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Modeling roadway temperatures for wildfire evacuation and assessment of pavement damage

Mohammadreza Barzegar[1] and Haifang Wen[2*]

Abstract

Wildfires can cause enormous loss of assets and human lives, and thus, timely evacuation from the wildfire zone is critical to saving lives. Understanding evacuation route conditions, including traffic and temperature data, is imperative for safe evacuation. This study modeled the temperature conditions of an evacuation roadway within a wildfire zone, using the 2018 Camp Fire in Butte County, California as an experiment. The numerical modeling program, FlamMap, was used in this study to analyze the temperature conditions of an evacuation route. The results show that the temperature of the evacuation roadway increased quickly in a matter of a few hours. The change of roadways temperatures ranged from 3°C to 297°C within five hours after ignition, depending on the specific location along the roadway and other conditions. The results from this study can be used to understand temperature conditions for effective evacuation and to estimate roadway damage as well.

Keywords Wildfire, Temperature, Evacuation, Damage, Modeling

Introduction

Wildfires are not novel phenomena, unfortunately, and thus have received much attention from various stakeholders. Wildfires in recent years in various locations have resulted not only in enormous loss in terms of assets and resources, but also human lives. These adverse outcomes are especially noteworthy due to people's increasing desire and tendency to live in suburban and rural areas more than at any time in history [1]. Reports from the National Interagency Fire Center indicate that annually an average of 64,100 wildfires have occurred in the United States and have burned an average of 27.5 billion square meters in the last decade [2]. According to the United States Fire Administration Department, fatalities caused by wildfires in 2018 had increased by 20% in comparison to 2009 and amounted to a total death count of 3,655 people. Similarly, property damage and economic loss by wildfires had increased substantially (almost doubled) by 2018, compared to 2009 and overall represent a loss of 25.6 billion dollars [3].

During a wildfire, one of the key priorities is to evacuate people safely and promptly. Evacuation via vehicles is the most practical and viable approach, provided sufficient time is available before smoke and the temperature on evacuation roadways become deadly. Numerous studies have been conducted to investigate possible factors that may impact evacuation progress. These study parameters include awareness [4], traffic loading rate, traffic route assignment [5], etc. However, temperature, especially that of evacuation roadways, has not yet been studied closely.

A number of studies have investigated cases of tunnel fires. For example, Kurioka et al. modeled a tunnel fire and estimated that the temperature of gases can reach

*Correspondence:
Haifang Wen
haifang_wen@wsu.edu
[1] Department of Civil and Environmental Engineering, Washington State University, Pullman, WA 99164, USA
[2] Department of Civil and Environmental Engineering, Washington Center for Asphalt Technology, Washington State University, Spokane Street, Sloan Hall Room 27, Pullman, WA 99164, USA

to 850 K [6]. Li and Ingason simulated another case of a tunnel fire and calculated the temperature of the gases to reach to 1623 K [7]. Nonetheless, boundary conditions of tunnel fires are far different from those of wildfires and the heat in confined tunnels can rise quickly which is sharply different from the temperatures in wildfires. In addition, the high temperatures of a wildfire coupled with traffic and emergency/rescue vehicles loads may lead to premature or accelerated damage to the pavement. Prolonged exposure of pavement to high temperatures may accelerate aging and/or cause the surface materials to deteriorate. Such outcomes are especially true for asphalt pavements because asphalt material is very sensitive to temperature. The stiffness of asphalt material decreases significantly as the temperature increases. A vehicle that otherwise would not cause damage to a roadway under normal design conditions is more likely to damage the pavement during a wildfire. For example, a normal passenger car under normal conditions would cause negligible rutting or cracking, if any, due to its low axle load [8]. However, under high temperatures within a fire zone, a passenger car could possibly cause permanent deformation as well as possible cracking of a thin pavement.

Therefore, understanding the pavement temperature on evacuation routes during a wildfire is of paramount importance for effective evacuation as well as estimation of roadway damage, or namely, asset loss. One complicating factor is that temperature is not constant or uniformly distributed within a wildfire zone. Temperatures of roadways within a wildfire area vary significantly depending on the climate, fuel, geography, etc. For example, the maximum wildfire temperature is at the front row of the fire (the fireline) and, as the fire passes the area, the wildfire temperature drops drastically. Researchers have reported that a wildfire's flame temperature is mostly in the range from 850 to 950 K [9]. Although several temperature terms have been used to characterize a wildfire, such as the fuel zone temperature, flame zone temperature, gas temperature, street temperature, and fuel particle temperature, the pavement temperature during wildfires has not been studied. The objective of this paper is to model the roadway temperature within wildfire zone, using the conditions of Camp Fire in 2018 as the experiment.

Methods and data

Temperature modeling

Numerical modeling can be employed to simulate wildfires and then determine the temperatures of roadways located within the fire zone and to account for various factors, such as topography, vegetation, weather conditions, etc. Several researchers have made significant headway in modeling wildfires. Clark et al. studied wildfire progression using Monte Carlo simulations and determined fire risk probability using known topography and fuel loadings [10]. Linn and coworkers developed FIRETEC, a software program that can predict fire spread [11, 12]. Mell et al. used two physics-based programs, the Wildland Fire Decision Support System (WFDSS) and FIRETEC, to model wildfires [13]. WFDSS is used to develop decision-making processes, model wildfires, and perform geospatial analysis whereas FIRETEC is focused mostly on the nature and behavior of the wildfire itself rather than its outputs. Scheller et al. developed Landis II, software that provides researchers with options for building wildfire models [14]. However, the cumbersome coding that is required to model wildfires in Landis II impedes the implementation of this program.

Other options include modeling wildfires via computational fluid dynamics, finite element analysis, or multi-physics analysis, but again, these methods are cumbersome for practitioners. Patton and Coen introduced the Weather Research and Forecasting (WRF)-Fire program to simulate wildfire behavior and propagation [15]. Andrews et al. developed Behave Plus, which has been a useful tool for wildfire scientists and environmentalists [16]. Finney introduced FARSITE, a popular program for modeling growth, intensity, and other wildfire behaviors [17]. In addition, Finney developed FlamMap, which is practical and precise [18] and is listed as one of the few programs approved by the United States Forest Service for its reliable modeling of wildfire. One of the main advantages of FlamMap that distinguishes it from other software programs is its incorporation of numerous fire behavior models, such as Rothermel's surface fire spread model [19], Van Wagner's crown fire initiation model [20], Finney's FARSITE [17], Scott and Reinhardt's crown fire calculation method [21], etc. that are embedded in the simulations. Therefore, FlamMap was used in this study to determine change of temperatures along the evacuation roadway.

To the authors' best knowledge, none of the current wildfire modeling programs, including FlamMap, provides spatial and temporal temperature distributions, which constitute the information of interest for this study. The modeling results obtained from FlamMap include the fireline intensity, flame length, heat unit area, etc. over time, however it does not provide the spatial temperature distribution. Therefore, the outcomes have to be converted into temperatures, especially along the evacuation route, for the purpose of assessing evacuation window and pavement damage.

The pavement cannot perfectly absorb all the energy radiated towards it. Some of this energy may be reflected or passed through the pavement. Thus, a coefficient of absorption for the pavement had to be considered.

Bobes-Jesus et. al. (2013) has estimated this coefficient to be equal to 0.8 [22]. In other words, only 80% of radiated heat flow towards the pavement will be absorbed by it.

Given the aforementioned considerations:

$$q_{net} = \alpha q_s \tag{1}$$

whereq_{net} = net heat towards pavement;α = coefficient for absorption.q_s = energy absorbed from radiation;

It should be noted that the heat flow received by the pavement (q_{net}) is much less than the radiated heat flow of wildfire (the output of the FlamMap software). The reason for this variation is the fact that radiation is a function of distance. Holman [23] has investigated the heat transfer relationship between two surfaces which are located in a distance of *r* from each other. The energy leaving a surface area of dA_1 in the direction of angle ϕ_1 is equal to Eq. (2). Also, the radiation arriving to an element with a surface area of dA_2 is equal to Eq. (3).

$$\text{Energy leaving} = I_b dA_1 \cos\varphi_1 \tag{2}$$

$$\text{Radiation arriving} = I_b dA_1 \cos\varphi_1 \cos\varphi_2 \frac{dA_2}{r^2} \tag{3}$$

where

I_b = source intensity;dA_1 = surface area emitting the energy;ϕ_1, ϕ_2 = angles of the direction of emission and the energy receiver;dA_2 = surface area receiving the radiation;r = distance between source of energy and energy receiver.

The energy leaving surface area dA_1 that arrives at dA_2 is a function of emissivity power (E_{b1}) of source 1 [23].

$$dq_{1-2} = E_{b1} \cos\varphi_1 \cos\varphi_2 \frac{dA_1 dA_2}{\pi r^2} \tag{4}$$

$$E_b = \pi I_b \tag{5}$$

where

I_b = Heat intensity.

Also, the energy leaving surface area dA_2 that arrives at dA_1 is

$$dq_{2-1} = E_{b2} \cos\varphi_2 \cos\varphi_1 \frac{dA_2 dA_1}{\pi r^2} \tag{6}$$

Therefore, the net energy exchange is

$$q_{net_{1-2}} = (E_{b1} - E_{b2}) \int_{A2} \int_{A1} \cos\varphi_1 \cos\varphi_2 \frac{dA_1 dA_2}{\pi r^2} \tag{7}$$

where

E_{b1} = Emissivity power created by source 1;

E_{b2} = Emissivity power created by source 2;

A_1 = Surface area of source 1;

A_2 = Surface area of source 2;ϕ_1, ϕ_2 = Angles between surface area source 1 and 2; andr = distance between two sources.

Sources 1 and 2 were assumed to be wildfire and pavement respectively. Because in a wildfire pavement emits a relatively trivial amount of energy, produced heat intensity of pavement is equal to zero ($I_{b2} = 0$).

Heat intensity of wildfire was obtained from outputs of FlamMap simulator. One of generated outputs is the fireline intensity per unit area, which is I_{b1} in Eq. 5. To find the change of temperature of a square meter of pavement, dA_2 was assumed to be 1 m^2 and surface area of wildfire was presumed to be 1 m^2. Therefore, final format of Eq. 2 is:

$$q_{net_{1-2}} = (\alpha \pi I_{b1}) \int_{r_1}^{r_2} \frac{1}{\pi r^2} dr \tag{8}$$

wherer_1 = shortest distance between wildfire and pavement;r_2 = maximum effective distance between wildfire and pavement.

The heat energy per unit area absorbed by pavement can be obtained by solving Eq. 8. Using Eq. 9, also known as heat capacity equation, temperature change of pavement can be calculated.

$$Q = mc\Delta\theta \tag{9}$$

where

Q = heat energy;m = mass;c = specific heat capacity; and

ΔΘ = change of temperature.

Modeling with campfire

The infamous 2018 Camp Fire in Butte County, California is used as an experiment in this paper to shed light on the modeling and behavior of roadway temperatures in a wildfire zone. This study examines an approach for wildfire methodology and measures temperature change of the road in a case of wildfire and can be instrumental in understanding ways that wildfires cause casualties during evacuation and can be used to estimate damage to roadways caused by wildfires.

On November 8, 2018, a wildfire occurred in Northern California that was the most devastating and deadliest in California's history [24] and the sixth deadliest in the United States since 1918. The wildfire was named Camp Fire due to its place of origin on Camp Creek Road [25]. The fire was caused by a faulty electric transmission line that had been dislocated from its original position due to extreme winds on the day of the incident [26, 27]. The fire spread quickly due to dry vegetation and strong winds and quickly reached the rural communities of Concow and Pulga. Within a few hours, Camp Fire had reached

the town of Paradise, destroying 95% of structures in its wake. Ultimately, the fire caused 85 human deaths and burned more than 620 million square meters [28]. The Camp Fire was fully contained by the first winter rainstorm 17 days after its ignition [29].

Landscape within the Camp Fire wildfire location was retrieved from the Landfire database [30] that includes different landscape aspects such as topography, vegetation type, various fuel categories, etc. Figure 1 shows the aspect theme of the landscape topography of the Camp Fire area. The topography includes information about the slope and geographical aspects of the area. The topography information is essential for the fire propagation development (which has already been taken into account by the program).

Figures 2 and 3 respectively show fuel sources (e.g., parched grass or bushes) and canopy (e.g., live plants) of the Camp Fire model area. Figure 2 indicates that most of fuels and vegetation can be divided into four main categories. Although each color in the fuel model map represents a specific category, the four colors that reflect the four main categories are yellow, brown, dark green, and azure. According to Scott and Burgan [31], the four main fuel types are: (1) moderately coarse continuous grass with an average depth of about 30.48 cm (yellow); (2) moderate fuel load with a depth of about 30.48 cm for which no grass fuel is present (brown); (3) grass or shrubs mixed with litter from the forest canopy and fuelbed comprised of highly loaded conifer litter with shrub understory (rich green); and (4) dead and down woody fuel (litter) beneath the forest canopy (timber litter) and moderate load and compactness that may include a small amount of herbaceous load (azure). Figure 3 shows the canopy, which refers to percentage of horizontal area that is covered by crowns of trees and other vegetation that may affect the rate of progress of a wildfire. As shown in Fig. 3, the lower right side of Highway 70 is mostly covered by trees or other live vegetation whereas at the upper left side of the roadway, while covered areas beneath trees or any other vegetation type are fairly spotty.

Moisture in fuel greatly affects a wildfire's ignition and progression. Data for fuel moisture, which is a function of geographical location and time, were retrieved from the United States Forest Services' Wildland Fire Assessment System [32]. Weather conditions, i.e., temperature, wind, precipitation, etc., also were obtained from the Wildland Fire Assessment System for the Cohasset, CA station, which is the closest station to the Camp Fire area [33]. Even though exact geographical locations of ignition points for the Camp Fire were never determined, reasonable approximations of fire ignition locations of the Camp Fire were provided by California Department of Forestry and Fire Protection

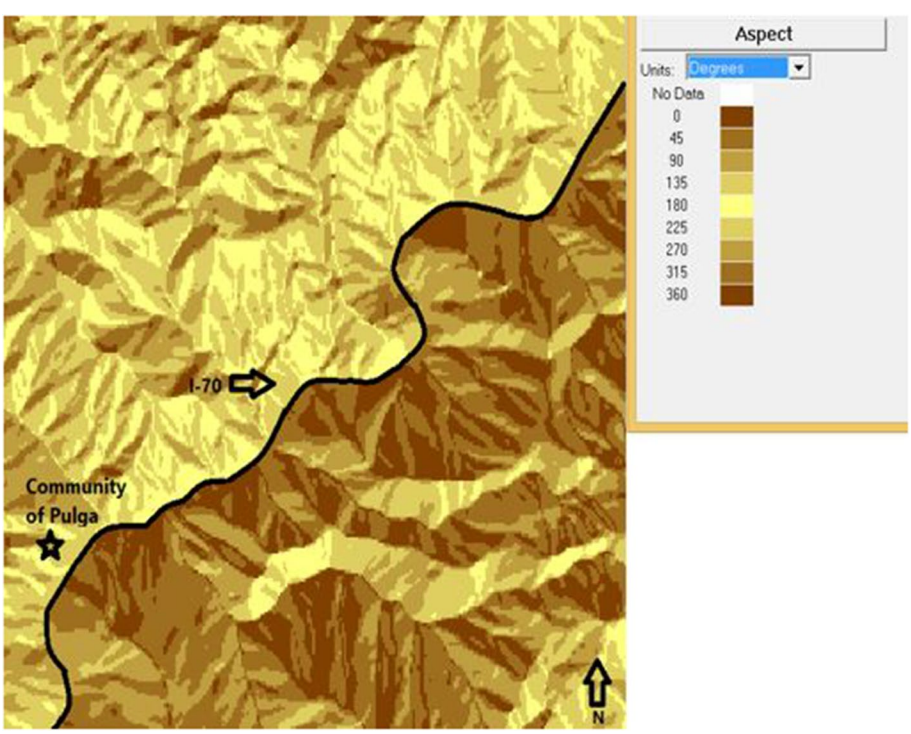

Fig. 1 Aspect theme of model area for the Camp Fire

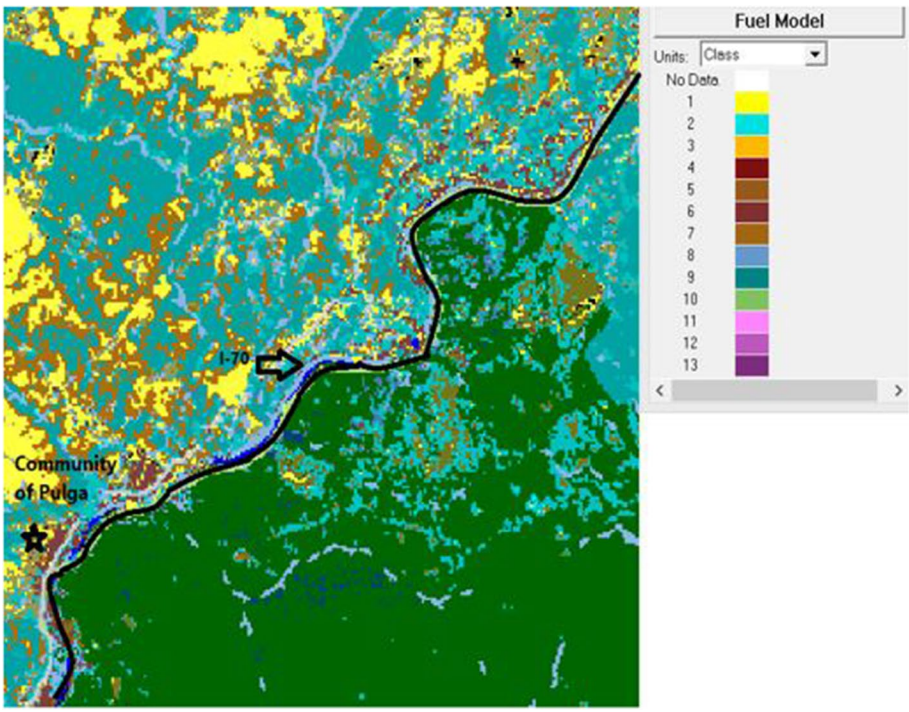

Fig. 2 Fuel model map of model area for the Camp Fire

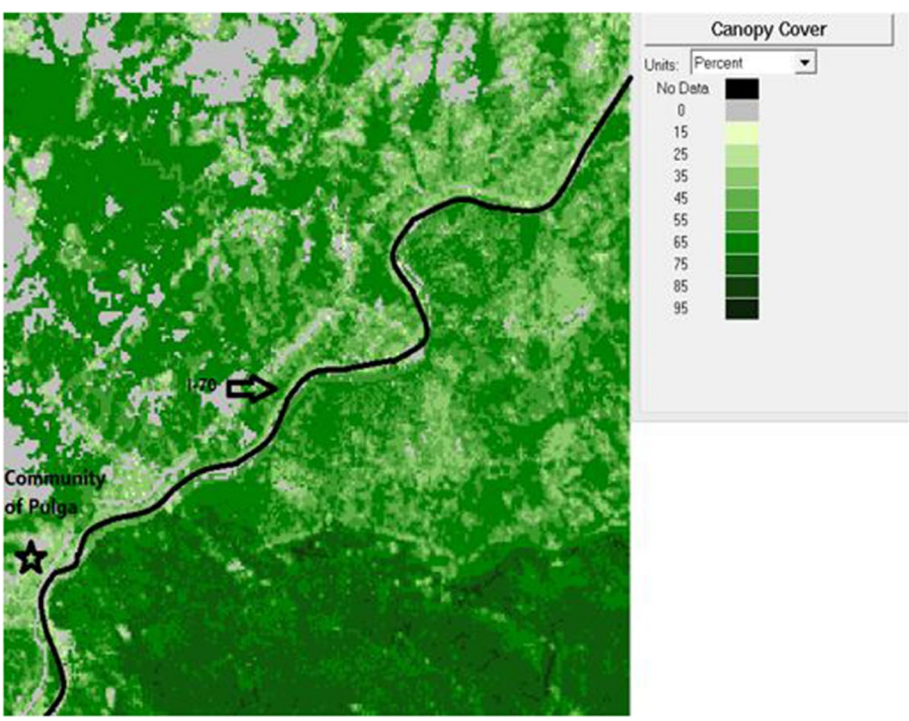

Fig. 3 Canopy cover map of model area for the Camp Fire

(CALFIRE) investigators [26], and post-hoc satellite images confirmed these ignition points, as shown in Fig. 4. These ignition points were input to FlamMap to ignite model fire. Its noteworthy that in model, evacuation roadway serves and is modeled as a barrier to the wildfire.

In order to measure effect of the shortest distance between wildfire and pavement two scenarios were evaluated. In the first scenario wildfire has the closest possible distance to pavement. Satellite images have revealed that the minimum distance between the road structure and the closest treelines is approximately 5 m [34]. In the second scenario the distance between wildfire and pavement is 10 m. In other words, the input of r_1 in Eq. 8 is 5 m for scenario 1 and 10 m for scenario 2. The maximum effective distance is assumed to be 20 m.

The inputs of mass and specific heat capacity in Eq. 9 are based on data shown in Table 1, which is obtained from literature review. Mass of pavement was calculated by multiplying the thickness of each layer of pavement by its density.

Assumptions shown in Table 1 were based on California Department of Transportation (CALDOT) specifications for typical thicknesses of a flexible (Hot Mix Asphalt) pavement in California [35].

The values shown in Table 1 for specific heat capacity and density of surface, base and subbase layers of pavement [36] were developed from work of Basheer Sheeba et. al. [36]. With known specific heat capacity and mass per unit area of pavement, change of temperature was obtained using Eq. 5.

Table 1 Specific heat capacity and mass per unit area of pavement

Layer	Thickness (m)	Density (kg/m3)	M per unit area (kg/m2)	Specific heat capacity (J/kgk)
HMA	0.2	2600	520	920
Base	0.29	2600	754	920
Subbase	0.4	2200	880	1800

Results and discussion

FlamMap was run for a time series that was based on post ignition. Figures 5, 6, and 7 show fireline intensity, flame length, and heat per unit area five hours after ignition, respectively. Modeling results show that fireline intensity, flame length, and heat per unit area were extensive south of Highway 70. Thus, Highway 70 served as a barrier to spread of the wildfire.

As shown in Fig. 8, nine points were selected along Highway 70 within the Camp Fire zone to demonstrate temperature variations along evacuation route. These variations may be explained by different distances between edge of the roadway and different fuel conditions.

The significant growth of temperatures at these nine locations (Tables 2 and 3), as well as the growth at

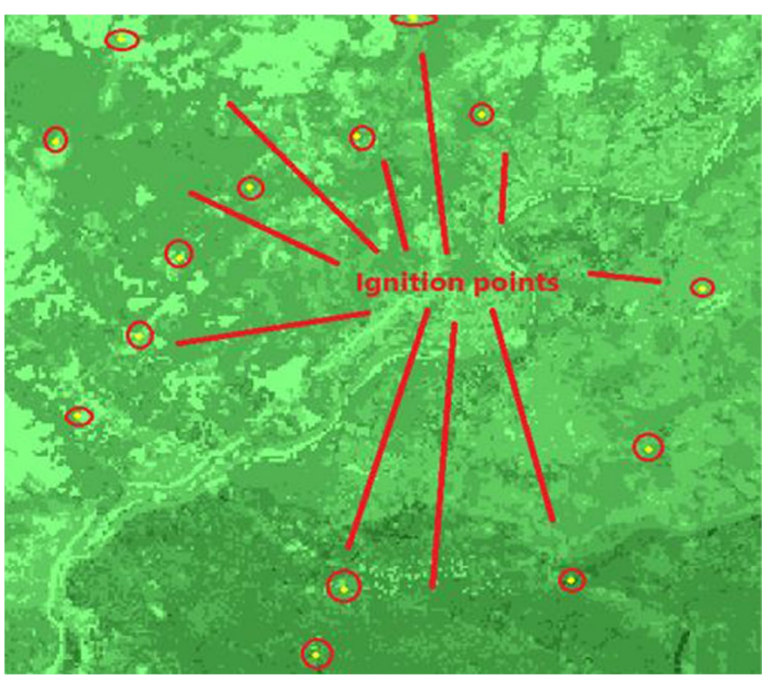

Fig. 4 Ignition points of FlamMap model of the Camp Fire

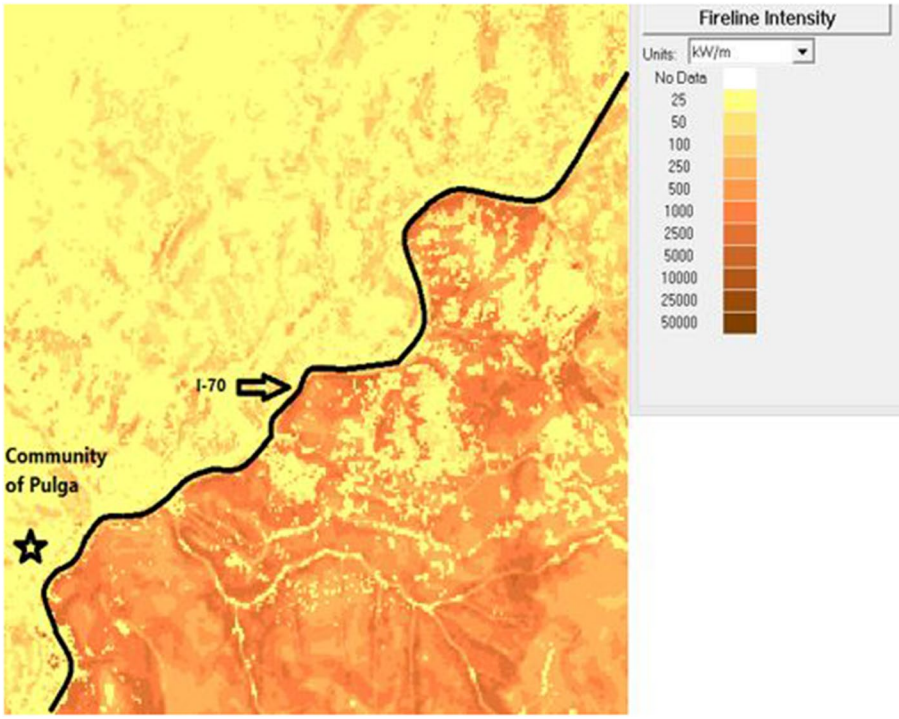

Fig. 5 Fireline intensity of the Camp Fire five hours after ignition

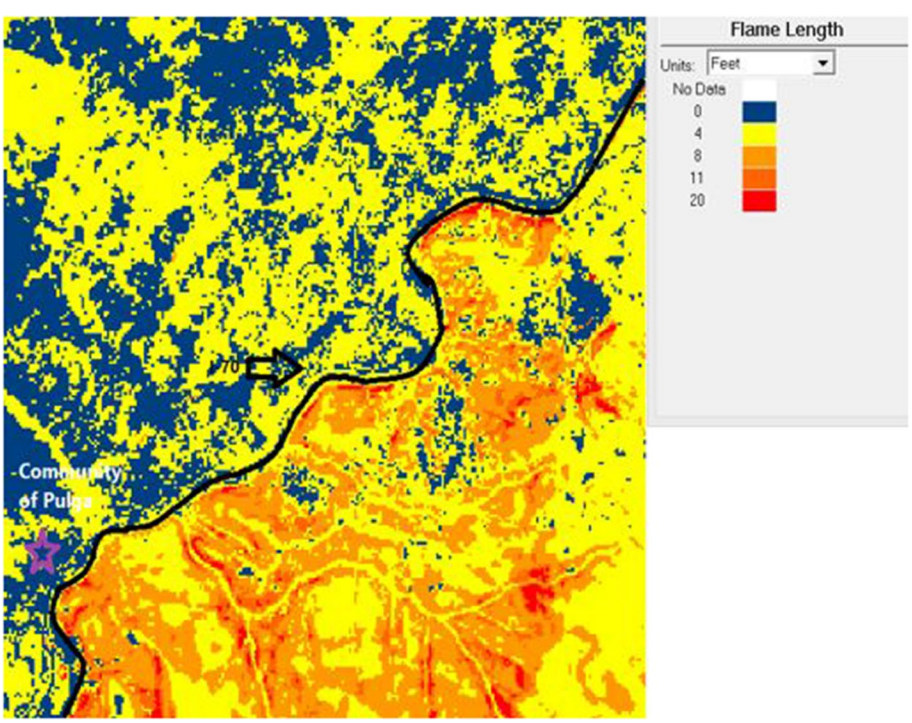

Fig. 6 Flame length of the Camp Fire five hours after ignition

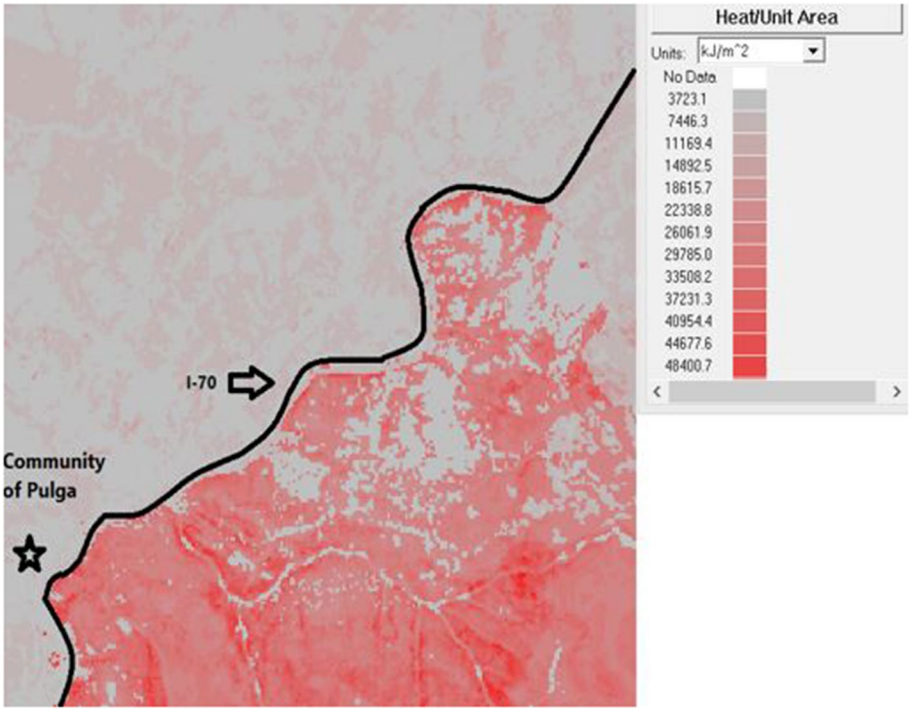

Fig. 7 Heat per unit area of the Camp Fire five hours after ignition

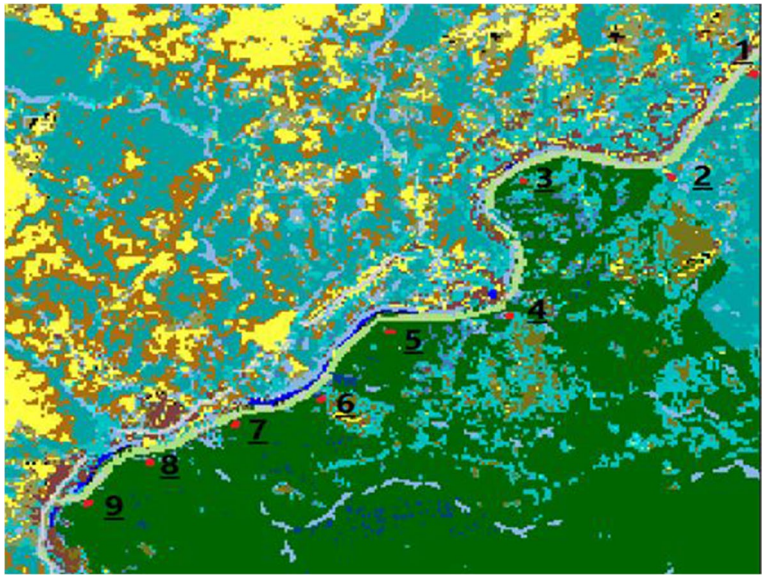

Fig. 8 Evaluated temperature points on FlamMap along Highway 70

5- and 10-m offset distances from edge of the roadway to fire, were calculated to study spatial distributions of temperatures. In addition, different time intervals after the wildfire was ignited, were modeled to evaluate temporal distributions of the temperatures. Table 1 shows increase of temperatures at the nine points along Highway 70 with an offset distance of 5 m over a series of time intervals; Table 2 provides the same data for points 10 m from the highway.

Change of temperatures along roadway at the 5-m offset ranged from 7°C to 297°C just five hours after ignition, depending on the fuel density. These high temperatures present significant risks to evacuation process. Point 9 showed the highest increase of temperature for both the 5- and 10-m offset distances, likely because of the highest fuel density at Point 9.

Moreover, rise of temperatures at these nine spots peaked at 20 h (post ignition) at both five meters (Fig. 9) and ten meters (Fig. 10) from fire.

At the offset distance of 10 m, the change in temperature decreased significantly from 5-m offset. More fuel was present at 5-m offset than at 10-m offset and that roadway itself, without plants and trees, may have served as an air supply pipeline to the wildfire.

Increase in temperature distributions illustrates how deadly a wildfire can be along an evacuation roadway. It must be noted that the temperature estimations in this study are only limited to the surface temperature of the pavement. The temperature increase in the inner layers of the pavement can also be predicted based on the surface

Table 2 Change of temperature at each point at 5-meter offsets

Time Lapse	Change of Temperature at Locations along Highway 70 (°C)								
	1	2	3	4	5	6	7	8	9
5 h	26.07	11.89	220.15	61.44	12.81	140.56	185.39	54.88	280.37
8 h	25.61	12.65	214.66	59.92	12.65	136.91	180.66	53.51	273.66
20 h	30.49	13.57	233.11	65.86	13.11	148.80	197.13	58.70	296.68
48 h	15.25	7.78	157.33	43.60	11.89	98.64	131.72	39.94	202.77

Table 3 Change of temperature at each point at 10-meter offsets

Time Lapse	Change of Temperature at Locations along Highway 70 (°C)								
	1	2	3	4	5	6	7	8	9
5 h	7.88	3.66	61.74	18.50	4.07	45.28	56.76	17.33	80.75
8 h	7.78	3.66	60.22	16.11	3.86	41.77	55.80	16.67	89.09
20 h	9.25	3.76	65.61	20.18	4.22	48.99	63.78	18.29	97.52
48 h	4.57	3.15	44.31	12.45	3.96	31.46	44.47	11.33	53.82

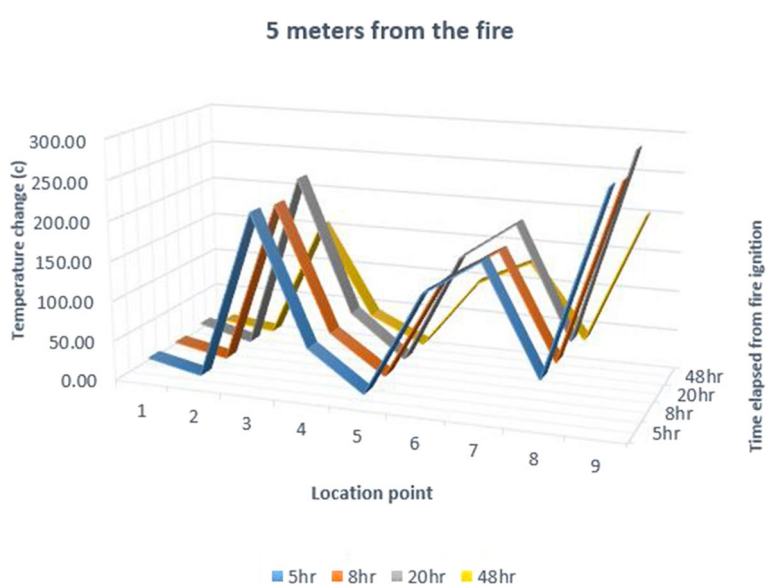

Fig. 9 Change of temperature distribution on Highway I-70 five meters from fire after different times post ignition

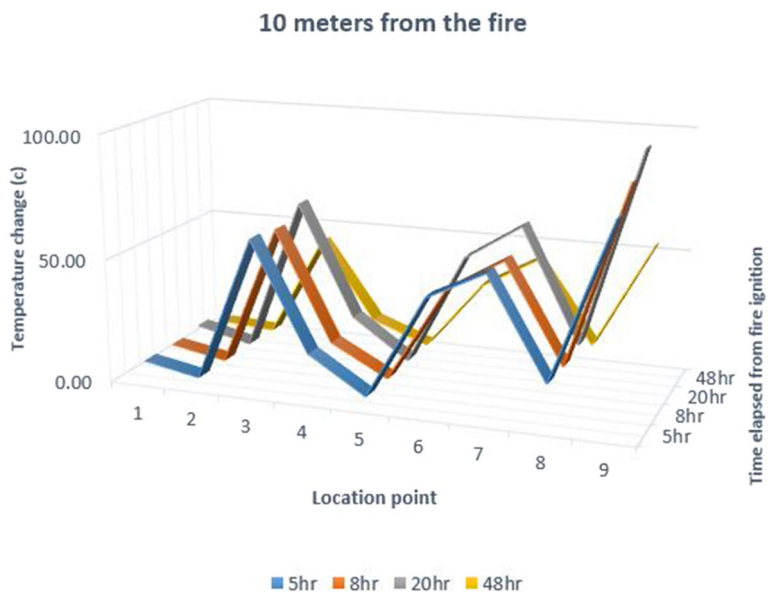

Fig. 10 Change of temperature distribution on Highway I-70 ten meters from fire after different times post ignition

temperature of the pavement [37]. Policymakers or rescue crews can draw useful information based on these simulation results, especially in terms of temperature, to devise drills or develop an evacuation plan for a specific area. In addition, quantification of temperatures along such roadways is instrumental in better understanding and assessing damage to roadway in order to estimate asset value loss.

Conclusions

Wildfire has received numerous attentions from various stakeholders in communities affected by these fires, particularly those in American West and the Pacific Northwest. During a wildfire, one of the key elements is to safely evacuate people in time. Evacuation via vehicle and roadway presents the most practical and viable approach, provided that there is sufficient time to evacuate before temperature on roadway and smoke becomes deadly. Understanding how context around a roadway contributes to changes in acceleration and drop off patterns in the temperature of wildfires can be instrumental in forecasting and preventing possible casualties during evacuation and in estimating the damage done to roadway.

The results of this study clarify that distance between the closest line of a wildfire and pavement of road has a substantial effect on temperature of that pavement. In other words, increasing this distance will substantially diminish the rate at which the temperature of the pavement grows. Consequently, if the area of cleared vegetation along road is widened, window of evacuation opportunity will be longer and eventually this clearing of fuel buildup will reduce temperature related distresses of the pavement.

It was found that temperature of roadway can increase quickly in a matter of a few hours. The increase of roadway temperature ranged between 3°C to 297°C just 5 h after ignition and peaked at 20 h, depending on the specific locations and other conditions of fuel and roadside vegetation. These finding underscores need for quick decision making in case of wildfire. Policies regarding road maintenance and evacuation should be established in such areas where likelihood of a wildfire is strong. However, these policies won't be effective unless evacuation is practiced regularly with attention to possible thermal behavior of fire along evacuation routes.

This study is the first small step in modeling the growth of temperature conditions along roadways involved in wildfires. Further studies are needed to relate the roadway temperature to actual operation during evacuation and quantify the damage to the roadway as well.

Abbreviations

WFDSS	Wildland Fire Decision Support System
WRF	Weather Research and Forecasting
CALFIRE	California Department of Forestry and Fire Protection

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Authors' contributions

M.B. retrieved the literature review and wrote the majority of the manuscript, collected the data and investigated the details of the case of study, established the mathematical model, conducted various simulation cases using the appropriate software and analyzed the results of the study. H.W.

devised the necessity of investigating the subject of this article, composed the organization of the study, contributed crucially to the assembly of the correct mathematical model, conceptualized the input and output of the study.

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Availability of data and materials
All the data used for this study can be accessed unrestrictedly through public websites as follows:
• The landscape was retrieved from https://www.landfire.gov/viewer/viewer.html.
• The fuel moisture files are available on https://www.wfas.net/index.php/national-fuel-moisture-database-moisture-drought-103.
• The weather forecast of mentioned station can be accessed through https://www.wfas.net/nfdrs2016/maps/.
• The location of the highway I70 was retrieved from https://www.google.com/maps/@39.8482066,-121.3927258,429m/data=!3m1!1e3

Declarations

Competing interests
The authors declare that they have no competing interests.

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