are assumed to occur randomly on residential and unclassified roads based on the randomly generated spot fire locations. If closures occur on one of the heavily used roads without alternative detours, negative outcomes are almost certain.

Implementing contraflow on Skyway Road leads to a statistically significant reduction in the time it takes to evacuate Paradise, but not in the final arrival time. This is in accordance with our understanding about the contraflow operation. It helps people to get out of the danger zone faster, but its impacts stop where contraflow stops. Contraflow is a labor-intensive measure and requires a great deal of coordination across jurisdictions. If resources permit, contraflow can be extended to facilitate evacuees reaching areas further away from the danger.

Last, having access to real-time traffic information does not show statistically significant different results in any metric. This is due to our assumption in the base case that without the real-time traffic information, evacuation vehicles can still get updates about the traffic situation from other means, even if less frequently, such as from word-of-mouth information regarding road closures or traffic congestion. This demonstrates the importance and potential benefits of having alternative means to communicate real-time traffic information. Even though alternative communication may be slow and reach a smaller audience than navigation apps such as Google Maps, it is still effective in maintaining at least the same level of evacuation performance compared to the alternative case, where timely real-time traffic information is available throughout the evacuation process.

Table 18. Random tests of different scenarios and t-tests of the summary statistics.

Scenario	Metrics						
	Time for 90% evacuees leaving Paradise (hours)	Time for 90% evacuees reaching destination (hours)	Maximum numbers of vehicles in gridlock (vehicles)	Maximum numbers of vehicles exposed to fire (vehicles)	Time of exposure (veh-hours)	Sheltering: no routes available (or detours too long) (vehicles)	Sheltering: waiting for too long (> 2.5 hours) (vehicles)
Base case	**5.39**	**7.58**	**1684**	**1667**	**17.1**	**471**	**47**
1 vehicle per household	2.93	4.27	77	531	3.52	14	0
p_value	0.0	0.0	0.0	0.001	0.0	0.061	0.184
2 vehicle per household	6.43	8.59	3279	1981	22.05	161	339
p-value	0.0	0.0	0.005	0.108	0.08	0.159	0.0
Phased evacuation	4.21	6.32	3980	2172	21.03	282	12
p-value	0.0	0.0	0.0	0.075	0.063	0.38	0.315
No fire-induced road closure	5.09	7.25	1357	1910	19.26	4	108
p-value	0.022	0.014	0.117	0.203	0.224	0.058	0.169
30% fire-induced road closure	5.63	7.81	1873	1448	15.78	503	67
p-value	0.129	0.122	0.466	0.239	0.379	0.912	0.642
3-lane westward on Skyway	4.25	7.32	1310	1399	13.25	191	0
p-value	0.0	0.03	0.113	0.15	0.025	0.223	0.184
4-lane westward on Skyway	3.37	7.21	1606	1068	9.44	36	0
p-value	0.0	0.026	0.677	0.008	0.001	0.07	0.184
Real-time traffic info after 10:30 AM	5.09	7.25	1586	1667	17.42	4	59.2
p-value	0.049	0.03	0.653	1.0	0.828	0.058	0.742

III-2.7 Key Findings from the Paradise Simulations

In this case study, the simulation models developed represent the Camp Fire evacuation process. Due to limited detailed data available regarding the event, the quality of the simulation depended on carefully designing the scenarios, selecting the input parameters and validating them against available observations. Another challenge was the difficulty of representing complex human behaviors through mathematical models, for example, evacuation routing behavior. When such discrepancies are observed between the behavior of simulated vehicles and common sense, adjustments were made to resolve these issues, for example, by adding myopic routing behaviors or route choices based on delayed traffic information. Lastly, due to the inherent randomness associated with numerical simulations, random repetitions were conducted to analyze the results statistically. Despite the challenges associated with these simulations, some insights can be gained from the analysis results.

Paradise, with a population of 26,682 (Maranghides et al., 2020), has only 4-5 roads that connect the town to the outside. The demand-supply ratio is relatively high. If these key evacuation routes are closed due to fire-induced hazards, it is almost impossible to evacuate the whole town in time in the face of rapid progression of the fire. From the supply-demand perspective, it is critical to maintain the normal operation of the key evacuation routes, e.g., through fuel management (e.g., removing dead trees and lower limbs along the roads) or having special personnel to clear any obstacles quickly. On the demand side, encouraging carpooling or having household members travel together requires fewer cars and could be a promising measure to increase evacuation efficiency and save lives. Practically, this strategy would involve education campaigns before the fire, recommending that residents pack essential personal belongings beforehand to save space in their vehicles.

On the traffic management and communication side, the contraflow measure is effective in helping evacuees to leave dangerous areas faster. However, it requires coordination between Paradise and neighboring towns and across agencies between the traffic operations and law enforcement teams. Measures to guarantee smooth communication and orderly coordination should be planned and even rehearsed beforehand as part of wildfire preparedness efforts.

In the simulation, the shelter-in-place outcome metrics represent the vehicles whose risk of remaining on the road would be higher than seeking safe shelters (e.g., those who do not have a path to reach their destination or have been queuing for too long). Such metrics are hard to predict in a quantitative manner as they depend on many random factors, such as where the road might be closed due to the fire. Given the randomness of these metrics as well as seriousness of the outcomes if shelters are unavailable, it might be beneficial to designate a few accessible locations in town as wildfire shelters (e.g., parking lots or fire-proof structures) and make them known to the residents as part of the evacuation preparedness plan. The capacity of these shelters can be determined together with the supply-demand analysis of the road network to keep the evacuation traffic load at a manageable level, e.g., being able to evacuate or offer shelter locations to the residents of the town in two hours.

III-3. Bolinas, CA

Our second study is situated in the community of Bolinas, CA. The natural environment and road network of Bolinas has been described in the previous "Methodology" section. The fire simulations and the communication process modeling are introduced in greater detail in "Part I" and "Part II" of this report. Here, we focus on the integration of the fire simulation model, the communications model and the traffic simulation model.

III-3.1 Integration of the fire, communications, and traffic models

Compared to the Camp Fire simulation, the Bolinas case study is more involved in that all the fire, communications, and traffic simulations were constructed by the members of the research team. This was both challenging in terms of the modeling, but also allowed us to focus on logical links between different models. As introduced in the methodology framework in Figure 1, the fire and communications simulations are used as inputs to influence the traffic simulation, from both the supply side and the demand side, as shown in Table 19.

Table 19. Bolinas model integration.

	Traffic simulation: the supply	Traffic simulation: the demand
Fire spread model	Roads are closed if a link is next to an active fire pixel (from the fire simulation), which has flame length longer than 2 ft.	Vehicles will depart if they are within 400m of the fire frontier, regardless of whether they have received the official evacuation order from one of the communication methods studied in this project.
Communication model	NA	Vehicle departure time is determined by the time that it receives the official evacuation order, plus a random 15-30-minute delay as preparation time for the evacuation.

A spatial map showing the fire extent and flame length by 30-meter cells by hour was developed for the Bolinas area. Figure 32 shows the fire spread data with an example of the first four hours of fire scenario 3 (the hypothetical weather condition, ignition point 3 case in Table 5). During the simulation, at every one-second time step, the distance between undeparted vehicles and the fire frontier is checked. If the distance is smaller than 0.25 mile, it is assumed that the residents perceive the danger and begin the evacuation immediately even though they have not received the evacuation order by other means. At every hour in the simulation, links are checked regarding whether it should be closed based on the flame length surrounding it. In fire scenario 3 as shown in Figure 32, the long flame length (red dots) will reach Mesa Road and the northeast corner of the Big Mesa area in the third hour. If the residents are notified of the evacuation order well before this time, they could safely evacuate. If the communication channels are blocked and the evacuation order could not be sent out efficiently, some vehicles might face the danger of being trapped inside the Big Mesa area.

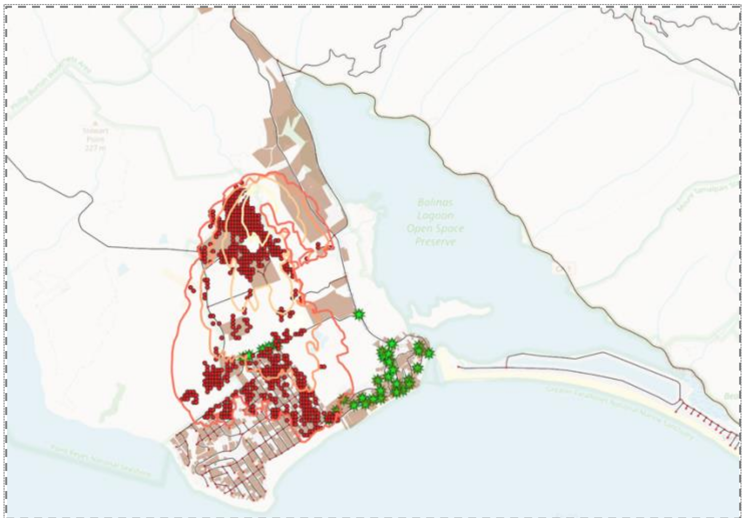


Figure 32. Fire footprint and flame length by hour. Note: The red dots indicate locations with flame length longer than 2 feet. The brown polygons show the residential parcels (households). The green stars show the locations of tourists.

A small modification has been made in the communications model that was eventually embedded in the traffic simulation. In Figure 10 in Part II, a fixed percentage of cognition-based evacuations (i.e., those who did not receive evacuation orders but decided to leave as they sense the fire is very close) is assumed. In the traffic simulation, this fixed percentage is set as the initial number of residents who use cognition-based evacuation. The final number of evacuees who decided to leave due to the proximity of the fire could be higher. This is because the spatial dimension of the traffic simulation allows the determination of cognition-based departures more accurately. In general, the faster the fire spreads into the residential or tourist areas, the higher the number of cognition-based evacuations becomes. However, this assumption does not apply to the communication scenario 1 (cell communication working), as in this communication scenario, most people can be notified about the evacuation order using one of the more efficient communication methods (e.g., social media, CodeRED/Nixle/AlertMarin alerts or cell phone calls) before having to rely on cognition-based signs of fire danger to make evacuation decisions.

III-3.2 Traffic Simulation Setup

Similar to the Camp Fire simulation, the road network for the Bolinas case study is obtained from OSM (Figure 33). It consists of 256 nodes and 605 links. Most of the roads are two-way/two-lane residential roads with a speed limit of 25-35 mph. The Bolinas roads join CA-1, which also has one lane per direction, but with a speed limit from 25-55 mph (the speed limit is lower when passing through Stinson Beach, a nearby community). Theoretically, contraflow could be instituted to expand the egress capacity on Mesa Road leading out of the residential area, as well as Olema Bolinas Road and Horseshoe Hill Road leading to CA-1. However, this action would then block access for external help.

The evacuation demand is assumed to be split into two parts, with one being residential evacuees and another being visitors. For the residential evacuees, land use parcels were used to determine the locations of each household. According to the parcel data (MarinMap, 2019), there are 595 household parcels in Bolinas. We further assumed that each household uses two vehicles, and their departure time is the same (sampled from a gamma distribution whose shape and scale parameters depend on the communication method). As for the tourists, their starting locations are assumed to be in the downtown area (beach visitors) or along Mesa Road (parking places for hikers). The total number of evacuation vehicles belonging to the tourists is assumed to be 300. For both local residents and tourists, their destinations are randomly sampled from two points on Highway 1 (red star in Figure 33) under the fire and communication scenario 1 (no regional fire) and they are considered safe once they reach either point. The fire and communication scenarios 2 and 3 assume that there is a regional fire in the north, which not only damages the communication infrastructure, but also could develop past the stretch of CA-1 that is north of Bolinas (as shown by the fire simulation results in Table 6 and Table 7). Under these scenarios, all evacuation traffic should be diverted to go south on CA-1 (Evacuation Destination 1 in Figure 33).

The departure time of each vehicle in the simulation is obtained based on the communication system dynamic models. The only modification made was to replace the fixed cognitive-based group (i.e., those who make evacuation decisions based on visual signs of the fire) with a variable population. By coupling with the fire spread model, whenever an undeparted vehicle is within 0.25 mile of the fire front, the vehicle starts the evacuation journey. As a result, the faster the fire progresses, the steeper is the rate of departure in this simulation. If the extent of the fire is limited, there will be a group of people in the far end of Bolinas not mobilized at all, given their distance from the fire front.

Vehicles automatically replan for the best route every five minutes even without access to the Internet. This assumption is made given the small size of the study area and the general familiarity of the evacuees with the road network. When a fire-induced road closure blocks the only evacuation route, or if heavy congestion occurs, a vehicle waits in its current position for a maximum of three hours before seeking to shelter-in-place. The closed road may reopen after a certain period of time, depending on the efficiency of road hazard clearance. The efficiency of clearing fire-induced road hazards, among others, is included as a variable in the scenario testing. Details of the scenario setup are given in the next section.

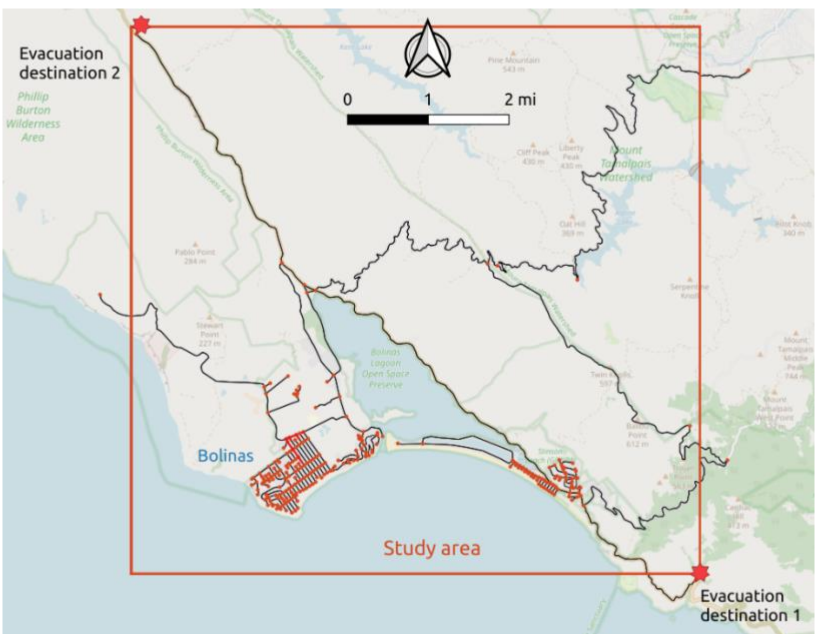


Figure 33. Map of the Bolinas network.

III-3.3 Scenarios Setup

Even though they are based on the same simulation method, the scenarios for the Bolinas case study are different from those for the Paradise case study, due mainly to two reasons. First, with 1,000 to 2,000 residents, the population of Bolinas is much smaller than Paradise, which has 20,000 to 30,000 residents that would need to be evacuated. The same goes for the size of the road network and emergency response resources. As a result, certain evacuation strategies (e.g., phased evacuation) would be hard to implement. Instead, the strategies chosen in the Bolinas study focus on those that are more relevant for small communities (e.g., clearing and reopening roads blocked by fire, creating space for sheltering-in-place). For the Bolinas case study, we have access to both the fire and communications models, which allow more diverse fire and communications scenarios to be considered.

Table 20 summarizes the scenarios considered for the Bolinas case study. Specifically, as there is no real event to calibrate the scenario design, the base case assumes an advantageous situation, i.e., no fire-induced road closure, a fully functioning communication network, and enough safe shelters for shelter-in-place if vehicles are forced to wait too long in traffic. The alternative scenarios investigate the outcomes if one or some of the base case assumptions are changed. In each alternative scenario, three fire sub-scenarios and three communications sub-scenarios are considered to study the interactions between different fire, communications, and traffic situations.

Among the four variables listed in Table 20, the fire and communications variables have been explained in detail in Part I and II of this report. For the remaining two variables, the "time to clear blocked roads" variable is a measure of the efficiency in clearing fire-induced hazards on roads, such as fallen trees or abandoned vehicles. Depending on the scale of the hazard, this task may be hard for the community to accomplish. In fact, in the PBS documentary on the Camp Fire, several people mentioned that a bulldozer operator from the local police department cleared obstacles on Pearson Road and saved lives (PBS Frontline, 2019). This scenario is especially worth considering for Bolinas because of the limited connectivity of the road network. Last, the "time wait before shelter-in-place" variable measures the feasibility of shelter-in-place for the evacuees. In the base case, we assumed that there are relatively ample amounts of safe shelters around the community (e.g., safe roadside spaces, parking lots or designated areas without fire fuels). As a result, a vehicle can leave the network (be removed from the evacuation simulation) if it has been trapped on the same link for more than three hours, or 30 minutes if it is next to an active fire. Sheltering-in-place may be particularly useful given the limited egress capacity of the road network in Bolinas. It not only could relieve the evacuation demand but also allow those in greater danger (e.g., those with respiratory disease) to leave rather than be trapped in traffic. In the alternative scenario, a no-shelter situation is studied, where there is no safe sheltering place in town and all vehicles have to leave (except for a few far away from the fire who do not comply with the evacuation order, as explained in the Section III-3.2).

Table 20. Scenarios for Bolinas study.

Scenario description	Fire ignition locations in Bolinas (1)	Communication scenario (2)	Time to clear blocked roads	Waiting time before shelter-in-place
Base case	Three locations inside Bolinas in Table 3, shown below. 	Communication sub-scenarios 1 (communications infrastructure not damaged by regional fire).	0 (no closure)	A vehicle shelters in place if it spends more than 3 hours on one link.
Communication disruption	As base case	Communication sub-scenarios 1, 2 & 3, where the cell infrastructures are damaged at an increasingly high level.	As base case	As base case
Time to reopen blocked roads	As base case	Communication sub-scenarios 1, 2 & 3, as above.	As base case, or alternatively: 1 hour, 5 hours (insufficient resources or personnel to clear the blocked roads).	As base case
Shelter availability	As base case	Communication sub-scenarios 1, 2 & 3, as above.	As base case	Vehicles do not shelter-in-place. Vehicles can only shelter-in-place at designated locations near the fire department.

Notes: (1) The three fire ignition location scenarios are from Part I of this report.
(2) The three communication scenarios are from Part II of this report.

III-3.5 Results

III-3.5.1 Base case

The base case results are presented first in Table 21 (graphical) and Table 22 (numerical). The results are disaggregated according to the fire locations (Locations 1, 2, and 3) and evacuee types (local residents or visitors). As a recap, the base case assumes a fully functioning communications system, which implies that about 85 percent of the local residents and 100 percent of the visitors can be informed of the evacuation decision using the relatively fast radio and cell-based communication methods (see Table 10 and Figure 10 in the communications modeling section).

The arrival curves for the base case scenarios are presented first. As seen in Table 21, the number of vehicles that participate in the evacuation in the base case is dependent on the fire spread characteristics. For a fire starting at location 1 (northwest of the Big Mesa, column 1 in Table 21), the fire simulation suggests that its footprint is relatively limited. In fact, it does not reach beyond the residential area. As a result, some evacuees who are located in the downtown area do not participate in the evacuation. This leads to the lower “final platform” in the arrival curve for fire location 1 compared to the other two fire locations. The arrival characteristics corresponding to fires starting at locations 2 and 3 are rather similar, with the arrival rate for fire location 2 being slightly higher. This can also be attributed to the characteristics of the fire: even though the fire starting at location 3 has a bigger footprint, the fire at location 2 actually reaches the residential area earlier, prompting earlier departures due to the visibility of the danger.

Table 21. Base case results.

Inputs and Assumptions

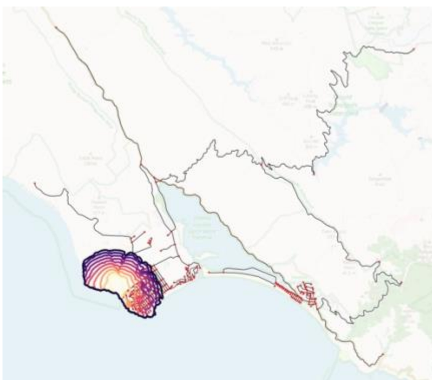
General:

- Communication scenario 1 (fully functioning cell communication system);
- No fire-induced road closures;
- Ample space for sheltering-in-place. Vehicles waited for 0.5 hour, or at least 10 times the link free-flow time, but no more than 1 hour before quitting the evacuation and sheltering-in-place;
- Two vehicles per local households (1,190 vehicles) and 300 vehicles used by visitors;
- No contraflow (keeping the inbound lane for external emergency support access).

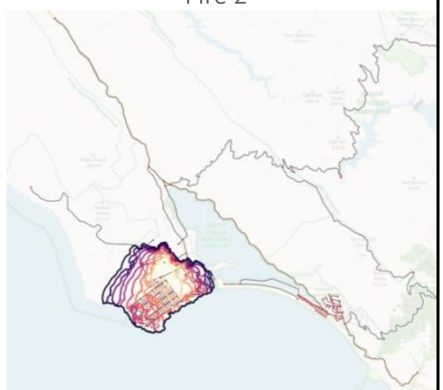
Specifics:

- Three different fire ignitions and spread as shown below.

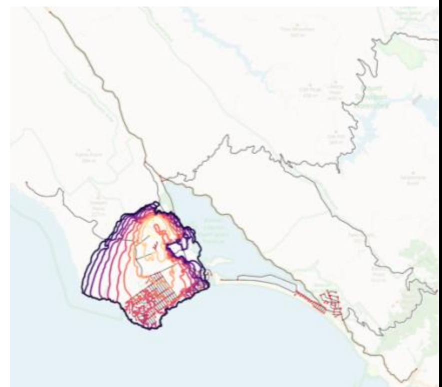
Fire 1



Fire 2

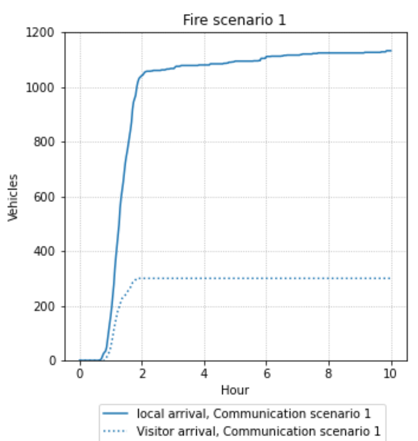


Fire 3

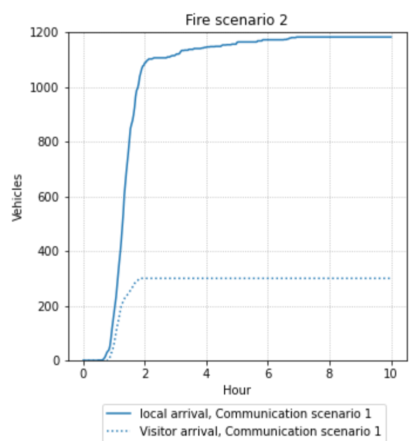


Outputs

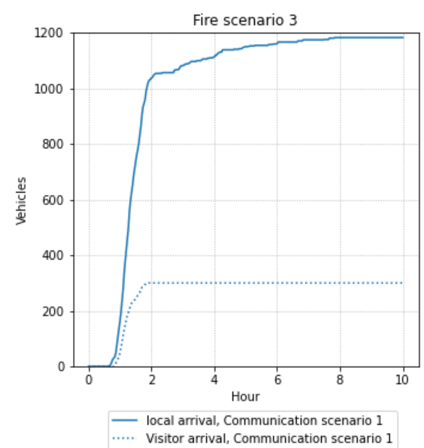
Arrival curve



Arrival curve



Arrival curve



The evacuation outcomes can also be studied more quantitatively with the help of metrics shown in Table 22. There are some commonalities in the evacuation outcomes corresponding to the three fire locations. First, it would take around 1-1.5 hours to inform and evacuate half of the local residents and the visitors under the base case. This is relatively fast due to the base case assuming a fully functioning road network and no fire-induced road closures. Secondly, there is no sheltering-in-place (not including those not participating in the evacuation due to their distance to the fire), also thanks to zero fire-induced road closures.

Other metrics in Table 22 share fewer similarities across the fire locations or the evacuee types and offer interesting insights about the evacuation process under the particular assumptions. Notably, it would take more than three hours to evacuate 90 percent of the local residents for a fire starting at location 1, but just two or three hours for a fire starting at locations 2 or 3. This is due to the specific communication patterns that the local residents are assumed to follow. In the base case, even though cell communication is functioning well, there is still a group of people who rely on visual signs (distance to the fire) to decide to leave. For the fire that starts at location 1, which never reaches the downtown area, some people do not participate in the evacuation (58 vehicles from the simulation, or 5 percent of the total number of local evacuation vehicles). The number of people who do not participate in the evacuation for a fire starting at locations 2 and 3 is close to zero, as the fire under these two cases spreads across the whole community. For visitors, we assumed that all of them will receive and comply with the evacuation order, and their evacuation decisions will be less affected by the starting locations of the fire. Thus, the times to evacuate 90 percent of the visitors are the same for all three fire locations. However, this assumption might be overly positive as in reality some cell communication carriers do not work in Bolinas. Section III-3.5.2 offers additional information regarding the outcomes with limited cell infrastructure functionality (i.e., AT&T and Verizon work but not T-Mobile in Bolinas).

Another metric in Table 22 is the fire exposure extent, expressed by the number of vehicles that need to travel through active fire, as well as the average time that they spend on road links with an active fire burning nearby. In the base case scenario, fire location 2 appears to be the most critical situation in terms of this metric, with 667 residential vehicles (56 percent) and 48 visitor vehicles (16 percent) exposed to fire. This is due to the close proximity of the fire at location 2 to the evacuation routes. The average time that a vehicle spends close to an active fire is small (no more than 5-6 minutes) for the base case simulation, again due to the assumption that there are no fire-induced road closures. Under such assumptions, the evacuation vehicles can leave the network relatively quickly, minimizing the fire exposure time. Section III-3.5.3 investigates more scenarios where the roads are closed for one hour or five hours.

Table 22. Numerical results from the base case simulation.

Groups	Metrics	Fire 1	Fire 2	Fire 3
Vehicles of local residents	**Time for 50% to arrive**	1.3 hour	1.3 hour	1.3 hour
	Time for 90% to arrive	3.1 hour	1.9 hour	2.9 hour
	# sheltering-in-place	0	0	0
	# not evacuated	58	8	8
	# exposed to fire (average time)	0	667 (6 min on average)	114 (1.5 min on average)
Vehicles of tourists	**Time for 50% to arrive**	1.2 hours	1.2 hours	1.2 hours
	Time for 90% to arrive	1.6 hours	1.6 hours	1.6 hours
	# sheltering-in-place	0	0	0
	# not evacuated	0	0	0
	# exposed to fire (average time)	0	48 (4 min on average)	0

Figure 34 presents the locations of the active fires as well as running and queuing vehicles for a fire starting at ignition point 2 (north of Mesa Road). We assumed the fire burns for one hour once it reaches a pixel. The red part indicates the length of the queuing vehicles on the road while the blue part indicates the length of the running vehicles (stacked at the beginning of the link). It can be seen that the most dangerous time is around one hour after the start of the fire, when the fire is actively burning near Mesa Road, while vehicles are queuing on Mesa Road waiting to merge onto Olema Bolinas Road. In the base case, the vehicle departure time is relatively concentrated as almost everyone can be notified of the evacuation order using one of the fast communication methods. This concentration of departures creates congestion at the intersection of Mesa Road and Olema Bolinas Road. However, if these critical egress routes can be kept clear, the queuing vehicles can be discharged relatively efficiently. This explains why no obvious queues are seen in the rest of the plots in Figure 34.

Overall, the base case represents a favorable scenario where the road network is not disrupted by the fire and people can be notified of the need to evacuate relatively efficiently. The locations and patterns of the fire spread can impact the evacuation outcomes, particularly for those that make evacuation decisions based on their distance to the fire. Also, given the abundance of fuels around the only evacuation route, the risk of fire exposure on the way out of Bolinas should be carefully considered. In the upcoming sections, more diverse scenarios will be explored that would be more challenging and disruptive than the base case.

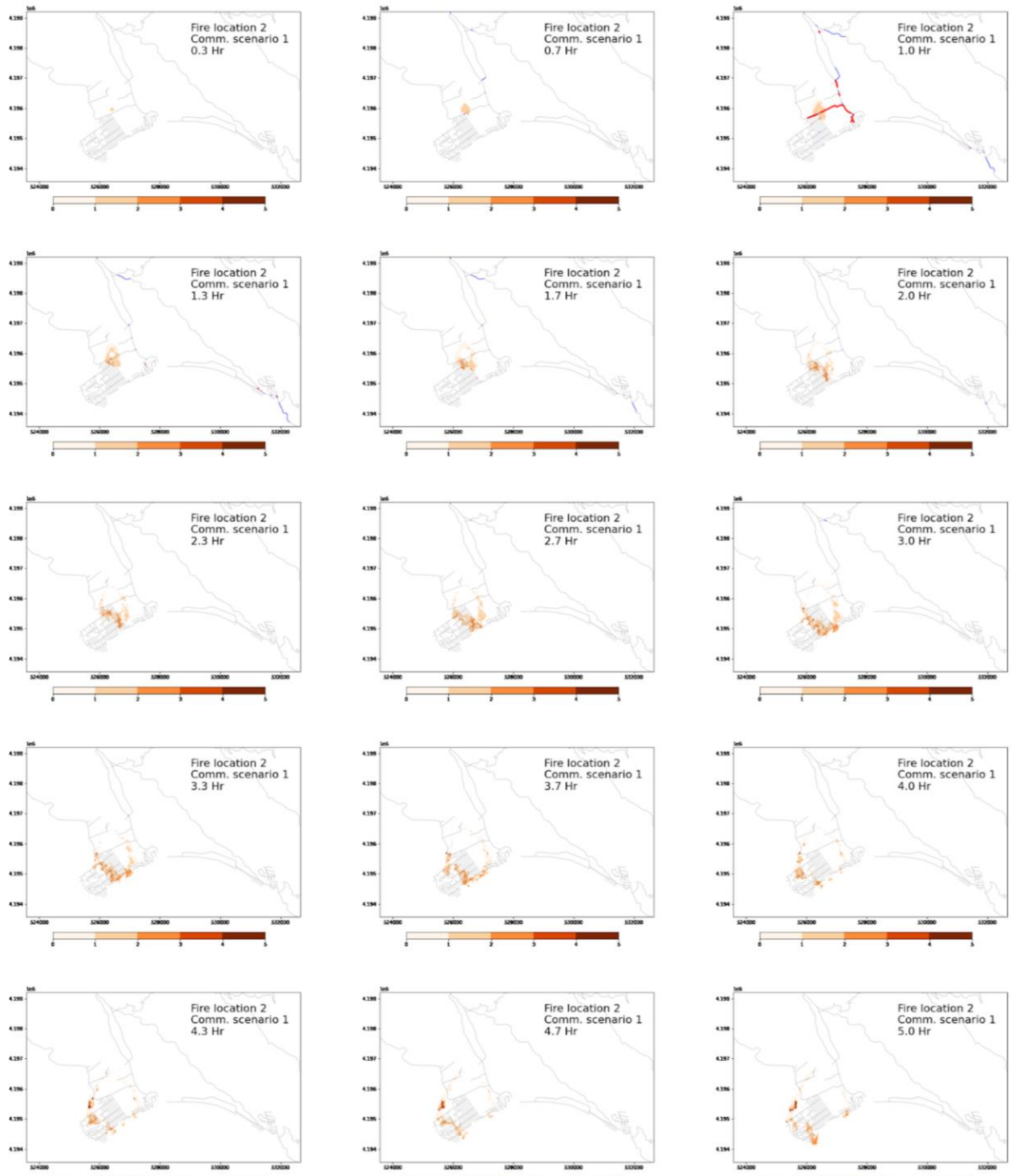


Figure 34. Vehicle fire interaction for the Bolinas case study. Base case, fire ignition location 2.

III-3.5.2 Communication disruptions

In Part II of this report, three communication system disruption situations were modeled. Labeled as 1, 2 and 3, they each represent 100, 50 and 0 percent functionality of the cell communication infrastructure. Among the few communication means identified, the cell-based communication methods (CodeRED/Nixle/AlertMarin alert, social media and cell phone messages) are the fastest in disseminating the evacuation order, except for fire radios and ham radios to which only a few local people have access. In the case when the wildfire event damages the cell communication infrastructure (e.g., from a power loss), evacuees have to rely on door-to-door notifications or visual judgements to make the evacuation decision. We assume visitors are not able to receive door-to-door notifications, thus they can only rely on cognition-based fire distance to determine the time of their evacuation. Such lack of efficient communication mechanisms to disseminate the evacuation order can greatly affect evacuation performance. The results of the evacuation outcomes under different fire and communication situations are presented below.

The arrival curves are presented first in Figure 35. The blue curves in Figure 35 represent the communication situation where the cell communication infrastructure is intact. i.e., the base case in Section III-3.5.1. The green and orange series each represent the arrival curves under a 50 percent or 100 percent disruption in cell communication. The effect of losing cell communication on the evacuation outcomes are easily noticeable; the more severe the damage to the cell communication system is, the longer it takes for the local residents and the visitors to be notified, evacuated, and arrive at their destinations.

Focusing on the local residents first, we assumed that 10 percent of the households receive the evacuation order from police radios and ham radios (the fastest communication methods). This amounts to about 120 vehicles and they are not affected by the loss of the cell-based communication network. As a result, the initial stage of the local residents' arrival curve (solid lines) varies only slightly across the communication situations (blue, green and orange). With no cell infrastructure damage, 75 percent of the households can receive the evacuation notification from cell-based communication methods, which are again relatively efficient and lead to the continuous increase in the arrival curve to around 1,000 vehicles (solid blue line). However, in communication situation 2 with half of the cell communication infrastructure being damaged, we assumed that only 40 percent of the households can still receive cellular communication and 50 percent need to rely on door-to-door notifications or visual signs to make the evacuation decision. Drawing a horizontal line at 1,000, it takes more than 1-2 hours longer to evacuate 1,000 local residents’ vehicles in communication situation 2 compared to the fully functioning case. The same goes for communication situation 3, where cell communication is completely dysfunctional, and the arrival curves start to bifurcate from the base case curve at about 120 vehicles (those who received notifications by radios) and it takes 2-4 hours longer to evacuate 1,000 local vehicles compared to the base case. After the first 1,000 vehicles, the arrival rates do not differ much, as at this stage, it is mainly those households who are relying on visual signs of the fire that are still evacuating.

Losing cell communication has an even greater impact on visitors, as they must rely completely on cell-based communications in the base case scenario. If the cell-based communication no longer functions, those affected can only rely on visual judgements of the distance to the fire to make the evacuation decision. The arrival curves of the visitors (dashed lines), as a result, reflect how fast the fire reaches them. Under fire scenario 1, since the fire stopped inside the residential area, very few visitors made the decision to evacuate in the communication situation 3 (dashed orange line in Figure 35(a)). If the cell communication infrastructure is partially functioning, as in the communication situation 2, at least half of the visitors can still receive the evacuation order and leave early (dashed green line in Figure 35(a)). For the other two fire scenarios, as the fire both reached the tourist areas (beachfront and trail starting locations), all visitors eventually had to evacuate (Figure 35(b) and (c)).

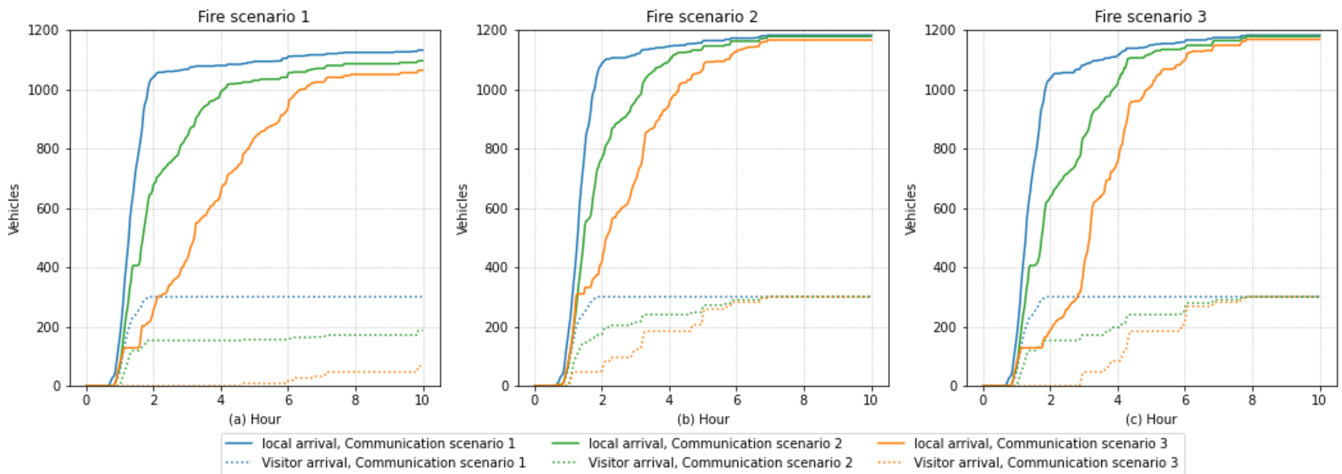


Figure 35. Arrival curves under different fire and communication sub-scenarios.

Figure 36 presents the changes in the average fire exposure time across different fire and communication situations. For fire scenario 1 (Figure 36(a)), the simulation predicts very low fire exposure. This is because the fire starts on the west side of the community, while the evacuation route goes to the east. The simulated fire does not progress fast, which gives plenty of time for the evacuees to leave through the unaffected part of the community (refer to Table 21 for the fire progression). The unexpected results come from fire scenario 2, where a fully functioning road network leads to the highest fire exposure compared to the partially or completely broken cell communication situations. The reason can be seen in Figure 37. The traffic density inside Bolinas is highest at around hour 1. However, under the communication situation 1, the vehicles departure times are the most concentrated, leading to congestion at the intersection of Mesa Road and Olema Bolinas Road. This is the place the fire reaches in one hour, with the highest number of vehicles in close proximity to the active fire. For communication situations 2 and 3, the vehicle departure times are less concentrated, thus the traffic jam around the Mesa/Olema Bolinas intersection is also less severe, allowing vehicles to leave the affected area in less time. As for fire scenario 3, as shown in Figure 38, the fire front in the simulation has not reached the road network while the main evacuation is going on. As a result, the fire exposure risk is lower than that of fire scenario 2 and different communication scenarios do not seem to have an impact on this metric.

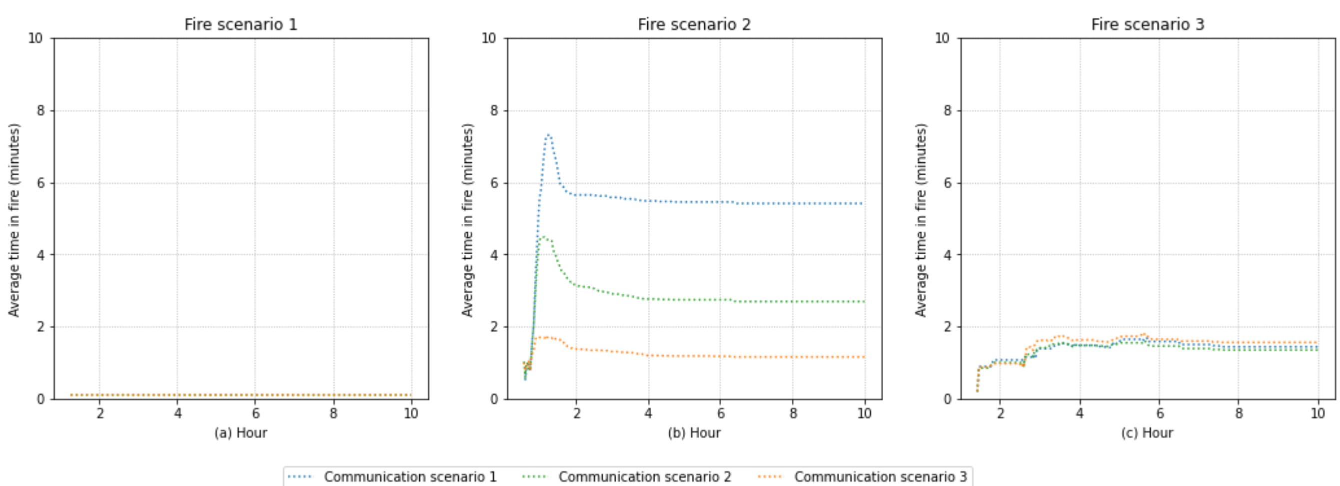


Figure 36. Average time on links with active fire burning nearby (no fire-induced road closures).

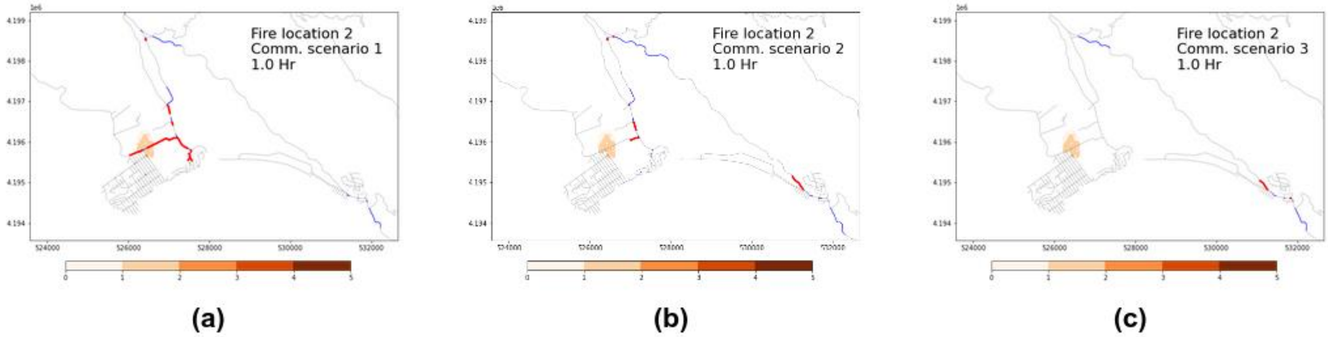


Figure 37. Locations of traffic and active fire under different communication situations, fire ignition point 2 (north of Mesa Road).

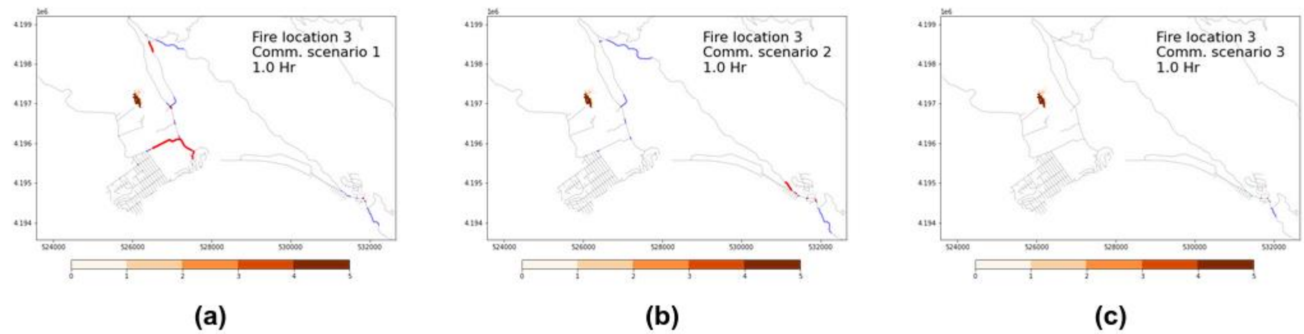


Figure 38. Locations of traffic and active fire under different communication situations, fire ignition point 3 (east of Horseshoe Hill Road).

The study of the communication scenario reveals that the communication system performance has a clear impact on the evacuation outcome based on the simulations. Without a cell-based communication system to deliver the evacuation order to the wider community of recipients in a timely manner, many evacuees have to rely on slow communication means to be informed of the situation and determine if and when to leave, which might delay the whole process. In addition, the fire and the communication situations together might have unexpected interactions. In one set of the scenarios presented (fire ignition location close to Mesa Road), early and concentrated departure, though beneficial to the final arrival rate, actually creates congestion right next to the active fire. Thus, the fire exposure risk becomes even higher compared to the more dispersed departure scenarios. Under such circumstances, implementing the contraflow strategy for a short period of time might be a viable choice to reduce the concentration of traffic close to active fire fronts.

Among the main cellular carriers in the U.S., only AT&T and Verizon have good coverage in Bolinas. Visitors who are on T-Mobile and Sprint will not receive cell phone-based evacuation orders even though the communication infrastructure is intact. As a result, the notification rates in communication scenarios 1 and 2 may be even lower. However, when parts of the visitor group receive the wildfire evacuation order, they may spread the news to other visitors in their vicinity. In future work, such informal communications can be integrated into the communications model in a way that is similar to the “door-to-door” communication mechanism considered for the residential evacuees.

The scenario outcomes presented in this subsection do not consider road closures or loss of capacity due to parked vehicles. In such cases, the egress capacity of Bolinas (around 2,000 vehicles per hour) should be able to support the evacuation of the community and the visitors in one hour or so. If this assumption does not hold, the evacuation process will be riskier and much more challenging.

III-3.5.3 Time to clear blocked roads

The effects of road closure on the evacuation outcomes are presented in this scenario. Given the dense vegetation coverage in Bolinas, as the fire progresses, some roads may be blocked due to fallen trees. In addition, there may be abandoned vehicles and other hazards that cause roads to be impassable. While we assumed that a fire burns actively for 60 minutes at a site, it may take much longer to clear the hazards even after the fire front has moved away. The base case assumes no road closure and the results are shown by the thinnest lines in Figure 39. One comparison scenario assumes that closed roads (where the flame length is longer than 2 feet from the fire simulation) will reopen in one hour (medium width lines) and another scenario assumes that they will reopen in five hours (thickest lines in Figure 39).

Examining the arrival curves in Figure 39, it can be seen that the closure time does not have an impact on the evacuation efficiency under fire scenario 1 (Figure 39(a)). The reason is that the fire in scenario 1 comes from the far-west side of the community. As it progresses eastward, it will trigger the evacuation of local residents and visitors, even before the official evacuation order is given. The fire progression direction is the same as the evacuation direction (west to east). Vehicles are able to leave the fire-stricken area using the west part of the road network, which at this moment still hasn't been damaged by the fire and is assumed to provide full capacity (about 2,000 vehicles per hour). This speed of evacuation is faster than the fire progression rate, thus road closures will not impact evacuation efficiency. This is indirectly validated by the outcome statistics in Table 23. There are relatively few vehicles exposed to fire under the fire sub-scenario 1.

The impacts of the road closure time are more obvious by visually examining Figure 39(b) and (c). The longer it takes to clear the fire-induced hazards (corresponding to thicker lines), the lower the arrival curves. Under the same fire scenario, the impact of long road closures is greatest under a damaged communication system. This is because a fully functioning communications system allows people to mobilize more quickly and leave areas that might be blocked by fire-induced hazards sooner. The worst case is shown in Figure 40, where the fire starts at location 3 (west of Horseshoe Hill Road) and the communications system is completely damaged. As the fire reaches the residential area and causes many closures inside the residential neighborhoods, some vehicles have not been informed of the evacuation early enough and are trapped by the road closures. This corresponds to the thickest orange line in Figure 39(c).

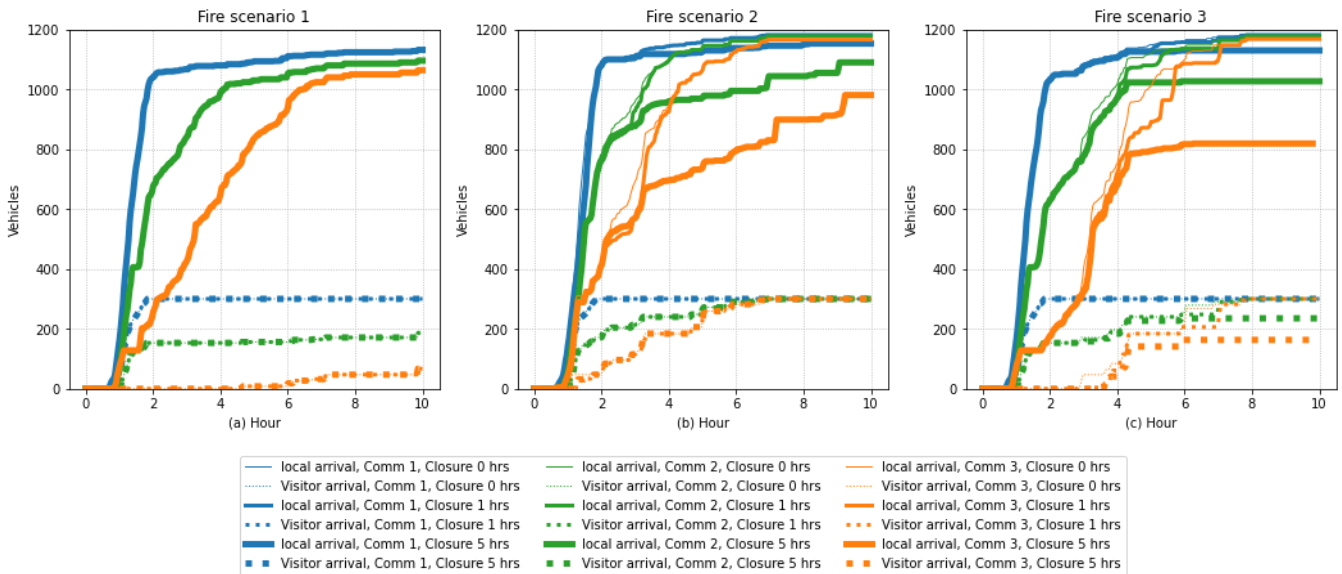


Figure 39. The effects of road closure time on the arrival curves.

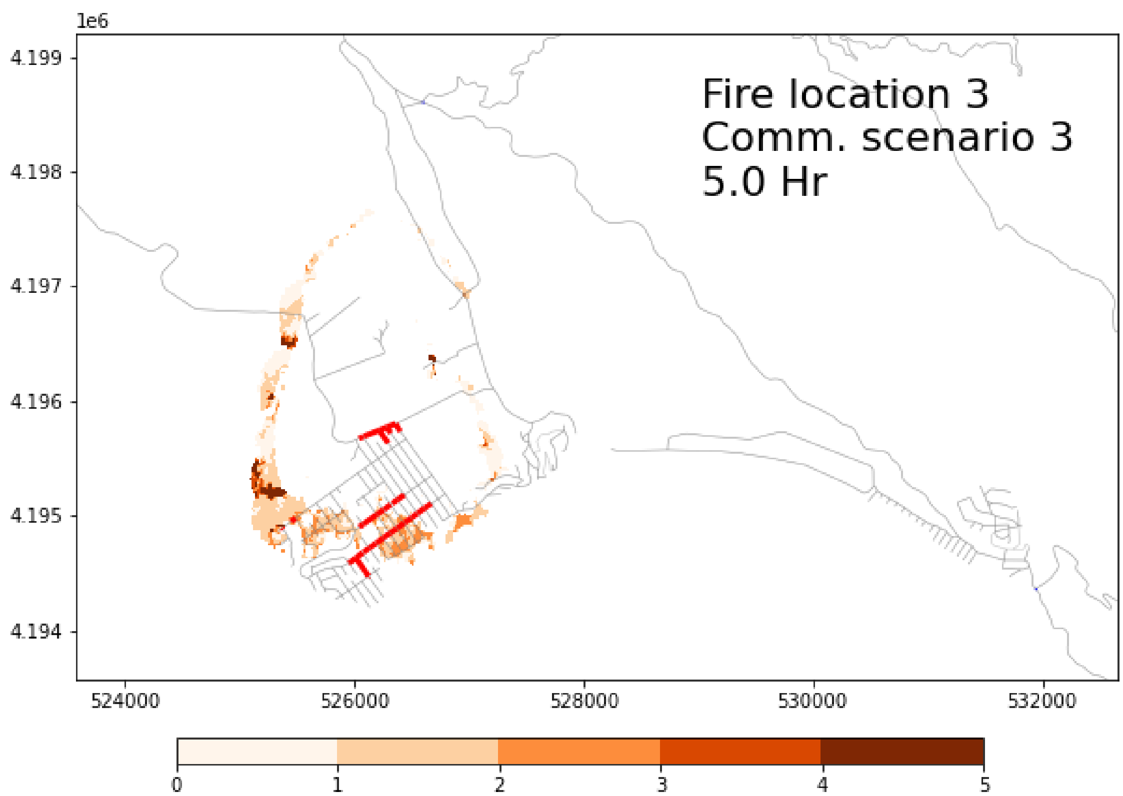


Figure 40. Locations of queues due to fire-induced road closures.

More quantitative results regarding the impacts of road closures are given in Table 23. Each column represents a fire scenario, and each sub-column indicates the road closure time (NC: no closure, C1: taking one hour to clear the hazard, C5: taking five hours to clear the hazard). Each row instead corresponds to a particular communication scenario, or evacuee type (residents and tourists). Two metrics are shown: (1) the number of vehicles that seek shelter-in-place when they cannot get out (e.g., they have been waiting for too long, or all feasible paths are closed due to fire); and (2) fire exposure risks in terms of the number and average time that the vehicles are on the links next to the active fire. The second metric is colored to reflect the impact of road closures, where blue means the metric is improved while red represents worse outcomes.

Road closure durations under fire scenario 1 do not seem to impact the evacuation metrics. As discussed above, this is due to the special pattern of fire scenario 1, which comes from the west side and goes behind the evacuation traffic. When the fire reaches a street, people are assumed to have already left, thanks to the cognition-based evacuation notification mechanism. As a result, all metrics under the “fire scenario 1” column do not vary across different road closure scenarios.

For road closures caused by fires 2 and 3, their overall trends are similar. First, only the long closures (“C5”) result in sheltering-in-place vehicles, all due to waiting for too long behind closed roads. This number varies from around 30 to as high as 200 vehicles. The lower the communication efficiency is, the higher the numbers of vehicles that need to seek shelter-in-place. For communication scenario 3, the number of vehicles that need to shelter-in-place is the highest. Secondly, road closures can prompt rerouting and reduce the number of exposed vehicles, as indicated by the blue texts in Table 23. This statement can be verified by Figure 41. As Mesa Road is closed under fire scenario 2, a greater number of vehicles take the detour and use Olema Bolinas Road out. Olema Bolinas Road is the only alternative if Mesa Road is closed, implying low redundancy in the road network and demonstrating the importance of keeping at least one of the two roads open to allow the evacuees to leave. However, even though the numbers of exposed vehicles are reduced, the average time that vehicles spend near fire hazards actually increases, due to the long wait behind closed roads.

Table 23. The effects of road closure time on the shelter-in-place counts and vehicles exposed to fire.

Vehicle type	Comm. scenarios	Metrics	Fire scenario 1			Fire scenario 2			Fire scenario 3		
			NC	C1	C5	NC	C1	C5	NC	C1	C5
Local residents	1	# shelter-in-place	0	0	0	0	0	29	0	0	37
		# exposed to fire (time)	0 (0 min)	0 (0 min)	0 (0 min)	667 (6 min)	97 (3 min)	75 (34 min)	114 (1 min)	66 (10 min)	68 (46 min)
	2	# sheltering-in-place	0	0	0	0	0	88	0	0	113
		# exposed to fire (time)	2 (0 min)	2 (0 min)	2 (0 min)	713 (3 min)	233 (10 min)	216 (64 min)	326 (1 min)	163 (32 min)	147 (98 min)
	3	# sheltering-in-place	0	0	0	0	0	185	0	0	191
		# exposed to fire (time)	4 (0 min)	4 (0 min)	4 (0 min)	779 (1 min)	425 (13 min)	404 (67 min)	676 (2 min)	369 (24 min)	350 (98 min)
Tourists	1	# sheltering-in-place	0	0	0	0	0	0	0	0	0
		# exposed to fire (time)	0 (0 min)	0 (0 min)	0 (0 min)	48 (4 min)	21 (0 min)	21 (0 min)	0 (0 min)	0 (0 min)	0 (0 min)
	2	# sheltering-in-place	0	0	0	0	0	0	0	0	45
		# exposed to fire (time)	0 (0 min)	0 (0 min)	0 (0 min)	58 (2 min)	30 (0 min)	30 (0 min)	84 (<1 min)	66 (9 min)	65 (63 min)
	3	# sheltering-in-place	0	0	0	0	0	0	0	0	65
		# exposed to fire (time)	0 (0 min)	0 (0 min)	0 (0 min)	68 (1 min)	54 (9 min)	54 (9 min)	164 (1 min)	132 (13 min)	110 (82 min)

Note:
NC: no road closure; C1: close for 1 hour; C5: close for 5 hours.
blue - metric is better than the comparison case (no road closure);
red - metric is worse than the comparison case (no road closure.)

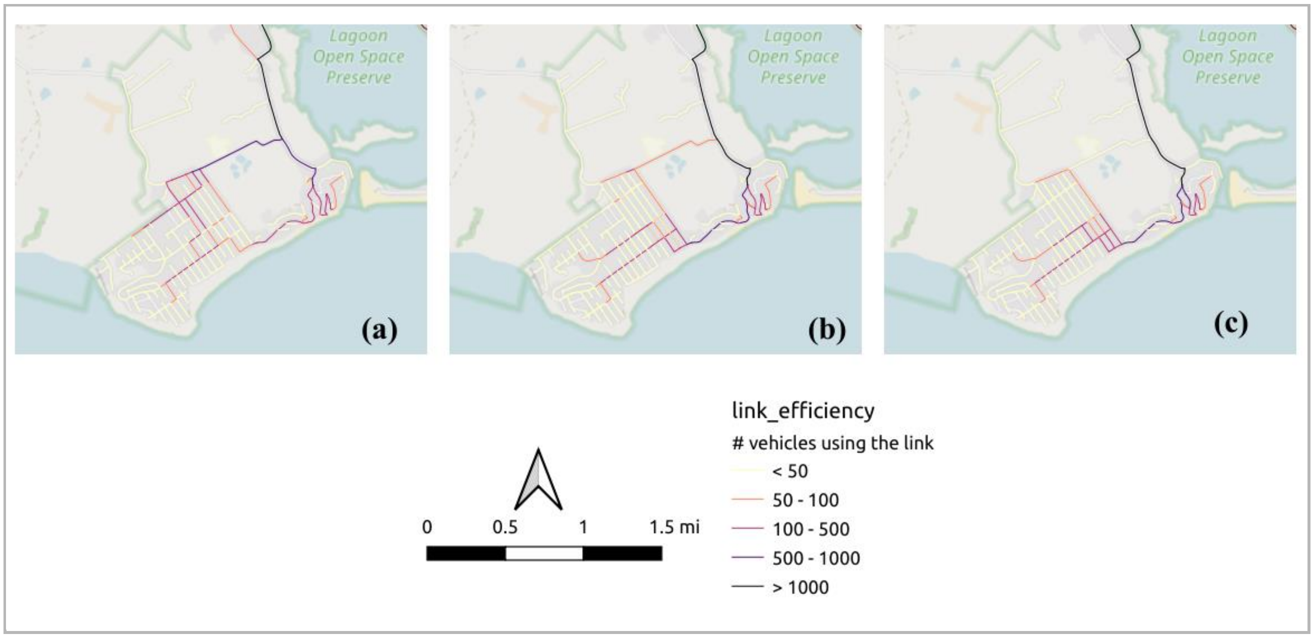


Figure 41. Link usage under different road closure times, fire location 2 (north of Mesa Road), communication scenario 1 (fully functioning). (a) No road closure; (b) 1-hour closure; (c) 5-hour closures.

III-3.5.4 Time waiting before shelter-in-place

The lack of redundancy in the evacuation road network is one of the biggest challenges of wildfire evacuation in Bolinas. Basically, all roads in the residential area in the east of Bolinas and the downtown area in the southwest merge into one of two roads (Mesa Road and Olema Bolinas Road), which then combine into a single road for about half a mile. The challenge is intensified by the presence of a dense grove of Eucalyptus trees along these traffic bottlenecks. Although as analyzed previously, while either road can still support the evacuation of most of Bolinas' residents from a traffic demand-supply point of view, the outcomes, if any obstacles further damage the capacity of the only evacuation route, could be serious.

Apart from the Eucalyptus trees on the land of the National Parks shown in Figure 3(d), there are also Eucalyptus trees inside Bolinas, where the key evacuation routes (Mesa Road and Olema Bolinas Road) meet. The potential worst case scenario where the roads become impassable for one hour due to the fires caused by the Eucalyptus trees is shown in Figure 42. In addition, if the fire's progression is rapid, it is not safe to shelter at home. Given the danger of not evacuating as well as the hazards along the evacuation route, sheltering in safe locations in town becomes the only available method to safeguard lives. Figure 42 shows the locations of the Eucalyptus Grove, the closed roads, as well as designated shelters.

Figure 42. Locations of the Eucalyptus Grove, the affected roads and proposed shelter locations.

Figure 43 shows the traffic simulation results in two scenarios, with or without sheltering places. Mesa Road and Olema Bolinas Road are assumed to be closed for one hour and reopened to traffic afterwards. The left panel shows the simulation results without sheltering locations. Long queues of vehicles develop upstream from the closed road locations. In comparison, as shown in the right column of figures in Figure 43, the vehicle queues become visibly shorter when the vehicles are given the option of leaving the road network and sheltering at safe locations. As only 300 sheltering spaces are assumed to be available, the queues cannot be completely avoided.

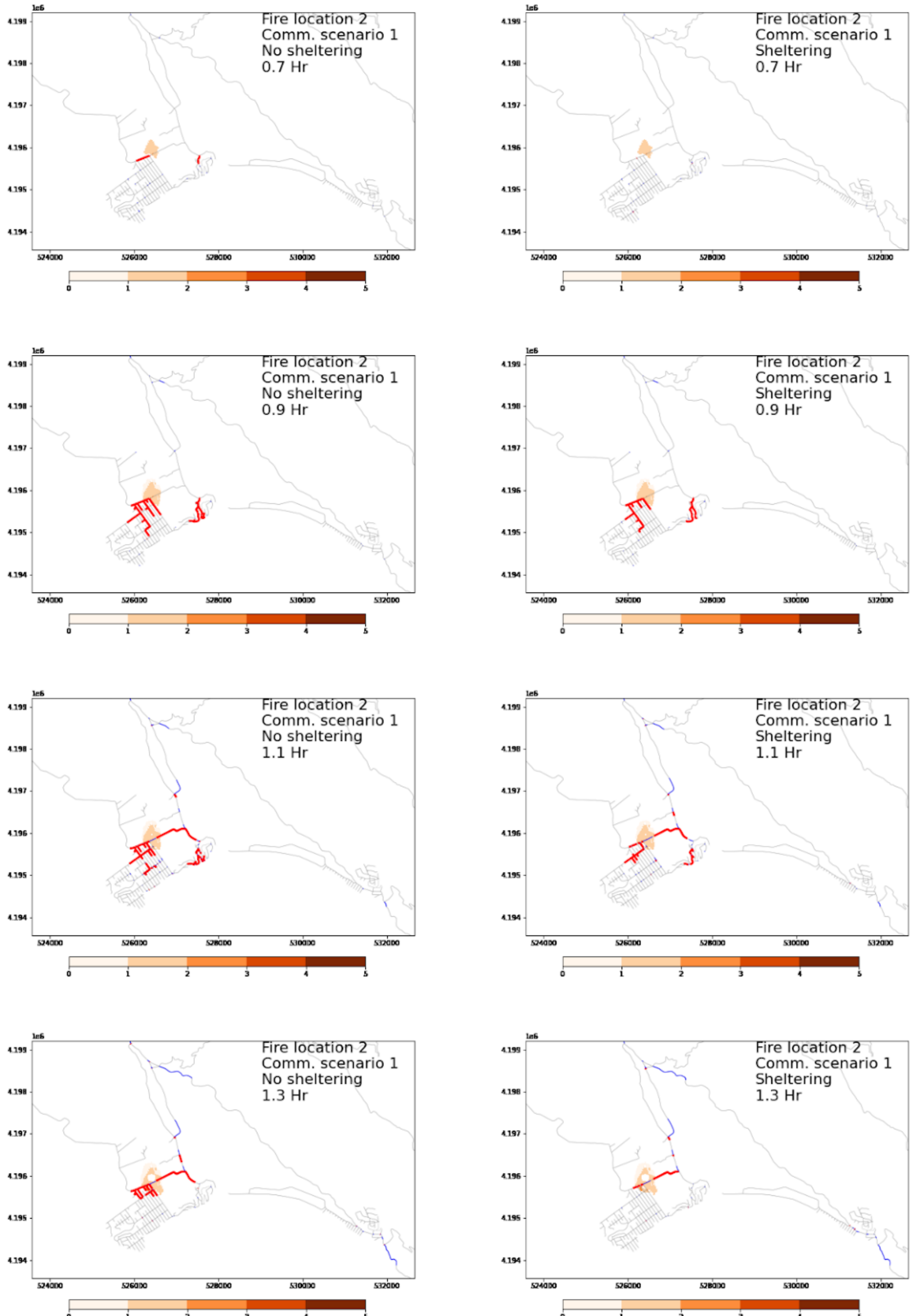


Figure 43. Impacts of shelter availability on evacuation vehicles. Left: no shelters are available. Right: 300 vehicle sheltering spaces are available as shown in Figure 42.

III-3.6 Key Findings from the Bolinas Case Study

Based on the Bolinas case study, we summarize the following findings.

First, an obvious challenge for Bolinas when evacuating the whole community in the event of a fire is having only one lane of evacuation route. This is less of an issue than in Paradise, as Bolinas would have to evacuate only about 1,200-1,500 vehicles. The demand-supply ratio is lower than Paradise, where 25,000 vehicles would need to be evacuated through five roads (most of which were also blocked by fire-induced hazards). For Bolinas, the main danger lies in the close proximity of the evacuation route to flammable eucalyptus trees. In other words, the traffic pinch point overlaps with a highly fire-prone location. If the fire develops rapidly within the community while the only evacuation route is blocked by burning or fallen trees (or abandoned vehicles, etc.), our simulations show a visible increase in the buildup of vehicles being trapped between the fire front and the blocked roads.

The availability and efficiency of means to disseminate the evacuation order can greatly affect the evacuation process. From the simulation results, the performance of the communication network could have comparable or even higher impacts on the evacuation outcomes as other risk factors, such as the different possible fire scenarios or the length of any road closures. In our simulations, we assumed that visitors to Bolinas would be more dependent on cell-based communication methods, while in reality, such methods may not be reliable for visitors as some main carriers are known to have no signals in Bolinas. The simulations assume that people will start to evacuate if they are within 0.25 miles of the fire, while in reality, pre-fire communication campaigns may be developed to educate the public to make better decisions for when to evacuate, especially for those not able/planning to shelter at home.

Even though not directly shown in the scenarios, it is likely that multiple communities around Bolinas would also be engaged in simultaneous evacuation. Highway CA-1 out of Bolinas is winding and narrow and further bottlenecks may be encountered along the way, such as where the traffic from Stinson Beach merges into CA-1. Similar to the Camp Fire evacuation, if a multi-town evacuation is expected, coordination between multiple communities (e.g., backup communication channels) should be carefully planned. A future study will include regional traffic evacuation modeling of the problem.

Lastly, given the unique geographical features and road topography of Bolinas, in case of the loss of the only evacuation route, safe shelters within the community should be provided. The existing parking spaces near the fire department are not likely to be sufficient in case of serious interruptions to the evacuation route. Other safe and accessible locations from the fire need to be provided in the community.

Discussion and Conclusions

Fire, communications, and traffic interactions

This study of different evacuation scenarios in the event of a wildfire examines the mutual and combined impacts of three dynamic processes (fire, communications, and traffic) in performance assessment procedures. Through case studies and models that test multiple scenarios, we identified the following connections.

First, fire can impact the communication process through two mechanisms. On the one hand, fire progression can potentially damage the cell communication infrastructure. This is especially problematic when a local fire occurs on the same day with a larger regional fire (or PSPS events), where communications to the outside are greatly impacted, resulting in a drastic increase in total notification time. On the other hand, the speed of the fire's progression can affect peoples' perceptions of the risks. A fast-moving fire may outpace the speed of evacuation order dissemination through existing communication channels. In such cases, strategies that rely on orderly communication and coordinated actions, such as phased evacuation, may not work. With a slow-moving fire, people in town who still are some distance away from the fire may not perceive the danger and urgency of the situation, particularly when they cannot be reached by other communication methods. As a result, it is critical to have multiple evacuation strategies in the portfolio to address the conditions of unusual fire speed or disrupted notification process (discussed in the next subsection).

Second, the fire also impacts the evacuation process directly by bringing down trees and power lines. The resultant fire-induced road closures can greatly impact the evacuation time. The issue is especially pressing in communities with low redundancy road networks. For places with few alternative routes out, the closure of roads could lead to severe traffic congestion as well as greater numbers of evacuees exposed to the fire danger. Furthermore, most of the Wildland Urban Interface communities are limited by resources and personnel and have foreseeable challenges in clearing fire-induced road closures in time. As a result, it may be sensible to emphasize sheltering-in-place options in these communities.

Third, the communication process has impacts on evacuation. With a damaged or partially damaged cell-based communications system, the evacuees may not be able to recognize the danger or the need to evacuate soon enough. This may lead to the loss of hours of valuable time in the evacuation process. This loss of time becomes especially critical when coupled with fire-induced road closures and the risk of being trapped within the fire zone. Moreover, the functioning of the cell-communication network also affects the availability and dissemination of the real-time traffic information to inform evacuees of the best evacuation routes. Such a loss of real-time information may have significant impacts on evacuation efficiency (Zhao and Wong, 2020).

Evacuation strategies

Traffic congestion during evacuation occurs where there is an imbalance in the supply of road capacity vs. the demand for travel. Thus, the design of evacuation strategies should focus on increasing the supply side or reducing the demand on the traffic network. In general, supply-side strategies include: contraflowing, adjusting traffic signals, and reducing the probabilities of fire-induced road closures. Demand-side strategies include car-pooling, phased evacuations, and offering safe shelters.

From our analysis of the two case studies, the most suitable strategies are context specific. For example, the Paradise road network is better connected within town, but there is still primarily only one road out of town. As a result, it becomes important to identify ways to limit the number of vehicles attempting to use that road. Where evacuation routes are limited, communities should focus on reducing the number of vehicles used by each household for evacuation (e.g., through carpooling, conducting public outreach regarding the benefits of having fewer vehicles for evacuation) or implementing phased evacuations. While for the Bolinas case study, in addition to evacuating local residents, there is also the need to notify and evacuate visitors. Here there are potential choke points not only on the only road out of town, but also in other parts of the area, such as near the residential side of Mesa Road, whose closure would lead to long detours. Given these constraints, successful evacuation strategies should increase the reliability of the communications system, efficiently address the fire-induced closures, and set up parking places for sheltering-in-place in case of a delayed evacuation.

Acknowledging the complex and potentially detrimental role played by fire and communication dynamics in evacuation, multiple strategies are needed to create a resilient response plan. For example, shelter-in-place locations could be planned and prepared for use, recognizing the risks of key evacuation routes being closed. Similarly, contraflow (and the corresponding communication protocols) that increase outflow capacity should be established efficiently, especially under urgent wildfire scenarios where phased evacuation is impossible. The difficulty of finding a single most effective strategy and the diversity of outcomes under multiple scenarios are already evident in the case studies presented in this report.

The functioning of the communications infrastructure also affects the choices of evacuation strategies. To our knowledge, interactions have not been well studied in the past research nor well considered in evacuation planning. With broken communication channels, evacuees are mobilized more slowly, potentially leading to longer time spent in proximity to active fires as the fire progresses. On the agency level, as seen in the Camp Fire evacuation, the loss of direct communications between agencies left certain strategies such as adjusting traffic signals or initiating contraflowing difficult to implement or coordinate. Under damaged communication network scenarios, the benefits of other strategies to ease the evacuation, such as reducing road downtime due to fire-induced road closures, are particularly obvious.

The results of this study highlight the importance of considering various fire scenarios and communication situations to make evacuation strategies robust and comprehensive. Developing effective evacuation strategies requires an in-depth understanding of the local environment, infrastructure, and organizational structures as well as the residents' likely behavior. Efficient simulation algorithms can greatly facilitate the assessment of the evacuation plan, as well as informing decision making at both the individual and the organizational level.

Challenges of current studies and future research directions

A primary limitation in this simulation and modeling study is the lack of behavioral data. For example, we can only assume the time and number of vehicles that a household would use to evacuate, evacuees' routing preferences, and their choices of destinations. Some of these uncertainties are not expected to influence the outcomes significantly, for example, the locations of destinations of the Bolinas evacuees along CA-1, as this choice is beyond the bottleneck of the evacuation (the only-way-out inside Bolinas). Some unknowns can be obtained by survey information, e.g., the number of vehicles per household for evacuation. Other aspects, particularly routing behavior, are hard to represent realistically. This is due to the lack of a viable theory (routing decisions in emergency evacuations), dynamically changing conditions in practice, and validation data. To produce a reasonably valid model despite the uncertainties, more effort is needed to tune and match the model with observations from site visits and documentary studies, such as the total estimated time of evacuation during the Camp Fire case. In addition, random repetitions of the model should be conducted to understand the statistical significance of the findings under the uncertainties from fire, communications, and traffic processes.

A second challenge is to establish long-term relationships with the local area to learn, adapt and implement the research findings. As a separate study, the research team is developing a set of evacuation games to engage the whole community, including both residents from different demographic backgrounds as well as organizations that are responsible for emergency response actions. It is hoped that these interactive and engaging exercises can raise individual's awareness of the importance of planning ahead, build a collective, mutual understanding between residents and local agencies of wildfire risk, as well as collect valuable research data from realistic experiments.

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Appendix

A.1 Fire Progression Simulation Using FARSITE

FARSITE predicts the spatio-temporal evolution of fires under various soil, fuel, and meteorological conditions. It was designed by Finney and further developed by the United States Forest Service, Rocky Mountain Research Station, Fire, Fuel, and Smoke Science Program (Firelab, 2020b).

FARSITE simulates the development of a forest fire as an elliptical wave expanding on a flat surface. In a given simulation period, ellipses are generated from points outlining the peripheral areas of the fire. Their outer edge represents the new fire front and is used to generate another wave of ellipses in the following time step (Huygens principle (Finney, 1998)). The results are different depending on whether the propagation happens under uniform or non-uniform conditions. Under uniform conditions, the wavelets have the same shape and size, keeping the outline shape as an ellipse. Under non-uniform conditions, the wavelets have different sizes depending on the local fuel, slope, and wind features.

The software is designed to take advantage of multiple mathematical models of fire propagation, which are useful to realistically simulate different aspects of a complex event such as a forest fire. The mathematical models used by FARSITE are applicable to surface fire, crown fire, post frontal combustion, fire acceleration and spotting. Surface fire is a type of fire fueled by a relatively homogeneous material under uniform wind and slope conditions, such as the fire spread under the level of the canopy without developing vertically. In contrast, a crown fire instead burns on the canopy level and spreads across the branches and leaves of the trees. An active canopy fire spreads much faster than a surface fire and releases more energy. Next, post frontal combustion refers to the situation where the fire front has passed but there are remaining combustibles with a longer burning time. Fire acceleration refers to the increase in speed of the fire since its initial ignition with constant environmental conditions such as wind, relative humidity or temperature. Finally, spotting is the occurrence of new ignitions over the front of the fire due to embers carried by the wind. Spot fire is an important aspect to consider especially in cases of strong winds, as spotting could start fires even far away, suddenly changing the course and the evolution of the overall fire footprint. In FARSITE, once the new ignition points have been identified through spotting, fires on these new ignition points are not simulated. Therefore, the spot fire does not impact the propagation of the main fire.

FARSITE is a semi-empirical model of fire propagation that allows the use of precise data about the terrain, fuel, and weather as inputs. It can produce several different types of outputs, images and vectors. It is a particularly efficient model and the simulation can usually be completed quickly. For these reasons, it can simulate different scenarios and produces outputs that can be integrated with the traffic simulation.

A.2 Simulating and Rendering 3D Fire and Smoke in WFDS

In a parallel ongoing project, 3D fire simulations were conducted to be used as inputs to a role-playing evacuation process simulator. The WFDS was used to create a realistic visualization of fire and smoke propagation in the air. It shows the way in which smoke obscures the view of the area around evacuees and how smoke can influence peoples' choices. However, due to its computational burden, the WFDS model is not used to inform the communication and traffic simulations in the case studies described in this report. Instead, it is being investigated as a potential tool for future research (specifically, a role-playing evacuation simulator integrated on the UNITY gaming platform). Current progress with the WDFS model and its planned usage will be discussed briefly in this section.

A.2.1 Wildland-Urban Interface Fire Dynamics Simulator

Physics-based combustion simulation is extremely complex. In the literature, there are few examples of this kind of model optimized for wildfires. One of these is the Wildland-Urban Interface Fire Dynamics Simulator (WFDS, by USFS, 2013), a physics-based extension of the fire model Fire Dynamics Simulator (FDS). WFDS has been developed through a collaborative effort between the United States Forest Service and the National Institute of Standards and Technology (NIST). It uses computational fluid dynamics to estimate the behavior of fluid flows in turbulent regimes, i.e., fire and smoke propagation, through the resolution of the Navier-Stokes equations optimized for low-speed flows. The model works with a reference domain divided into cells and the cell size represents the resolution of the whole model. WFDS is different from the FDS because it also considers the influences of the terrain and the spread of fires through vegetation. There are two types of fire simulations in the WFDS. The first one is based on the semiempirical component (indicated as WFDS-LS). This type models the fire front propagation like FARSITE but has no physical processes simulated. It simulates only the fire perimeter growth and how it moves across the landscape. The second option is the Physics Based Component (WFDS-PB), which simulates the fire as a combined outcome of the environment, processes of combustion, wind, the amount of solid fuel burning, and heat transfer. Computational fluid dynamics (CFD) methods are used to solve the equations.

A.2.2 3D simulation results

The WFDS-PB model is used to create 3D fire and smoke effects. The inputs are prepared with the Input File Creator software accompanying the WFDS and uses the elevation, domain, ignition point and rate of spread output from FARSITE. An effort was made to make sure the WFDS simulation matched the 2D FARSITE simulation results as closely as possible, as in the future we may consider combining the 2D and 3D fire simulation results in a more sophisticated framework (e.g., using 2D results for quick simulation and 3D for user interaction). We first attempted to calibrate the WFDS model to generate the same results as FARSITE. This led to a similar 3D fire effect as the FARSITE results, though not exactly the same due to the discrepancies in the inputs supplied to the two different types of software. Regarding the weather information, in FARSITE it is easy to obtain the appropriate inputs through the software FireFamilyPlus that is able to process the data recorded by weather stations. In WFDS there is no direct connection with this type of data, so all the information used as inputs constitute the mean of the values used in FARSITE. Also, not all the weather parameters considered by FARSITE can be modelled in WFDS, so there are differences in the base data in attempting to model a complex simulation. A second difference is due to the optimization of the fuel model. WFDS system works with cells. The simulation covers a large area, and the number of cells would be too large if the simulation area is divided based on the small dimension of the fuel model cells. So, the fuel model in our WFDS results is less accurate, because a number of different types of fuel are combined into one cell. Besides, in WFDS, although it is possible to define the vegetation inputs with specific parameters, it is difficult to find all the empirical data for all the fuel classes involved in the model. This is not an issue in FARSITE, which is a semiempirical model so almost all information related to the behavior of the fuel is already included in the software.

Therefore, a second approach is taken that supplies the rate of spread output from FARSITE into WFDS. The rate of fire spread was calculated by FARSITE. WFDS makes use of such results and generates the 3D effect based on it. The results of the 3D fire and flame propagation from WFDS is shown in Figure A1.

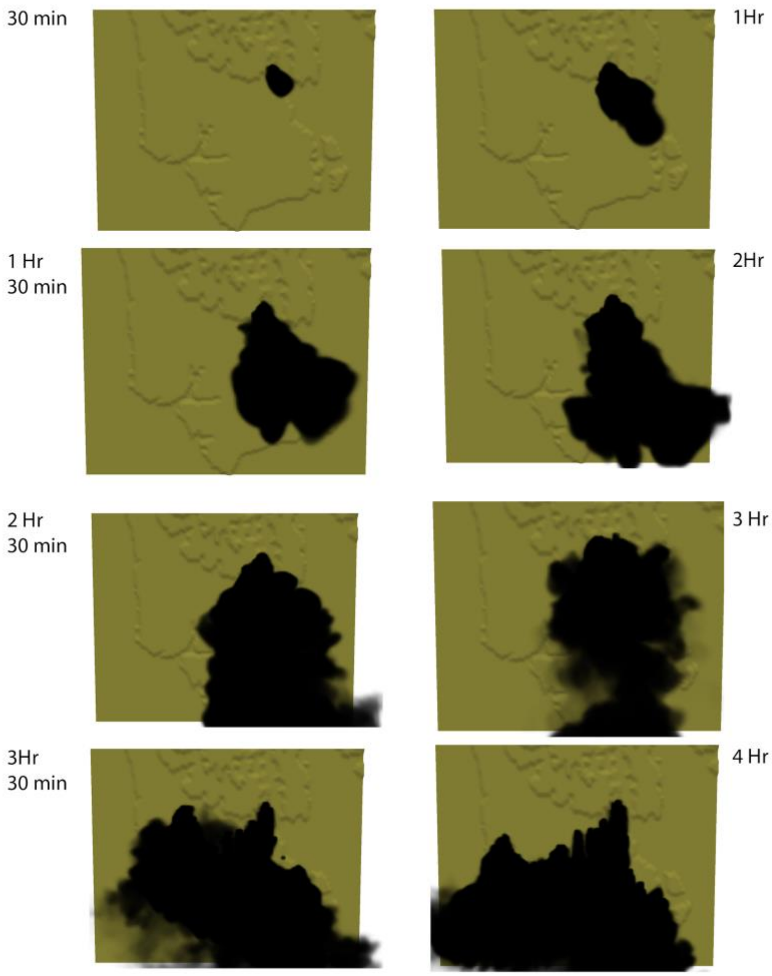

Figure 44. Visualization of the 3D smoke generated from the WFDS model.