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Evaluating Road Resilience to Wildfires: Case Studies of Camp and Carr Fires

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RESEARCH REPORT

Institute of Transportation Studies | UNIVERSITY OF CALIFORNIA

Evaluating Road Resilience to Wildfires: Case Studies of Camp and Carr Fires

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December 2023

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16. Abstract

Between 2017 and 2018, California experienced four devastating fires, including the Camp and Carr Fires. After fires, road infrastructure is crucial for safe removal of hazardous materials and waste to landfills and recycling facilities. Despite the critical role of pavements in this process, there has been little quantitative evaluation of the potential damage to pavements from truck traffic for debris removal. To address this knowledge gap, data on truck trip numbers and debris tonnage following the Camp and Carr Fires were used to calculate changes in equivalent single axle loads and traffic index over the pavement's design life (the age at which reconstruction would be considered). Simulations were conducted on existing pavement structures to assess potential additional damage based on increased traffic indices. Pavement structural design simulations showed that out of the nine studied highways, one exhibited a reduction in cracking life of about two years from debris removal operations. However, fatigue cracking was significantly accelerated for Skyway, the major road in the Town of Paradise, failing 14.3 years before its design life. A methodology similar to the one presented in this study can be adopted in debris management planning to strategically avoid vulnerable pavements and minimize damage to the highway network.

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Wildfires, pavements, disaster resilience, mechanistic-empirical pavement design, debris removal, traffic loads, fatigue cracking, rutting, case studies

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Disclaimer

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List of Acronyms and Abbreviations

AB	aggregate base
BUT	Butte County
DOT	Department of Transportation
EB	eastbound
ESAL	equivalent single axle loads
FDR-C	full-depth reclamation with cement
GVW	gross vehicle weight
HMA	hot mix asphalt
ksi	kilopounds per square inch
NB	northbound
SB	southbound
SHA	Shasta County
TEH	Tehama County
TI	traffic index
UCPRC	University of California Pavement Research Center
WB	westbound
WIM	Weigh-in-Motion (refers to stations run by Caltrans)
YUB	Yuba County

Executive Summary

Executive Summary

Introduction

California had a series of four devastating fires in 2017 and 2018, which ranked among the most destructive fires in the history of the United States until 2023 (Zurich North America, 2019). Pavements facilitate the removal and transportation of various types of waste from fire-affected areas to major landfills, construction, and demolition recycling facilities. However, the damage caused by debris removal operations to pavements, especially those designed for lighter truck traffic, is not typically quantified. However, this type of study is essential for traffic planning for debris removal after disasters, to minimize damage to existing infrastructure.

Traffic Information and Pavement Structures

The roads taken by the debris hauling trucks, the total load, and the number of truck trips to each facility during the debris removal activities were identified in this project. The Camp Fire created the largest hazardous material cleanup operation in the United States history until 2023. The disaster recovery included the removal of over 3.6 million tons of waste and used a significant number of resources (Constant Associates, 2020). After the Carr Fire, around 521,619 tons of debris were removed, and 46,807 truckloads were reported (Tetra Tech, Inc., 2020b).

Using the gathered truckload and truck trips, the traffic index (TI) for each highway taken was computed. The changes in TI from debris trucks from the Camp Fire ranged between 0.02 for Interstate 5 NB[1] (TEH 28-41) and 1.53 for Skyway in the Town of Paradise. Highway 191 SB (BUT 0-10) and 70 EB (BUT 0-20) had the highest number of debris truck trips, resulting in the highest added equivalent single axle loads (ESALs) and high TI change of 1.12 and 0.23, respectively. Skyway, which carried most of the debris trucks out of Paradise also had a high change in TI of 8 to 9.53. The total amount of debris and consequently loaded truck trips was much less for the Carr Fire, resulting in an added TI of only 0.04 for Highway 299 EB (SHA 19-23) and 0.02 for Interstate 5 SB (SHA 4-19).

The materials and pavement structures required for pavement simulations were gathered from the latest cross-section information based on extracted cores available in the iGPR-Core database.

Pavement Simulations

CalME v3.0, mechanistic pavement design software jointly developed by the California Department of Transportation (Caltrans) and the University of California Pavement Research Center (UCPRC), was used for

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[1] Roadway abbreviations: SB, southbound; EB, eastbound, etc. The term in parentheses indicates the county for the mile marker: BUT, Butte; SHA, Shasta; YUB, Yuba.

the pavement simulations. Based on the CalME results, the impact of debris trucks on pavements’ 20-year cracking and rutting lives was determined using the adjusted Tis.

For rutting, the structure of nearly all the simulated pavements was sufficient in terms of rutting resistance for 20 years of existing truck traffic and the additional truck traffic generated from the Camp Fire. The only exception was Highway 65 SB (YUB 4-9), which experienced rutting before the 20-year mark. Regarding the Carr Fire, both simulated highways successfully accommodated the additional truckloads from fire debris removals without any rutting failure during the 20-year design life (the time after which reconstruction would be considered).

In terms of fatigue cracking, the structures of five pavement sections were adequate to resist fatigue cracking failure for 20 years despite the additional truck loads from Camp Fire. However, the structures of two highway sections were inadequate to pass the 20-year cracking criteria of 10%. These sections include 99 NB (BUT 32-43) and 65 SB (YUB 4-9). In the case of Skyway, the TI increased from 8 to 9.53, resulting in a significant cracking life reduction of 14.1 years.

Regarding the Carr Fire, Highway 299 EB (SHA 19-23) successfully accommodated the additional truckloads from fire debris removals without cracking failure during the 20-year design life. In contrast, Interstate 5 SB (SHA 4-19) did not have sufficient structural capacity to resist the cracking failure without considering the Carr Fire traffic. The TI change from debris removal was insufficient to induce additional fatigue cracking.

Conclusions

The study indicates that wildfires could impact pavement life, especially in terms of fatigue cracking; however, the extent of the damage depends on fire debris size, which leads to additional truck traffic and the structural capacity of the pavement structure. A methodology similar to the one presented in this study can be adopted in the debris management planning phase to strategically avoid vulnerable pavements and minimize damage to the highway network.

Changes in the axle load spectra, season of debris removal, and pavement condition at the time of debris removal were not included in the pavement simulations in this study. A more accurate pavement performance modeling can be achieved using modified axle load spectra representing the exact debris removal truck loads. Pavement functional characteristics such as roughness were not included in this study.

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Introduction

Background

The combined impacts of global climate change and human development in the wildland-urban interface have heightened the risk of catastrophic wildfires in many regions worldwide, exposing approximately one-third of the United States' population to these risks (Conservation Biology Institute and the Nature Conservancy, 2020; Radeloff et al., 2018). California witnessed a series of four devastating fires over 14 months in 2017 and 2018, which ranked among the most destructive fires in the history of the United States until 2023 (Zurich North America, 2019).

Transportation infrastructure is vital during fire events for evacuation, rescue operations, goods transportation, and access to critical services (Fraser et al., 2022). Therefore, understanding fire's immediate and direct impact on asphalt and concrete pavement infrastructure is crucial. Apart from the crucial role of pavements during disasters, they are critical in post-fire recovery. Depending on their nature and extent, disasters can leave large volumes of debris and demolition waste (Brown et al., 2011). In the wake of a wildfire or other disasters, the safe and efficient removal of disaster-generated debris is critical in minimizing impacts on public health and the environment and affects the overall recovery and reconstruction process. The social, environmental, and economic importance of efficient post-disaster debris removal and disposal has been highlighted in the literature (Hu et al., 2019). These materials include a wide range from household items and household hazardous waste to demolition waste, ash, soil, sand and mud, dead trees and vegetation, mixed metals, vehicles and vessels, charred wood, and other debris (Brown et al., 2011; Domingo and Luo, 2017; Karunasena and Amaratunga, 2016).

Pavements facilitate the removal and transportation of various types of waste from fire-affected areas to major landfills, construction, and demolition recycling facilities. However, the damage caused by debris removal operations to pavements, especially those designed for lighter truck traffic, is overlooked (Reinhart and McCreanor, 1999). Overall, it has been reported that the indirect costs associated with disasters, including road damage by debris hauling trucks, are difficult to quantify (Brown et al., 2011). California wildfires posed an unprecedented challenge for the state Departments of Transportation (DOTs) to urgently estimate the magnitude of economic impacts on the road infrastructure. Therefore, a road damage assessment method is needed so DOTs and local governments can develop a timely response to minimize road network damage while facilitating efficient debris removal.

This study aimed to address this knowledge gap by collecting accurate data on the truckloads and number of trips involved in debris transportation following two major wildfires in California as case studies. Subsequently, pavement simulations were conducted to analyze the actual routes taken by the trucks to transport the debris to landfills and recycling facilities to determine any potential fatigue and rutting life-shortening. The presented case studies provide valuable insights into the induced physical impact and include a hypothetical fire intensity study as an example of how the potential impact of future events to the physical road network can be estimated. Understanding and quantifying the damage caused by fires to the pavement structure helps DOTs prioritize and allocate resources to address the vulnerable transportation infrastructure in high-risk wildfires and other climate-related hazards. By addressing the potential impacts of post-fire transportation on the road network, agencies can help ensure the transportation system's continued functionality, safety, and resilience, even in the aftermath of wildfires.

Impact of Fire on Pavements During a Fire

A study modeled the temperature conditions along the roadway during the Camp Fire. The predicted temperature increase ranged from 7°C to 297°C five hours after ignition, depending on the conditions of the fuel and roadside vegetation (Barzegar and Wen 2023). Based on these temperature changes and the asphalt binder's flammability is around 300°C (572°F) (Zhu et al., 2021), asphalt pavements are usually not prone to burning during wildfires. Nevertheless, ignition can occur if combustible materials such as trees and vegetation, oil and flammable fuel, and vehicle gases catch fire on the pavement, generating high-temperature fire. In such cases, the damage is generally confined to the area of the abandoned burning object, leading to localized surface scarring, thermal degradation of the asphalt pavement, such as detachment of aggregate as the binder is consumed, and thermal deformability, mainly based on experimental studies of tunnel pavements in fire (Puente et al., 2016; Toraldo, 2013). Images of an asphalt pavement before and after exposure to a localized fire are shown in Figure 1 from a study by Puente et al. (2016). However, widespread damage can result from the intense heat in wildfire-stricken areas, causing the asphalt to soften and deform or crack under the weight of heavy fire trucks and emergency traffic (Peker, 2021).

Figure 1. Pictures of asphalt pavement before and after a fire experiment from (Puente et al., 2016)

In the case of rigid pavements, concrete is a non-combustible material, does not usually burn during fires, and is considered to have a higher thermal load resistance than asphalt pavements (Toraldo, 2013). See comparison pictures of asphalt and concrete specimens during a fire test in Figure 2.

Figure 2. Asphalt (left) and concrete (right) exposed to 750°C (1382°F) heating experiment from (Rimac et al., 2014)

However, burning objects on concrete pavements may induce chemical-physical damage to the pavement at the location. Much of the thermal damage in concrete is from the degradation of mechanical properties deteriorating to loss of bound water in cement hydrates at around 100°C (212°F). The decomposition of calcium hydroxide occurs at temperatures ranging from 450°C to 500°C (842°F to 932°F). The disassociation of calcium carbonates occurs at much higher temperatures of over 700°C (1292°F) (Daware et al., 2023; Puente et al., 2016; Sancak et al., 2008). These physiochemical processes in portland cement concrete during heating at various temperatures are shown in Figure 3.

These types of immediate damages to construction materials during an active fire from high temperatures, especially to concrete foundations and structures and pavements in tunnel fires, are discussed extensively in the literature (Khoury, 2000). Studies are also abundant in the literature on other potential hazards post-fire, such as landslides, mudslides, and other consequences (Rengers et al., 2020). However, as mentioned earlier, a knowledge gap exists in understanding the level of pavement damage from debris hauling trucks after disasters such as wildfires. Therefore, this study focused on addressing this knowledge gap.

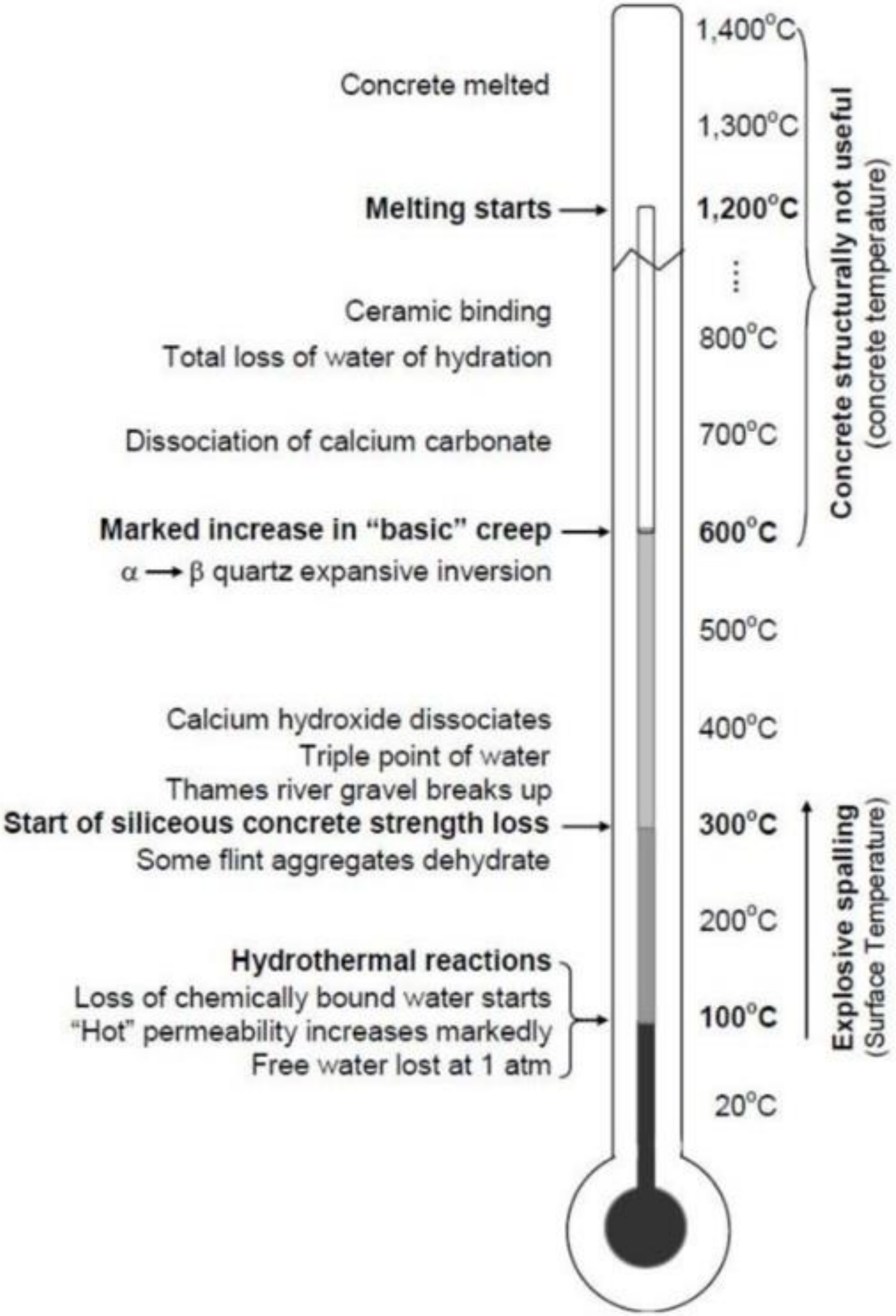

Figure 3. Physiochemical transformation of portland cement concrete during heating, from (Khoury, 2000) Case Studies of California: 2018 Camp Fire and Carr Fire

Description of Fire Event: Camp Fire, Butte County

Paradise has been at high risk for wildfire, threatened by 13 fires in northern California since 1999 (Constant Associates, 2020). The Camp Fire incident in November 2018 burned 153,336 acres, killed 86 people, injured three others, and destroyed 18,804 structures, equivalent to 95% of homes and businesses in Paradise City. Around $12.5 billion in insured losses were reported, making this fire the costliest disaster worldwide in 2018 (Cal Fire, 2022; Hamideh et al., 2022). The disaster recovery included the removal of over 3.6 million tons of waste and used a significant number of resources as the Camp Fire created the largest hazardous material cleanup operation in the United States' history (Constant Associates, 2020). The debris consisted of 2.24 million tons of burned debris and ash, 710,000 tons of recycled concrete, 680,000 tons of contaminated soil and ash, and 52,000 tons of recycled metal, as well as dead trees and vegetation. The cleanup resulted in 600,000 total trips, according to the report published by the California Department of Resources Recycling and Recovery (CalRecycle) (Tetra Tech, Inc., 2020a).

Photos of the fire-stricken area before, during, and after the Camp Fire incident taken from Google Maps™ are shown in Figure 4, Figure 5, and Figure 6.

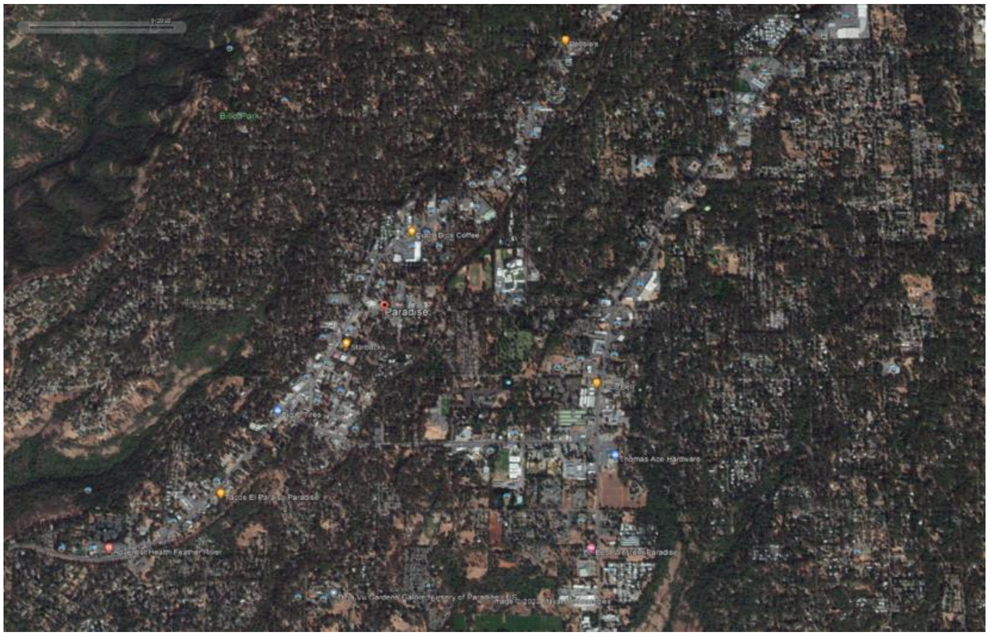

Figure 4. Paradise before the wildfire in September 2018 (Google Maps™)

Figure 5. Paradise during the wildfire in November 2018 (Google Maps™)

Figure 6. Paradise after the wildfire in December 2018 (Google Maps™)

Summary of Paradise Road Damage Assessment Reports

The Town of Paradise performed damage assessments on the town's roads post-fire, pre and post-debris removal in 2019. Two pavement damage categories were identified in the damage assessment forms: pavement scarring due to abandoned burning vehicles and post-fire heavy truck traffic damage due to the removal of 3.7 million tons of debris. The Town conducted pavement condition surveys in January 2019 (after the fire incident, pre-debris removal) and September 2019 (eight months after the fire incident, post-debris removal). The surveys provided information about the pavement damages immediately after the fire and evidence of damage after eight months of heavy truck traffic in and out of the Town for debris hauling.

Survey results and four pavement performance metrics are presented in Table 1. The results show that the longitudinal and transverse cracks expanded to become alligator cracks, indicating failure over the eight months due to water/moisture and heavy loads. Rutting was significant throughout the roadway network, particularly over segments where trucks were stopping repeatedly.

Table 1. Summary of Pavement Condition Surveys performed in January 2019 (pre-debris removal) and September 2019 (post-debris removal)

Performance Metric	January Condition	September Condition	Pavement Deteriorated? Yes or No
Cracking	Moderate/Good	Moderate	Yes — Increase in cracking
Roughness	Moderate/Good	Moderate	No - Minimal Increase in Deterioration
Rutting	Moderate	Moderate/Poor	Yes — Isolated Deterioration, especially in areas where truck traffic repeatedly starts and stops
Texture	Moderate	Poor	Yes - Major deterioration

Overview of Paradise Road Rehabilitation Plan Post Debris Removal

The Paradise roadway network was divided into On-System[2] and Off-System[3] corridors, and both systems were divided into three zones, as seen in Figure 7.

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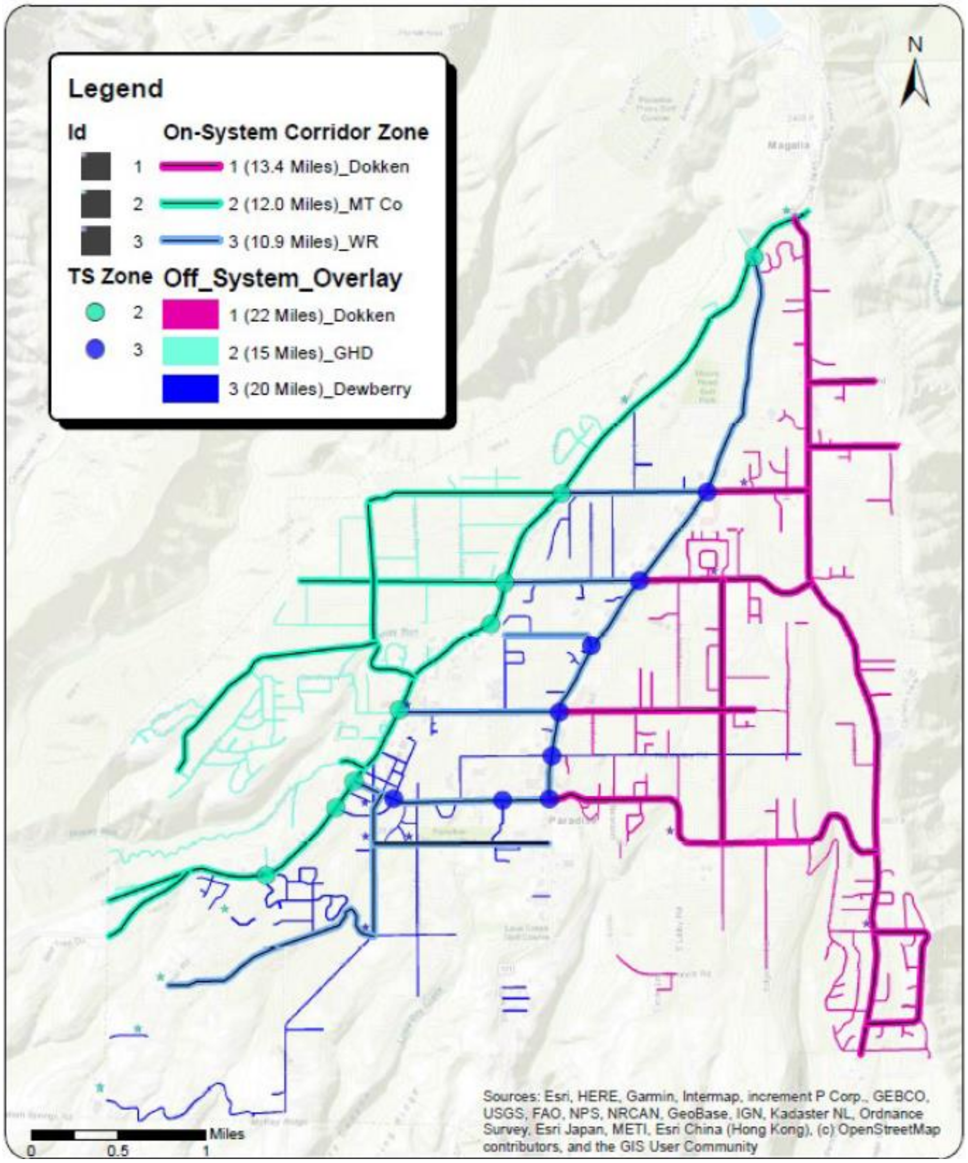
[2] Federal Highways Administration/National Highway System

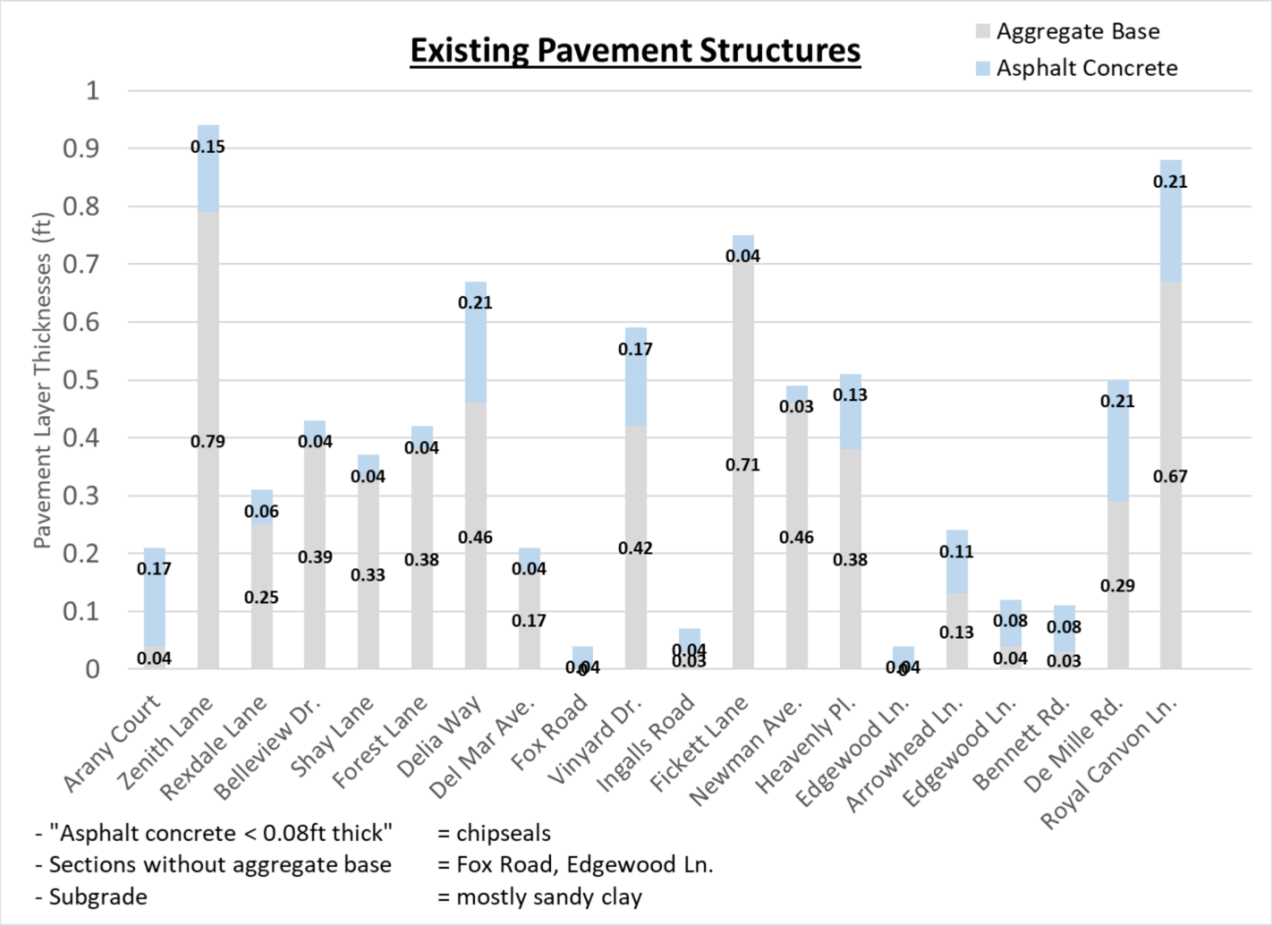
[3] non-Federal Highways Administration/National Highway System



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

Figure 7. Paradise road network divided into On-System and Off-System zones

A geotechnical pavement design memorandum was then prepared for each zone within the system, detailing road rehabilitation strategies for different sections within the zone. Cores were also taken from several zone locations to study road damage further. Figure 8 shows an example of existing structures from the Off-System Zone 1.



- "Asphalt concrete < 0.08ft thick" = chipseals
- Sections without aggregate base = Fox Road, Edgewood Ln.
- Subgrade = mostly sandy clay

Note: AB: Aggregate Base and AC: Asphalt Concrete

Figure 8. Existing pavement cross-sections for the Off-System Zone 1

Depending on the damage identified from the surveys, different rehabilitation strategies were proposed: mill and hot mix asphalt (HMA) overlay; dig out and burn scar repair; pulverization of the existing structures and rebuild; and full-depth reclamation with cement (FDR-C). Table *2* shows these strategies proposed for example sections from On-System Z2 and Z3. Skyway is the major road that was used to haul all debris out of the Town, and therefore, it was decided to include Skyway in the pavement simulation analysis in this study. The recommended strategies for a few segments of the Skyway were either mill and overlay with digout and FDR-C or HMA over the aggregate base (AB). An example of HMA over AB is presented in Table 2.

Table 2. A few example sections from the On-System Zone 2 and 3

Zone	Core ID	Road	Station	Ref	Street Direction	Existing Structures			Existing Roadway Pavement Condition	R-Value	Traffic Index (6-8)	Proposed Rehabilitation					
												% dugouts	FDR-C		Deep lift section	Digout section	
						AC thickness (ft)	AB thickness (ft)	Subgrade Soil Type					HMA (ft)	FDR-C (ft)	HMA (ft)	HMA (ft)	AB (ft)
3	B24	Elliott Road	27+50	“ELT”	E-W	0.35	0.42	Sandy Lean Clay	Poor	N/A	8	95	0.3	1.15	-	-	-
3	B21	Bille Road	85+80	"BIL"	E-W	0.35	0.17*		Good			10			-	-	-
3	B26	Pearson Road	4+30	"PEA"	E-W	0.29	0.67		Poor			80			-	-	-
3	B4	Clark Road	Pearson Road to Central Park Drive	-	N-S	0.21	0.75	Sandy Lean Clay	Poor	15	8	90	-	-	0.95	0.35	1.35
2	C1	Skyway Road	Town Limit (south end) to Neal Rd	-	N-S	0.50	0.92	Lean Clay with Sand	Fair	8	8	28	-	-	0.9	0.35	1.35

* Raveled Asphalt Concrete

AC:	Asphalt Concrete
AB:	Aggregate Base
FDR-C:	Full Depth Reclamation with 3-5% cement stabilizer
HMA:	Hot Mix Asphalt

FDR-C is an in-place recycling technique that is quick and avoids the production of construction material waste. In March 2022, a scope of work change was submitted for the uncompleted permanent work by the Town of Paradise for the off-system roadways. The following are the items of work proposed:

- Pavement Structural Section Repairs
    - FDR-C
    - Pulverized Roadbed
- American with Disabilities Act (ADA) Curb Ramp Reconstruction
- Utility and Monument Adjustments
    - Adjust Utilities/Monuments to Grade
    - Re-establish Monument

The current scope of work for the road network includes replacing asphalt concrete pavement, 0.25 ft HMA, aggregate base, roadway, thermoplastic traffic tripe, and inductive loop detector, which were indicated in the plans.

Description of Fire Event: Carr Fire – Shasta and Trinity County

The Carr Fire incident occurred on July 23, 2018, due to a spark produced from the wheel rim of a vehicle with a flat tire (East et al., 2021). The fire burned 229,651 acres of fields, killed seven people, destroyed 1,614 residential and commercial structures (Cal Fire, 2022), and resulted in more than $1.6 billion in damages (Whiskeytown and Us, 2021). The Carr Fire, at this moment, is the seventh-largest and sixth-most destructive fire in the history of California (East et al., 2021). Unlike the Camp Fire, where undamaged structures were comprehensively recorded in Post-fire Damage Inspection reports by Cal Fire, only aerial imagery was used for the Carr Fire (Schmidt, 2020). Around 521,619 tons of debris were removed, and 46,807 truckloads were reported. The debris included metals, ashes (soil and debris), soil, scrape, and concrete (Tetra Tech, Inc., 2020b).

Before, during, and after photos of the Carr Fire taken from Google Maps™ are shown in Figure 9, Figure 10, and Figure 11.

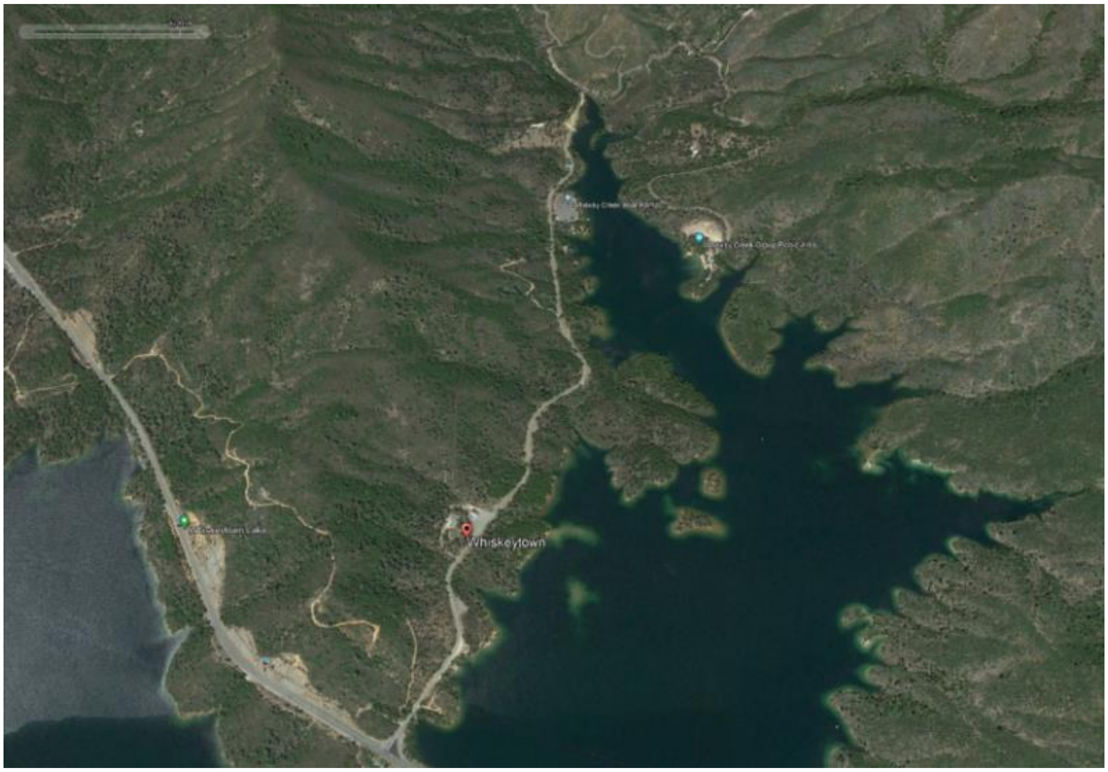


Figure 9. Before Carr wildfire in June 2018 (Google Maps™)

Figure 10. During Carr wildfire in July 2018 (Google Maps™)

Figure 11. After the Carr wildfire in February 2020 (Google Maps™)

Method of Traffic Load Quantification and Pavement Damage Assessment

Truck Traffic Counts and Loads

According to the Camp Fire Debris Removal Operation Traffic Management Plan report (the State of California, Department of Transportation and California Highway Patrol, and California Department of Resources Recycling and Recovery, 2019), seven facilities received 3.66 million tons of wildfire debris, including metals, debris ashes, soil scrap, concrete, and asbestos, from the Camp Fire-stricken sites. The total debris was hauled by 309,239 truck trips from the fire sites to the facilities between February and August 2019. Table 3 shows the roads taken by the hauling trucks, the total load, and the number of truck trips to each facility during the debris removal activities.

Table 3. Main Routes, Truck Load, and Number of Trips to each Facility. Source: (State of California, Department of Transportation and California Highway Patrol, and California Department of Resources Recycling and Recovery, 2019)

Site	Waste Management Destination	Main Routes of the Debris Removal Trucks	Load (ton)	No. of Trips
Camp Fire	Recology Ostrom Road Landfill	Highway-191 Southbound (Paradise), Highway-70 Southbound (North of Orville), Highway-65 Southbound (Junction at 70)	1,552,522	113,107
	Waste Management Anderson Landfill	Highway-99 Northbound (Chico), Highway-5 Northbound (Red Bluff), West Anderson Road	718,523	56,519
	Butte County Neal Road Landfill	Neal Road (Paradise)	629,830	46,817
	Granite Pacific Heights Recycling Facility	Highway-191 Southbound (Paradise), Highway-70 Southbound (North of Orville)	451,097	39,133
	Franklin Neal Road Recycling Facility	Neal Road (Paradise)	256,007	20,957
	Odin Metal Processing Facility	Highway-191 Southbound (Paradise), Highway-70 Southbound (North of Orville)	51,915	32,695
	Crown Metals Recycling Facility	Highway-191 Southbound (Paradise), Highway-70 Southbound (North of Orville)	22	11

Site	Waste Management Destination	Main Routes of the Debris Removal Trucks	Load (ton)	No. of Trips
	Total		**3,659,916**	**309,239**
Carr Fire	Waste Management – Anderson Landfill	Highway-5 Southbound, West Anderson Road	411,540	37,413
	Crystal Creek Aggregate	Highway 299 Southbound near Shasta	54,809	4,983
	Troy Leckey Land Clearing	Highway 299 Southbound near Shasta	25,889	2,354
	West Central Landfill	Swasey Drive, Placer Road	17,280	1,571
	Steel Mill Recycling	Not identified	7,136	649
	J.F. Shea Construction	Highway-5 Southbound,	4,965	451
	Total		**521,619**	**47,420**

The study included only the traffic analysis for debris removal post-disaster. Any traffic surge from fire suppression and rescue activities during the active fire event were not included in the study. The baseline truck traffic information for the selected highway sections was acquired from the Traffic Census Program, annually updated by the California Department of Transportation (Caltrans) (Caltrans, n.d.). The baseline truck traffic information includes each section's annual daily traffic and truck percentages by axle types (two-, three-, four-, and five-axles). The additional truck traffic volumes caused by removing wildfire debris were added to the 2019 baseline truck traffic volumes for the corresponding highway sections.

This study focused on the highway sections to compare the performance of asphalt pavement with two scenarios (the baseline scenarios without wildfire and those with wildfire truck traffic) for 20 years of pavement service lives. To choose a proper strategy for traffic load characterization for pavement design, an initial case study was performed for one highway section as an example. This case study is discussed as follows.

Load Spectra Case Study for 99 NB (BUT 32-43)

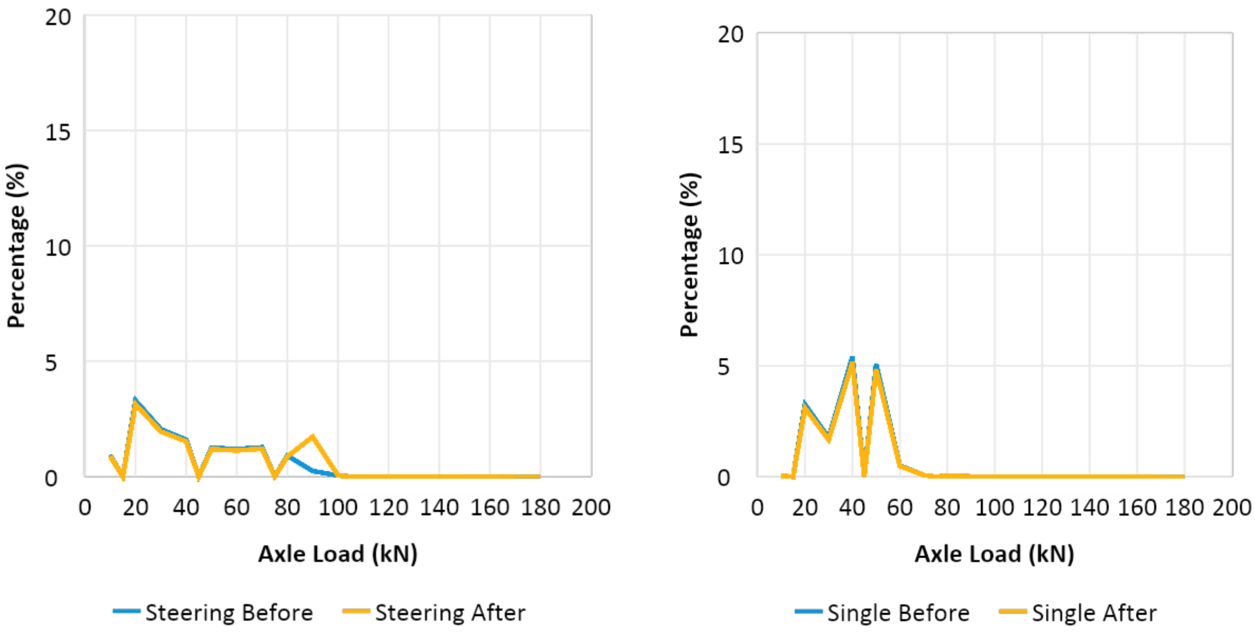
Axle load spectra are the load distribution tables of axle types (steering, single, tandem, and tridem) and the axle loads occurring within each type associated with truck counts. Axle load spectra reflect the truck loading characteristics in mechanistic-empirical pavement design. Along with the total number of trucks passing over a pavement, axle load spectra answer the question, “What proportion of axle type X with axle load Y within that number of trucks will this pavement be subjected to?” by showing the frequency of all axle types and axle loads. The number of passes of each axle load of a given axle type determines the damage, and the repeated simulation for each axle type during the design years determines the total damage to the pavement by all axle loads. The amount of each distress, such as cracking, is calculated from the total damage. Caltrans operates 132 Weigh-in-Motion (WIM) stations at key highway locations. These WIM stations collect, process, and store data on truck traffic—including truck classifications, speeds, gross vehicle weights (GVWs), and axle loads (Caltrans(a), n.d.). The University of California Pavement Research Center (UCPRC) periodically obtains these data to update the axle load spectra used in the Caltrans pavement management system's performance models and Caltrans's concrete and asphalt pavement project-level simulation and design programs. To generate traffic inputs for pavement design and pavement management, in 2018, the UCPRC took axle load distributions from all the WIM stations for the 11 years from 2004 to 2015 and grouped the axle load spectra into five representative spectra. Of these five representative spectra, the most appropriate were then assigned for each of the highway sections studied. Figure 12 shows the WIM spectra on the California highway segments populated by the decision tree approach in the California Pavement Management System (PaveM) (Kim et al., 2023).

Figure 12. Designated WIM spectra to each segment of the Caltrans highway network

State Route 99 northbound (Butte County, postmiles 32-43), one of the major highways used to assess the significance of the debris trucks' impact on load spectra, was chosen for analysis. WIM spectra 3 is the medium axle load spectra among the five-axle load spectra in California highway networks, and it was used as the baseline axle load spectra for the scenario without wildfire debris hauling truck trips.

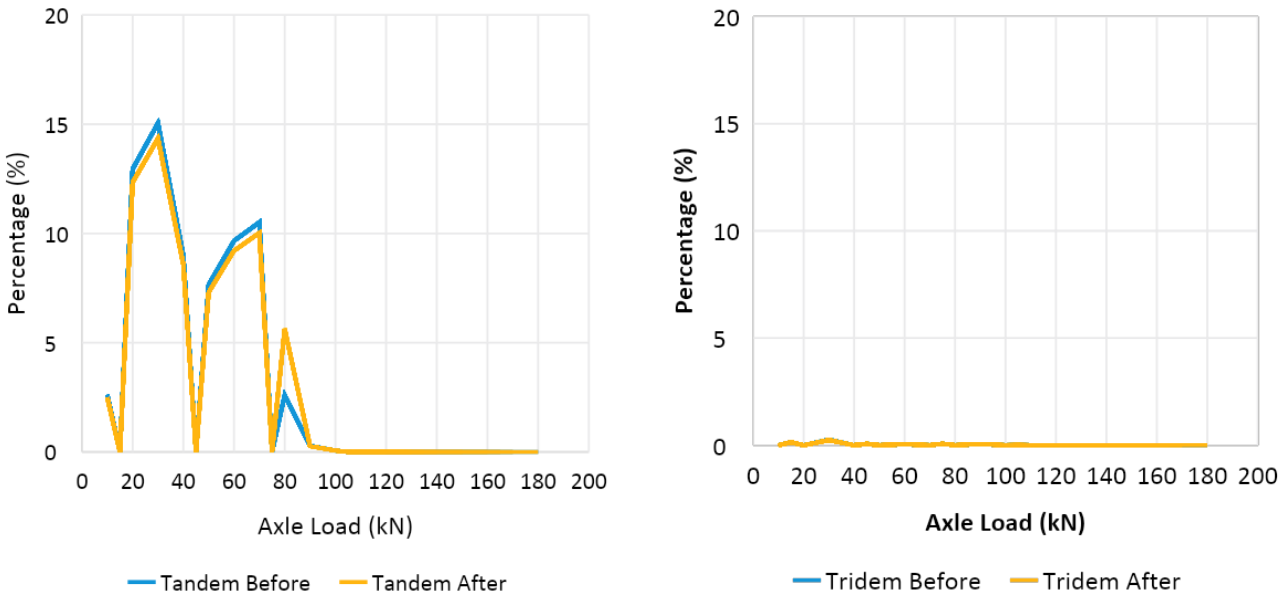
For the scenarios with wildfire hauling truck trips during each month from February to August 2019, the exiting steering, single, tandem, and tridem axle load spectra in the WIM Spectra 3 were modified to reflect the actual additional monthly truck trips by converting the additional monthly trips of two-, three-, four-, and five-axle trucks to the additional portions of steering, single, tandem, and tridem axles in each month of the active debris haul period. Figure 13 (a)-(d) shows the load spectra per axle type with and without the Camp Fire. As shown in the figures, the change in the axle load groups for each axle type was small from the wildfire debris haul when considered for a 20-year analysis period.

The largest change in the number of axles was approximately 9% in June 2019. The average change in the number of axles was 4% for the seven-month active debris haul period. This change in axle load spectra for the seven months over 20 years of analysis period was not significant enough to make a noticeable difference with and without wildfire debris haul truck trips. Based on this initial study, it was decided to use the before-fire WIM spectra for the highway sections with adjustments to other traffic parameters, as discussed below.



(a) steering axle

(b) single axle



(c) tandem axle

(d) tridem axle

Figure 13. The load spectra per axle type for State Route 99 (Butte County, postmiles 32-43) before and after Camp Fire (the average from February to August 2019): (a) steering axle, (b) single axle, (c) tandem axle, (d) tridem axle

Truck Load Characterization

In the two scenarios, equivalent single axle loads (ESAL) and traffic index (TI) values were calculated, and the axle load spectra were chosen from the Caltrans pavement management system (PaveM) (Table 4) (Caltrans, n.d., n.d.). TIs in the scenarios with wildfire were slightly higher than those in the baseline scenario without wildfire because the wildfire scenarios included the truck trips to remove the wildfire debris in 2019. Interstate 5 sections showed a slight difference (0.02 for northbound and 0.03 for southbound) because the truck traffic without the debris removal trucks was already high, at around 14.0 for 20 years of design life. However, the Skyway section in Paradise showed the largest difference in TI (8.0 without- and 9.53 with wildfire trucks) because this section carried small traffic without wildfire trucks.

Five axle load spectra were developed by the decision tree analysis using Caltrans WIM data in a previous study (Caltrans, n.d.). Spectra 1 is the lightest axle load spectra, and Spectra 5 is the heaviest. Interstate 5 northbound sections (Tehama County, postmile 28 to 41), which served the debris removal trucks after the Camp Fire, showed Spectra 4, the second heaviest axle load spectra. The Interstate 5 southbound section (Shasta County, postmile 4 to 19), which served the debris removal trucks after the Carr Fire, showed Spectra 3, the medium axle load spectra, because Interstate 5 functions as the longitudinal freight corridor in California. State Highway 99 sections (Butte County, postmile 32 to 43 and Tehama County, postmile 0 to 24) also showed Spectra 3 in PaveM (Caltrans, n.d.).

The traffic data, including traffic volumes, ESALs, and TIs used for simulations, are shown in Table 4. The changes in TI from debris trucks from the Camp Fire ranged between 0.02 for 5 NB (TEH 28-41) and 1.53 for Skyway in Paradise. Highways 191 SB (BUT 0-10) and 70 EB (BUT 0-20) had the highest number of debris truck trips, resulting in the highest added ESALs and high TI change of 1.12 and 0.23, respectively. Skyway, which carried most of the debris trucks out of Paradise also had a high change in TI of 8 to 9.53. The total amount of debris and consequently loaded truck trips was much less for the Carr Fire, resulting in an added TI of only 0.04 for 299 EB (SHA 19-23) and 0.02 for 5 SB (SHA 4-19).

Table 4. Traffic Data of the Selected Section for CalME Simulations

Fire Site	Road Section (County, Postmiles)	Traffic Volume (two-way)					20-Year ESAL			Calculated TI		WIM Spectra
		Trucks	2 axles	3 axles	4 axles	5+ axles	ESAL Without Fire	ESAL from Fire	Total ESAL	Without Fire	With Wildfire	
Camp Fire	99 NB (BUT, 32-43)	5,906	4,245	288	123	1,250	27,919,880	570,400	28,490,280	13.38	13.41	3
	99 NB (TEH, 0 -24)	1,764	589	96	31	1,048	7,894,910	570,400	8,465,310	11.51	11.61	3
	5 NB (TEH, 28-41)	7,197	769	281	114	6,033	42,950,180	570,400	43,520,580	14.09	14.11	4
	191 SB (BUT, 0-10)	424	160	126	34	103	1,151,870	1,876,800	3,028,670	9.15	10.27	1
	70 EB (BUT, 0-20)	3,095	1,179	393	202	1,321	11,232,200	1,876,800	13,109,000	12.00	12.23	2
	70 EB (YUB, 8-25)	2,703	612	555	178	1,358	11,323,420	1,140,800	12,464,220	12.02	12.15	2
	65 SB (YUB, 4-9)	4,827	2,075	1,012	506	1,234	13,283,730	1,140,800	14,424,530	12.25	12.37	1
	Skyway in Paradise	-	-	-	-	-	371,661	1,251,200	1,622,861	8.00	9.53	-
Carr Fire	299 EB (SHA, 19-23)	890	552	94	11	233	2,191,550	80,960	2,272,510	9.88	9.92	3
	5 SB (SHA, 4-19)	4,225	1,011	181	47	2,986	38,235,350	415,840	38,651,190	13.89	13.91	3

Pavement Simulations

CalME v3.0, mechanistic pavement design software jointly developed by Caltrans and the UCPRC, was used for the pavement simulations. CalME uses an incremental-recursive damage process. In the model for fatigue damage of asphalt layers, for example, the strain, the modulus, and the temperature may change from increment to increment. Therefore, the first step in the process is to calculate the "effective" number of load applications that would have been required, with the present parameters, to produce the condition at the beginning of the increment. In the second step, the new condition, at the end of the increment, is calculated for the "effective" number of load applications plus the number of applications during the increment. This must be repeated for each combination of axle type, load level, and the daily period during the increment. A load spectrum is used to distribute truck traffic into these combinations.

For asphaltic permanent deformation (rutting), CalME uses a shear-based approach developed by Deacon et al. (2002) for rutting prediction of the asphalt layer. Shear deformation is assumed to control the rutting in the asphalt. The rutting estimates use computed values of shear stress τ, and elastic shear strain, γ^e, at a depth of 2 in. beneath the edge of the tire. Also, the model assumes rutting occurs solely in the top 4 in. of the HMA layer, Equation (1)

$$rd_{AC} = K \times \gamma^i \times h \qquad (1)$$

where: rd_{AC} is the vertical rutting depth in the asphalt concrete
γ^i is the permanent (inelastic) shear strain at a 2-inch depth,
K is a value relating permanent shear strain to rutting depth, and
h is the thickness of the HMA layer, with a maximum value of 4 inch.
The permanent strain can be calculated from the gamma function shown in Equation 2:

$$\gamma^i = A \cdot \exp\left(\alpha \times \left[1 - \exp\left(-\ln(N)/\gamma\right) \times \left(1 + \ln(N)/\gamma\right)\right]\right) \times \gamma^e \qquad (2)$$

where: γ^e = corresponding elastic shear strain (inch/inch),
N = equivalent number of load repetitions, which is the number of load repetitions at the stress and strain level of the next time increment to reach the permanent shear strain calculated at the end of the current time increment, and
A, α, and γ are material-dependent model parameters.

Permanent deformation of unbound layers such as lightly cemented or unbound materials is based on the vertical resilient strain at the top of the layer $\mu\varepsilon$ and stiffness of layer, E:

$$d_p = A \times MN^{\alpha} \times \left(\frac{\mu\varepsilon}{\mu\varepsilon_{ref}}\right)^{\beta} \times \left(\frac{E}{E_{ref}}\right)^{\gamma} \qquad (3)$$

where: d_p = the permanent deformation in the layer,

MN = the number of load applications in millions,

$\mu\varepsilon_{ref}$ = the normalizing strain,

E_{ref} = the normalizing stiffness, and

$A, \alpha, \beta,$ and γ are material-specific model parameters.

The *CalME* asphalt concrete fatigue cracking model uses a multi-layer elastic program as the response submodel. In *CalME*, only traffic-related fatigue damage is considered. Details of the model can be found in (Rongzong Wu, 2021; Wu et al., 2018). The key part of the model is Equation 4 for estimating fatigue life, *MNp*:

$$MN_p = A \times \left(\frac{\varepsilon}{\varepsilon_{ref}}\right)^{\beta} \times \left(\frac{E}{E_{ref}}\right)^{\beta/2} \quad (4)$$

where: ε is the bending strain at the bottom of the asphalt layer, negative for tensile,

E is the mix stiffness,

e_{ref} = -200 microstrain (-200×10^{-6} in./in.) is the reference bending strain,

E_{ref} = 435 ksi is the reference stiffness, and

A and β are material-dependent model parameters.

Once the fatigue damage is determined, the percent of wheel path cracked, denoted as CRK, is assumed to relate to the fatigue damage through the following transfer function:

$$CRK = \frac{100}{1+\left(\frac{\omega}{\omega_{50}}\right)^{\beta}} \quad (5)$$

Where ω is the calculated fatigue damage,

ω_{50} and β are model parameters to be determined through field calibration, and

ω_{50} represents fatigue damage corresponding to 50%-wheel path cracking.

Each parameter may depend on additional factors such as pavement structure type, climate condition, and HMA layer thickness. Note that ω_{50} depends on the physical meaning of the fatigue damage predicated by the model used, and it can be any value between 0 and 1.0. The assumed transfer function represents an S-shaped curve that matches the observed field cracking progression. The mid-portion slope of the s-shaped curve is controlled by β. Accordingly, β is called the shape parameter, and it is always negative, with a higher absolute value suggesting a steeper ascent.

Pavement Structures

The materials and pavement structures for CalME simulations were defined using the latest cross-section information based on extracted cores in the iGPR-Core database. iGPR shows the pavement structure profile by mapping the density of the structure layers with the data detected from a ground penetrating radar (University of California Pavement Research Center, n.d.). Time and postmile (PM) treatments were extracted from the PaveM (Caltrans, n.d.), as shown in Table 4. Other information included in the table includes the route name, direction, county, postmile, last treatment, and most updated structure of each pavement structure for both the Camp and Carr Fires. The subgrade soil type was unavailable for some sections but was sandy soil (SC) for those with available information.

Therefore, SC was considered the subgrade type for all pavement sections. As seen in Table 5, most highway sections were hot mix asphalt (HMA), varying between 0.5 and 0.9 ft. Two sections of 99 NB (BUT 32-43) and 65 SB (YUB 4-9) had a 0.15 ft rubberized hot mix asphalt overlay, and one was a portland cement concrete section. Almost all sections had an aggregate base (AB), except highway 191 SB (BUT 0-10), which had a cement-treated base layer, and highway 99 NB (TEH 0 -24), which had a portland cement concrete layer. Only Highway 70 EB (BUT 0-20) had an aggregate subbase layer. Table 5 also includes the structure of the main artery in Paradise, called Skyway, that was used to haul all the city debris from the Camp Fire out of Paradise City.

Table 5. Pavement Structure of Roads Used to Haul Debris to Waste Management Facilities

Fire	Name: Highway Number, Direction (County, Postmiles)	Time and PM of last treatment Year (Postmiles)	Pavement Structure (ft)*					
			RHMA	HMA	PCC	AB	CTB	ASB
Camp Fire	99 NB (BUT 32-43)	2015 (PM30-PM37)	0.15	0.55	-	1.75	-	-
	99 NB (TEH 0 -24)	2012 (PM12-PM24)	-	0.90	0.50	-	-	-
	5 NB (TEH 28-41)	2011 (no record after 2011)	-	0.85	-	1.65	-	-
	191 SB (BUT 0-10)	2013 (PM0-PM11)	-	0.55	-	-	0.65	-
	70 EB (BUT 0-20)	2014 (PM13-PM17)	-	0.75	-	0.50	-	0.75
	70 EB (YUB 8-25)	2015 (PM 14-PM15)	-	0.75	-	1.00	-	-
	65 SB (YUB 4-9)	2011 (no record after 2011)	0.15	0.55	-	0.50	-	-
	Skyway in Paradise	-	-	0.50	-	0.92	-	-

Fire	Name: Highway Number, Direction (County, Postmiles)	Time and PM of last treatment Year (Postmiles)	Pavement Structure (ft)*					
			RHMA	HMA	PCC	AB	CTB	ASB
Carr Fire	299 EB (SHA 19-23)	2012 (PM19-PM20)	-	0.90	-	0.40	-	-
	5 SB (SHA 4-19)	2017 (PM4-PM6)	-	0.50	0.75	1.00	0.25	-

* RHMA, rubberized hot mix asphalt; HMA, hot mix asphalt; PCC, portland cement concrete; AB, aggregate base; CTB, cement treated base; ASB, aggregate subbase.

The CalME input parameters and their defined values for the pavement section are summarized in Table 6. The results are presented in terms of rutting and cracking life in years. The performance criteria for rutting was set to 0.4 inches and 10% for cracking, based on the Caltrans Maintenance Manual, Chapter A (Caltrans, n.d.). The deterministic simulation for 20 years was used to predict median pavement life (i.e., with 50% reliability). The simulation start date for each pavement section was defined as the latest time of the last treatment presented in Table 5.

Table 6. CalME Input Parameters used for all Simulated Sections

Parameter	Quantity	Parameter	Quantity
Traffic	As shown in Table 4	Binder Type	Mix with PG 70-10
Climate Zone	Inland Valley, California	Subgrade Type	Silty Sand (SC)
Simulation Duration	20 years based on Caltrans design practice	HMA Modulus-E (ksi)	722.0*
Vehicle Speed	43.75 mph	HMA Modulus-E (ksi)	1,230.6*
Simulation Type	Deterministic: reliability = 50%	PCC Modulus-E (ksi)	5076.3*
Rutting Performance Criteria	0.4 in.	AB Modulus-E (ksi)	45.0*
Cracking Performance Criteria	10%	CTB Modulus-E (ksi)	1508.1*
Structure	As shown in Table 4	ASB Modulus-E (ksi)	35.0*

* These values represent the statewide medians of layer moduli used for routine pavement designs. For the HMA layer, the moduli are determined for 20°C and 10Hz loading frequency. AB, aggregate base; ASB, aggregate subbase; CTB, cement-treated base; HMA, hot mix asphalt; PCC, portland cement concrete; ksi, kilopounds per square inch.

Results and Discussions

Impact of Fire Debris Truck on Pavement Lives

The outcomes of the CalME simulations are presented in Figure 14 for rutting life and Figure 15 for fatigue cracking life for both the Camp Fire and Carr Fires. A rutting life of 20 years demonstrates a pavement that has passed the 0.4-inch rutting criteria. The affected pavements by the fire truck traffic are identified with a vertical arrow on each graph.

As seen in Figure 14, the structure of nearly all the simulated pavements was sufficient in terms of rutting resistance for 20 years of existing truck traffic and the additional truck traffic generated from the fire. The only exception is 65 SB (YUB 4-9), which experienced rutting before the 20-year mark. Without considering fire debris truck traffic, 65 SB (YUB 4-9) rutting life was 12.8 years, which decreased by 2.1 years due to the trucks from the Camp Fire debris removal. This is attributed to inadequate HMA (0.55 ft) and AB (0.5 ft) thicknesses in this pavement section, which were insufficient to support the existing traffic loads of 13 million ESALs. The situation was then exacerbated by the added stress from fire truckloads, which increased the TI from 12.25 to 12.37. On the other hand, Skyway demonstrated no rutting failure despite the additional truckloads of debris.

Regarding the Carr Fire, both simulated highways successfully accommodated the additional truckloads from fire debris removals without any rutting failure during the 20-year design life.

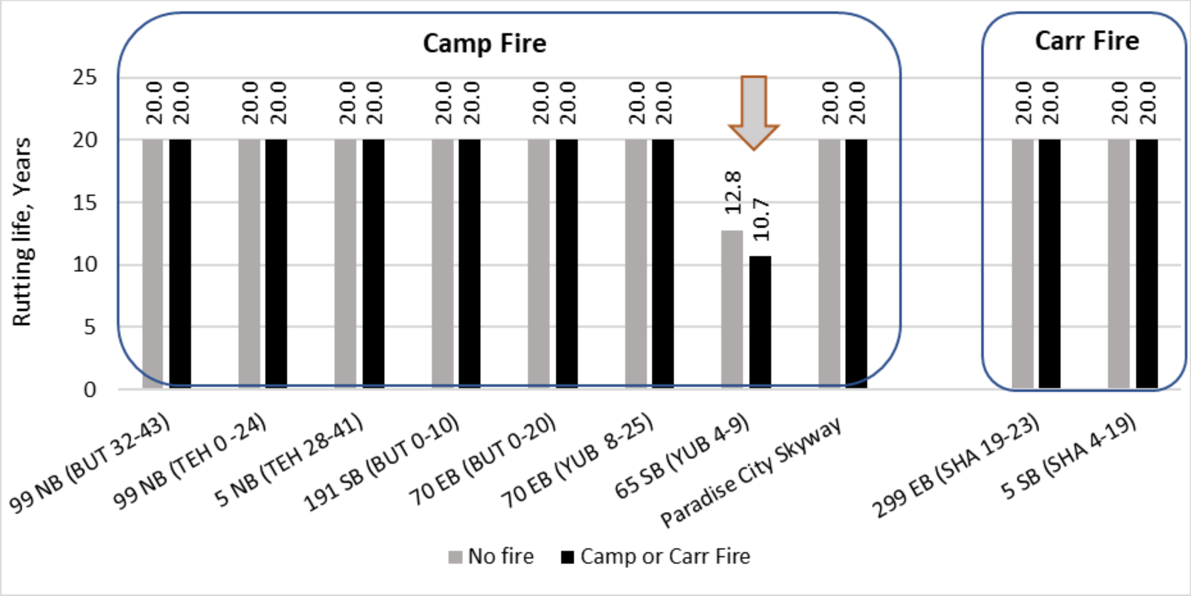


Figure 14. Impact of Fire Debris Removal generated by Camp and Carr Fires on the rutting life of the pavements on roads taken to waste management facilities (the arrow shows the impacted road)

Regarding fatigue cracking, as seen in Figure 15 a, the structures of five pavement sections were adequate to prevent fatigue cracking failure for 20 years despite the additional truck loads from Camp Fire. However, the structures of two highway sections were inadequate to pass the 20-year cracking criteria of 10%. These sections include 99 NB (BUT 32-43) and 65 SB (YUB 4-9). For 99 NB (BUT 32-43), the TI did not change with the added trucks from Camp Fire. Therefore, the cracking life of this section did not change considering fire debris trucks. On the other hand, fire debris truck traffic was enough to increase the TI of 65 SB (YUB 4-9) from 12.25 to 12.37, which reduced the cracking life of this section from the already low 10.3 years to 9.2 years. This reduction in cracking life for this section is commensurate with its rutting failure behavior discussed in the previous section.

In the case of Skyway, the TI increased from 8 to 9.53, resulting in a significant cracking life reduction of 14.1 years.

Regarding the Carr Fire, Highway 299 EB (SHA 19-23) successfully accommodated the additional truckloads from fire debris removals without any cracking failure during the 20-year design life. In contrast, Highway 5 SB (SHA 4-19) did not have sufficient structural capacity to resist the cracking failure with or without considering the traffic from the Carr Fire. The TI change from debris removal was not large enough to induce any additional fatigue cracking.

The correlation between the HMA thickness of the failed sections and their cracking life is shown in Figure 15b. The strong correlation between the HMA thickness and the cracking life (R^2 = 0.86) suggests that when there is additional truck traffic from fires, the thickness of HMA plays a significant role in the cracking life. The conclusion from this study could be that vulnerable pavements could easily be identified as those not having sufficient structure to withstand their existing traffic.

Another analysis, shown in Figure 15 c, strongly demonstrates that greater changes in TI of the failed sections caused a more significant decrease in the cracking life, with a high coefficient of determination (R^2 = 0.99).

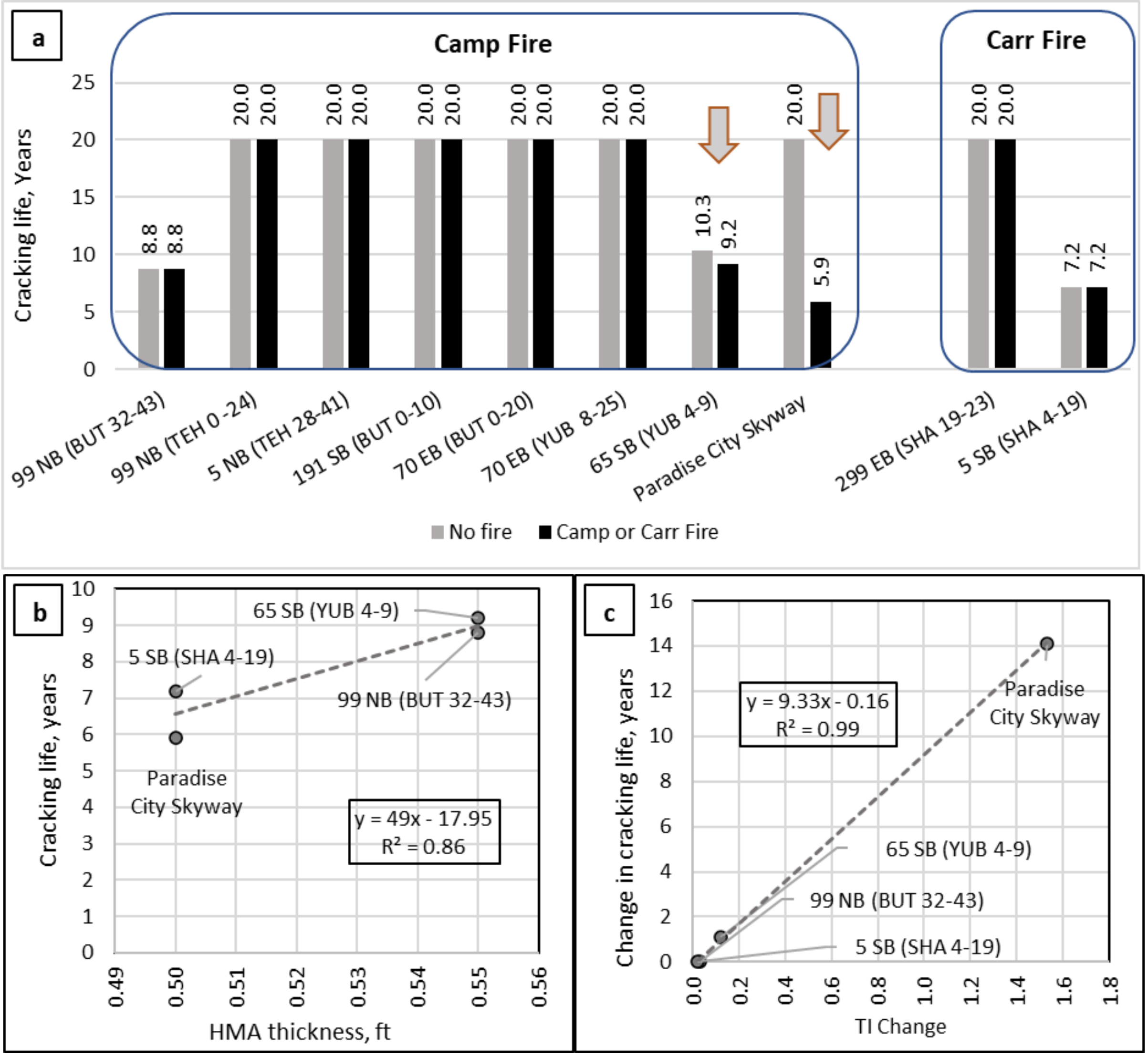


Figure 15. (a) Impact of fire debris removal generated by Camp and Carr Fires on the fatigue cracking life of the pavements of roads taken to waste management facilities (arrows show the impacted roads); (b) Correlation between HMA thickness and cracking life of the pavement structures within 20 years; (c) The correlation between change in TI and change in the cracking life of the pavement structures within 20 years

Sensitivity Analysis

Figure 16 and Figure 17 present hypothetical scenarios in which events with similar debris truckloads as those of the Camp or Carr fires are repeated twice and thrice within the 20-year design life of the previously simulated pavements.

Based on the result shown in Figure 16, by multiplying the traffic generated by the Camp and Carr fires, the rutting life of most of the simulated sections remains at least 20 years, while two sections showed some changes. As mentioned, the high traffic volume for the structure of 65 SB (YUB 4-9) caused the rutting failure of this section, which intensified with the Camp Fire but did not change significantly with the hypothetical second and third fires. The second and third fires increased the TI by 0.11 and 0.11, respectively, compared to the first fire's TI.

In contrast, the second and third fires had a significant impact on the rutting life of Skyway, which can be attributed to the high amount of traffic in this section (TI = 10.21 and 10.66 by considering the second and third fires, respectively) compared to the existing traffic (TI = 8).

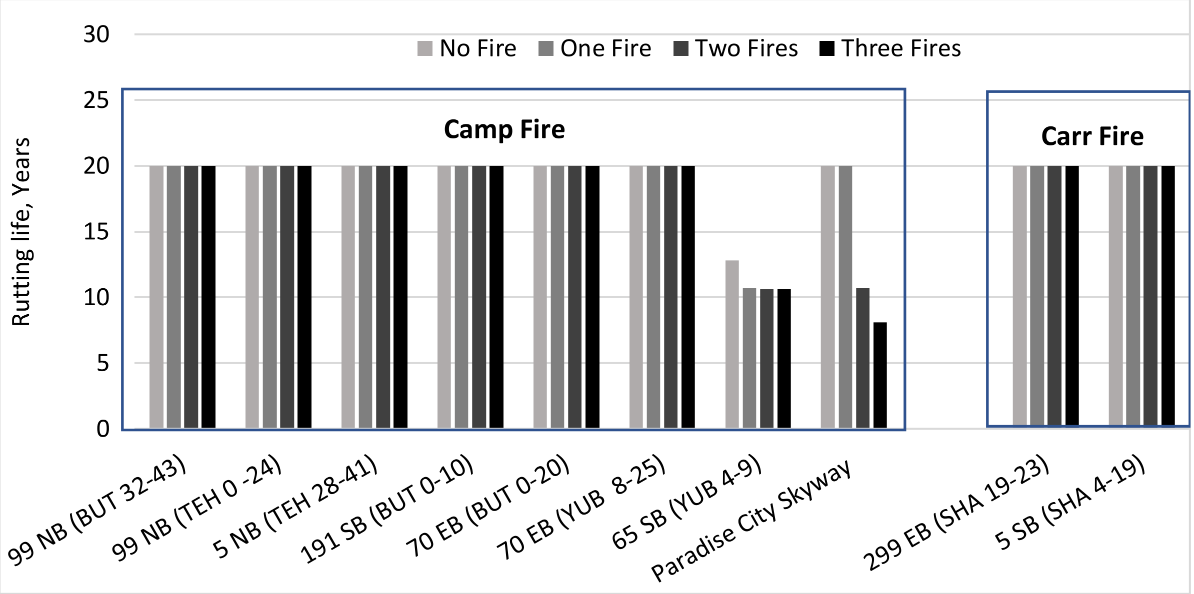


Figure 16. Impact of the actual fires and hypothetical second and third fires on the predicted rutting life

As shown in Figure 17, similar to the first fire, the second and third fires decreased the cracking life of 65 SB (YUB 4-9) and Skyway, while they did not change the cracking life of 99 NB (THE 0-24), 5 NB (TEH 28-41), 191 SB (BUT 0-10), 299 EB (SHA 19-23), and 5 SB (SHA 4-19) sections. However, due to the higher traffic volumes generated by considering all three fires, the cracking life of the 99 NB (BUT 32-43), 70 EB (BUT 0-20), and 70 EB (YUB 8-25) sections decreased by 0.6, 3.9, and 17.8 years, respectively.

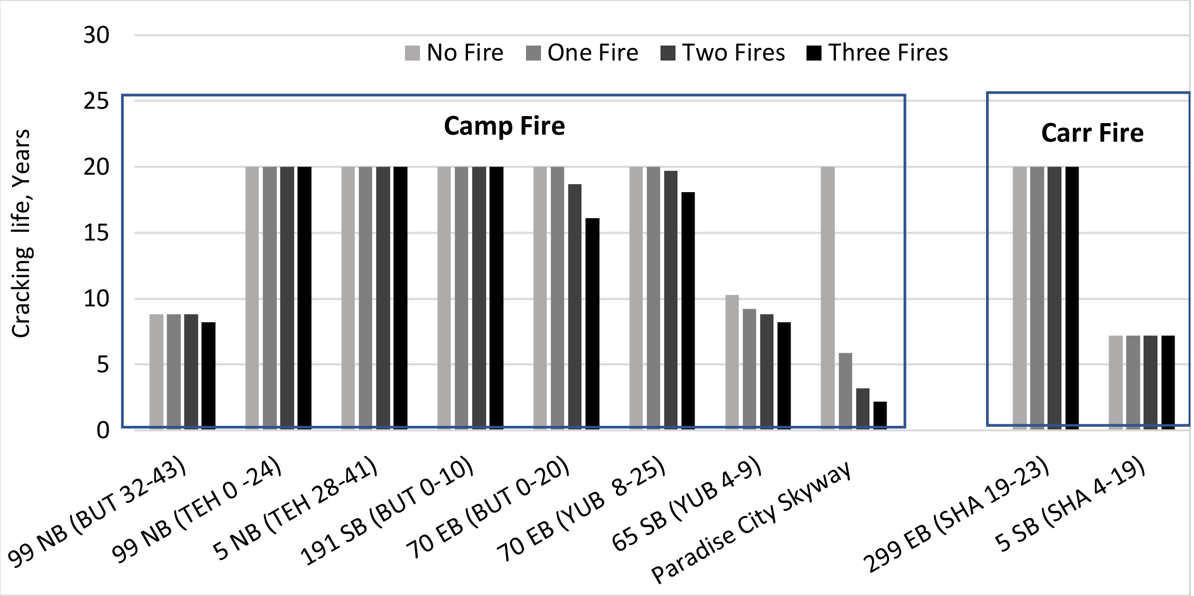


Figure 17. Impact of the first actual fires and hypothetical second and third fires on the fatigue cracking life

Study's Limitations

As discussed earlier, the adjusted traffic parameter used in the CalME pavement simulations was the 20-year traffic index (TI). In reality, debris truckloads were applied to the pavement in one season (from February to August 2019) in one year and would induce a change to the axle load spectra in that season. To investigate the impact of the simplified traffic assumption (design-life modified TI vs. modified axle load spectra), the modified load spectrum for one highway section was developed, as discussed in detail in the section Load Spectra Case Study for 99 NB (BUT 32-43). For the select highway section 99 NB (BUT 32-43), the TI remained unchanged when considering the debris traffic, so this was a good case for the evaluation. The CalME results are presented in Table 7 in terms of rutting and cracking for three cases. These cases are No Fire: WIM 3 axle load spectra, Camp Fire: modified WIM 3, and Camp Fire WIM 3 axle load spectra.

Although the modified load spectrum did not alter the rutting life of this section compared to the case without a change in the spectrum, it did reduce the cracking life by 0.6 years. Based on these results, considering the modified load spectrum caused by a fire in the actual months led to a slightly lower cracking life than using WIM 3 with no modifications (8.2 years vs. 8.8 years). This change resulted from a heavier axle load during months when additional traffic from the Camp fire was added to the existing traffic. However, this shortened fatigue life of 7.2 months was not captured in the Camp Fire: WIM 3 case.

Table 7. The cracking and rutting life of the 99 NB (BUT 32-42) with considering modified load spectrum

Failure	No fire: WIM 3	Camp Fire: modified WIM spectra	Camp Fire: WIM 3
Rutting (years)	20.0	20.0	20.0
Cracking (years)	8.8	8.2	8.8

This limitation especially concerns the highway sections where the truckloads of debris were not large enough to induce a change greater than 0.1 in TI. Changes in TI are considered in CalME in increments of 0.1. Therefore, the cracking and fatigue lives remained unchanged for the highway cases where the debris traffic was insufficient to increase the TI by at least 0.1. Therefore, the performance of these sections might be overestimated in this study.

Another limitation of this study is that CalME is a pavement structural design tool focused on cracking and rutting as the design criteria. Therefore, the impact of the debris trucks on functional parameters such as the International Roughness Index (IRI) was not considered in this study.

Conclusions

The results of the pavement simulations in this study showed that the structures that were not strong enough, such as Highway 65 (YUB 4-9), with a relatively thin HMA layer and base layer, showed signs of early fatigue cracking failure. No record of structural rehabilitation was found in the database for Highway 65 (YUB 4-9) after 2011, which showed an inadequate structural capacity to withstand existing and additional truck loads. If rehabilitation activities were performed on this section after 2011, then the pavement simulation must be rerun to include the stronger structure. Due to the inadequate structural capacity, the slight increase in TI on highway section 65 SB (YUB 4-9) due to traffic to remove debris contributed to the reduction of cracking life by almost one year. On the other hand, highway pavement structures 99NB (THE 0-24), I-5 NB and SB, 191-SB, 70 EB, and 299 EB showed no signs of failure over the design even with the additional truck traffic resulting from debris haul to landfill or recycling facilities. It could be concluded that the vulnerable pavements could be identified as those not having a sufficient structure to withstand their existing traffic for the studied fires.

The major city road in Paradise, Skyway, carried most trucks that hauled the debris out to facilities. The increase of 1.53 in traffic index had a significant effect on this pavement's fatigue cracking life, showing almost a 75% reduction in cracking life.

In the case of the Carr Fire, which generated 14% of the debris of the Camp Fire, the additional truck traffic did not affect the pavement life of the highways in Shasta County used for debris removal.

The sensitivity analysis of increasing the number of fire events to two and then three showed that multiple wildfire events with the same intensity as the Camp and Carr Fires could affect the pavement structure life, especially the cracking life, even the sections that were not affected due to a single fire event such as 70 EB.

The study concluded that wildfires could impact pavement life, especially in terms of fatigue cracking. However, the extent of the damage depends on the fire debris size, which leads to additional truck traffic and the structural capacity of the pavement structure.

Recommendation for Future

It is recommended that axle load spectra are developed for each highway section considering the truckloads and their time of application to use in pavement simulation for a more realistic forecast of pavement damage. The case studies presented in this report can be extended to include pavement simulations for other fire incidents to arrive at broader and network-level conclusions that state agencies and local governments can use for resilient planning in the future. Furthermore, vulnerable highway sections can be identified and avoided as part of traffic planning during debris management operations. The impact of fire and debris removal operations on the required preservation and maintenance activities on the affected highways was not considered in this study and could be included in future studies.

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