Preliminary Investigation (PI-0278)

Caltrans Division of Research, Innovation and System Information

Traffic Modeling of Potential Emergency Wildfire Evacuation Routes

Requested by
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May 28, 2021

The Caltrans Division of Research, Innovation and System Information (DRISI) receives and evaluates numerous research problem statements for funding every year. DRISI conducts Preliminary Investigations on these problem statements to better scope and prioritize the proposed research in light of existing credible work on the topics nationally and internationally. Online and print sources for Preliminary Investigations include the National Cooperative Highway Research Program (NCHRP) and other Transportation Research Board (TRB) programs, the American Association of State Highway and Transportation Officials (AASHTO), the research and practices of other transportation agencies, and related academic and industry research. The views and conclusions in cited works, while generally peer reviewed or published by authoritative sources, may not be accepted without qualification by all experts in the field. The contents of this document reflect the views of the authors, who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the California Department of Transportation, the State of California, or the Federal Highway Administration. This document does not constitute a standard, specification, or regulation. No part of this publication should be construed as an endorsement for a commercial product, manufacturer, contractor, or consultant. Any trade names or photos of commercial products appearing in this publication are for clarity only.

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Executive Summary

Background

During the Camp Fire in 2018, people using a primary evacuation route to leave the area experienced a significant traffic delay because of recent road improvements that reduced roadway capacity. To avoid similar delays during wildfire events, California Department of Transportation (Caltrans) is interested in using roadway design to facilitate mass emergency evacuations. By modeling potential evacuation routes when developing transportation projects, the agency could evaluate the impacts of those road improvements.

Caltrans is gathering information from other state departments of transportation (DOTs) about traffic modeling tools and other practices they use when designing roadway improvements to examine the operational impacts of mass emergency evacuations during wildfire events. Of particular interest are the modeling procedures and recommendations that enable highway designers to develop projects that facilitate the most efficient evacuation of impacted communities while allowing access by emergency vehicles. Findings from this investigation will inform Caltrans' efforts to develop modeling tools, practices and guidance for managing emergency wildfire evacuation events and using highway design to facilitate evacuation.

Summary of Findings

Survey of Practice

An online survey was distributed to western and southwestern state DOT members of the American Association of State Highway and Transportation Officials (AASHTO) Committee on Design, Committee on Planning and Committee on Traffic Engineering. Transportation agencies from five states responded to the survey:

- Arizona (two responses).
- Idaho.
- Nevada.
- Oregon.
- Utah.

None of these states currently uses or has plans to use modeling tools and other practices to evaluate potential emergency wildfire evacuation routes when designing road improvements for highways in areas with high fire potential.

Four respondents provided information about their agencies' practices with mass emergency evacuations:

- Arizona DOT's Transportation Systems Management and Operations staff does not use modeling tools during the design phase because of the capabilities of the agency's Systems Technology Group.
- Idaho Transportation Department uses modeling tools for evacuation routes but doesn't have plans to use them for potential emergency wildfire evacuation routes. According to the survey respondent, evacuation options in the state are generally few and obvious. The respondent noted, however, that insights could be obtained by modeling potential emergency fire evacuation routes and that the agency will "give it some thought to develop in the near future."

- Until 2020, wildfire had not been an issue in Oregon. Currently Oregon DOT uses tools to analyze evacuations for other disasters such as a chemical plant failure, and it uses a statewide model for analyzing the long-term impacts of large-scale emergencies such as earthquakes. These tools are capable of providing information for wildfire evacuations, and the agency has “started conversations” about using them for wildfire specifically.
- Utah DOT regularly uses modeling tools to evaluate impacts to diversion routes for construction and emergencies such as crashes, floods, mudslides and bridge hits, but not for wildfire evacuations. To develop these diversion routes, the agency uses probe data, Iteris ClearGuide, radar data, Freeway PeMS (Performance Management System), PTV Vissim modeling software and MAXVIEW for traffic signals. The respondent noted that it would not be difficult to apply these same approaches to wildfire evacuations.

Related Research and Resources

A literature search of domestic and international in-progress and published research identified resources in the following categories:

- State guidance and research.
- Evacuation modeling.
- Evacuation behavior.
- Modeling tools.
- Related resources.

Tables summarizing these resources are presented by topic area beginning on page 5. Each table provides the publication or project title, the year of publication if research is completed and a brief description of the resource. Significantly more detail about the resource can be found in the **Detailed Findings** section of this report.

Gaps in Findings

Response to the survey was very limited with only five state DOTs participating. None of these agencies has experience using modeling tools and other practices to evaluate potential emergency evacuation routes for wildfire specifically when designing road improvement projects in high fire potential zones. In addition, none of the agencies has formal plans to use modeling tools and practices for wildfire evacuation route planning in the future. As a result, minimal information was gathered related to modeling tools, and no information was received from the survey related to human behavior in evacuations. Additional inquiries to the western and southwestern states that did not respond to the survey could provide information and guidance related to modeling and planning.

Next Steps

Moving forward, Caltrans could consider:

- Contacting Utah DOT about the modeling tools it uses to evaluate impacts to diversion routes for construction projects and nonwildfire emergencies. The respondent noted that these approaches could be applied to wildfire scenarios, and the respondent was willing to address any inquiries about the agency’s practices.
- Following up with Oregon DOT about the informal efforts underway at the agency to use existing modeling tools for wildfire specifically.

- Querying Arizona DOT for more information about its Systems Technology Group's capabilities related to emergency route planning and modeling.
- Contacting nonresponding state DOTs to potentially uncover other agency experience with wildfire evacuation route planning when designing road improvement projects in high fire potential areas.
- Reviewing the findings of the literature search, which include information related to evacuation route modeling and human behavior during evacuations from both domestic and international publications and resources.

State Guidance and Research

Publication or Project (Date)	State	Excerpt From Abstract or Description of Resource
Evacuation Route Design Guidance (December 2020)	California	Addresses road features that facilitate evacuations, including geometric considerations; travel lanes, shoulders and turn lanes; intersections; Complete Streets features; barriers and guardrails; and bridges, tunnels and other structures.
Fire Hazard Planning Technical Advisory (November 2020)	California	Provides a robust planning framework for addressing fire hazards, reducing risk and increasing resilience across California's diverse communities and landscapes. Policies and practices provide guidance for fire hazard prevention and mitigation, disaster preparedness, and emergency response and recovery.
Disaster Preparedness and Safety Element (undated)	California	Presents policies to make developed areas more accessible to emergency vehicles and reliable for evacuation.
Town of Mammoth Lakes General Plan (September 2019)	California	Includes policies that aid emergency evacuation and access to emergency vehicles.
City of Westlake Village General Plan (January 2019)	California	Presents wildfire policies and implementation actions.
Mass Evacuation Plan: City of Malibu (August 2020)	California	Describes evacuation, traffic management and communication strategies to safely and effectively evacuate the community during life-threatening emergencies. Five traffic control plans are included.

Evacuation Modeling

Publication or Project (Date)	Domestic or International	Excerpt From Abstract or Description of Resource
A Spatial Optimization Model for Resource Allocation for Wildfire Suppression and Resident Evacuation (December 2019)	Domestic	Presents an integer two-stage stochastic goal programming model for comprehensive, efficient response to a wildfire including firefighting resource allocation and resident evacuation.
Setting Wildfire Evacuation Triggers by Coupling Fire and Traffic Simulation Models: A Spatiotemporal GIS Approach (September 2018)	Domestic	Couples fire and traffic simulation models to set wildfire evacuation triggers and allow estimates of evacuation time using a traffic simulation model rather than relying on expert judgment.
Scalable Evacuation Routing in a Dynamic Environment (January 2018)	Domestic	Uses a review of evacuation routing algorithms to develop a new algorithm that is faster and can generate better evacuation routes.

Publication or Project (Date)	Domestic or International	Excerpt From Abstract or Description of Resource
Wildfire Evacuation Modeling (2010)	Domestic	Analyzes evacuation route capacity, volume-to-capacity ratio, evacuee destinations, number of cars permitted to evacuate and background traffic to support rapid-response evacuation in wildfire events.
Wildfire Evacuation Scenario in Colorado: Comparison of Adapted Four-Step Metropolitan Planning Organization Modeling Results and Planning Process Findings With Actual Experience (2014)	Domestic	Demonstrates the effectiveness of extensive advance planning, accurate modeled evacuation simulations and traffic control plans in a successful no-notice, mandatory evacuation.
Traffic Modeling for Wildland-Urban Interface Fire Evacuation (March 2019)	International	Shows the importance of dynamic modeling structures that consider behavioral variability and route choice, activity-based models for short-notice evacuation planning, and macroscopic traffic simulation for real-time evacuation management.
e-Sanctuary: Open Multi-Physics Framework for Modelling Wildfire Urban Evacuation (December 2017)	International	Describes a novel framework for modeling wildfire urban evacuations that is based on multi-physics simulations to quantify the evacuation performance. Three components of wildfire urban interface evacuation are considered: fire spread, pedestrian movement and traffic movement.
Joint Evacuation and Emergency Traffic Management Model With Consideration of Emergency Response Needs (2015)	International	Investigates the joint planning of evacuation operations and emergency traffic management while accounting for emergency response needs. A two-stage optimization model uses minimization of total evacuation time and minimization of total network travel time to produce results that address operational needs and enhance overall transportation network performance.

Evacuation Behavior

Publication or Project (Date)	Domestic or International	Excerpt From Abstract or Description of Resource
Understanding California Wildfire Evacuee Behavior and Joint Choice-Making (May 2020)	Domestic	Describes two simple binary choice models to evaluate and compare the factors that influence evacuation decisions and two portfolio choice models that assess multidimensional evacuation choice. A series of evidence-based recommendations are provided for local, regional and state agencies.
Research in Progress: Evacuation Behavior and Its Mobility Impacts in Coastal Communities From Across the Nation	Domestic	Seeks to develop a better understanding of the travel flow principles that govern the evacuation process and their impact on the mobility of a community for different hazard types, including wildfire. Completion date: June 2021.

Publication or Project (Date)	Domestic or International	Excerpt From Abstract or Description of Resource
A Modelling Framework for Householder Decision-Making for Wildfire Emergencies (December 2019)	International	Proposes a mathematical framework aimed at simulating how householders perceive the risk associated to wildfires and how they take protective actions in response to such threats.
Should We Leave Now? Behavioral Factors in Evacuation Under Wildfire Threat (2019)	International	Reviews North American and Australian research into wildfire evacuation behavior factors that influence residents' actions, which can make wildfire evacuation modeling challenging. Researchers suggest ways that authorities might reduce the numbers of residents who delay evacuating following a wildfire warning.
Simulation of Wildfire Evacuation With Dynamic Factors and Model Composition (January 2016)	International	Simulates evacuation response using the IBM Evacuation Planner, a web interface that allows users to run evacuation simulations using environmental variables such as the location and starting time of the fire, the placement and capacity of shelters, and wind velocity.
IBM Evacuation Planner (undated)	International	Describes the tool used to "conduct detailed investigations of hypothetical bushfire scenarios."
A Review on Travel Behaviour Modelling in Dynamic Traffic Simulation Models for Evacuations (2012)	International	Reviews mathematical model formulations underlying traffic simulation models used in evacuation studies and resulting behavioral assumptions. Travelers' decisions regarding the choice to evacuate, departure time choice, destination choice and route choice are predicted through simulation.

Modeling Tools

Publication or Project (Date)	Domestic or International	Excerpt From Abstract or Description of Resource
Evacuations: Wildfire and Emergency Management (2021)	Domestic	Creates custom traffic models for public safety evacuation planning. The software provides traffic flows in relation to fire simulations and the time of their progression; locates potential traffic congestion points; identifies key escape routes and plans for resource allocation; uses population modeling to estimate vehicle and foot traffic; and integrates rich real-time data with remote sensor gathering.
Out of Harm's Way: Enabling Intelligent Location-Based Evacuation Routing (Summer 2012)	Domestic	Describes ArcCASPER (Capacity-Aware Shortest Path Evacuation Routing), a custom ArcGIS Network Analyst tool that uses a state-of-the-art routing algorithm to produce evacuation routes to the nearest safe area for each evacuee or group of evacuees. The algorithm determines realistic traversal speeds for each road segment based on road capacity and number of evacuees, and considers road capacity and travel time to create routes that minimize traffic congestion and evacuation times.
Spatial-computing/CASPER (2021)	Domestic	Discusses the value of CASPER to help city officials, public safety and other emergency departments plan evacuations intelligently and efficiently.
CASPER: Intelligent Capacity-Aware Evacuation Routing (April 2014)	Domestic	Discusses the algorithm's ability to generate reliable and realistic routes and decrease global transportation time by at least an order of magnitude without diminishing performance.
Clarifying Evacuation Options Through Fire Behavior and Traffic Modeling (2011)	Domestic	Presents a case study in which ArcView with Network Analyst was used to evaluate evacuation options during wildfire. Fire growth patterns, road network factors and population characteristics were analyzed to recommend evacuation routes. Time- and distance-based transportation models were also developed to identify preferred and alternate evacuation corridors.
The Simulation of Wildland-Urban Interface Fire Evacuation: The WUI-NITY Platform (April 2021)	International	Provides a platform to enhance situational awareness during evacuation scenarios by coupling modeling layers of the fire, pedestrian and traffic movement to predict evacuation behavior over time.

Related Resources

Publication or Project (Date)	Domestic or International	Excerpt From Abstract or Description of Resource
Evaluating Rural Pacific Northwest Towns for Wildfire Evacuation Vulnerability (2021)	Domestic	Uses a high-resolution spatial data set of wildfire burn probability and mean fireline intensity to conduct a regional-scale screening of wildfire evacuation vulnerability for nearly 700 rural towns in Oregon and Washington.
Mapping Wildfire Evacuation Vulnerability in the Western US: The Limits of Infrastructure (April 2013)	Domestic	Presents an inventory and ranking of the most difficult wildfire-prone areas to evacuate in the West due to constrained egress. Findings suggest that these areas are "prime candidates for emergency planning, and monitoring their development is a growing need."
Evacuation Transportation Modeling: An Overview of Research, Development and Practice (February 2013)	Domestic	Presents a review of highway-based evacuation modeling and simulation, and its evolution over the past decade. The review includes the major components of roadway transportation planning and operations, including the current state of modeling in the forecasting of evacuation travel demand, distribution and assignment of evacuation demand to regional road networks to reach destinations, assignment of evacuees to various modes of transportation, and evaluation and testing of alternative management strategies to increase capacity of evacuation networks or manage demand.
Guidance on Design and Construction of the Built Environment Against Wildland Urban Interface Fire Hazard: A Review (2020)	International	Presents a systematic review of standards, codes and guidelines for the design and construction of the built environment against wildfire urban interface fire hazard from North American, European and Oceanic countries. The discussion includes the influence of land and environmental factors, and road access requirements.
New Approaches to Evacuation Modelling for Fire Safety Engineering Applications (June 2019)	International	Presents an interdisciplinary review of evacuation modeling that includes psychology/human factors, sociology, applied mathematics, transportation, and dynamic simulation and biomechanics.

Detailed Findings

Background

During the Camp Fire in 2018, people using a primary evacuation route to leave the area experienced a significant traffic delay because of recent road improvements that reduced roadway capacity. To avoid similar delays during wildfire events, California Department of Transportation (Caltrans) is interested in using roadway design to facilitate mass emergency evacuations. Modeling potential evacuation routes when developing transportation projects could allow the agency to evaluate the impacts of those road improvements.

Caltrans is investigating the traffic modeling practices used by other state departments of transportation (DOTs) that consider mass emergency evacuations during wildfire events and the impacts of road design standards on highways used as evacuation routes during those events. This information will inform efforts to develop modeling tools and practices that enable highway designers to design projects that facilitate the most efficient evacuation of communities with high fire potential while allowing access by emergency services. In addition, guidance will be developed for managing emergency wildfire evacuation events and how highway design can facilitate evacuation.

Survey of Practice

An online survey was distributed to western and southwestern state DOT members of three American Association of State Highway and Transportation Officials (AASHTO) committees:

- Committee on Design.
- Committee on Planning.
- Committee on Traffic Engineering.

Survey questions are provided in Appendix A. The full text of survey responses is presented in a supplement to this report.

Summary of Survey Results

Transportation agencies from five states responded to the survey:

- Arizona (two responses).
- Idaho.
- Nevada.
- Oregon.
- Utah.

None of these states uses modeling tools and other practices to evaluate potential emergency wildfire evacuation routes when designing road improvements for highways in areas with high fire potential, and none has plans to use modeling tools or other practices. Four respondents provided additional information about this issue:

- *Arizona.* Transportation Systems Management and Operations does not use modeling tools during the design phase because of the capabilities of the agency's Systems Technology Group.
- *Idaho.* The agency uses modeling tools for evacuation routes but doesn't have plans to use them for potential emergency fire evacuation routes, although the respondent noted

this application is “reasonable” and “a good suggestion.” He added that evacuation options are generally few and obvious in the state. But insights could be obtained by modeling potential emergency fire evacuation routes, and the agency will “give it some thought to develop in the near future.”

- *Oregon*. Historically, wildfire has not been an issue in the state, however, events in 2020 “likely changed the priority.” Oregon DOT currently has tools to analyze evacuations for other disasters (such as a chemical plant failure) and a statewide model for analyzing the long-term impacts of large-scale emergencies (such as earthquakes). (*Note*: Oregon State University has performed agent-based modeling for earthquake evacuation.) The respondent noted that these tools are capable of providing information for wildfire evacuations, and the agency has “started conversations around using our tools for wildfire specifically.”
- *Utah*. The agency regularly uses modeling tools to evaluate impacts to diversion routes for construction and emergencies such as crashes, floods, mudslides and bridge hits, but not for wildfire evacuations. To develop these diversion routes, the agency uses probe data, Iteris ClearGuide, radar data, Freeway PeMS (Performance Management System), PTV Vissim modeling software and MAXVIEW for traffic signals. The respondent noted that given Utah DOT’s experience with rerouting traffic for other scenarios, “it would not be difficult to apply the same approaches” to wildfire evacuations.

Supplemental Resources

Utah

Traffic Modeling Guidelines, Utah Department of Transportation, undated.
https://www.udot.utah.gov/connect/business/design/traffic-modeling-guidelines/
From the web page:

> UDOT [Utah DOT] uses PTV Vissim to simulate all modes of traffic operations at various stages of a project including concept, design and construction. As PTV releases new versions of Vissim, UDOT develops an updated base file for consultants to use. These base files include custom vehicles and speed profiles appropriate specifically for Utah.

Data references, including PTV Vissim and Freeway PeMS (which provides public access to point data collected from UDOT’s freeway traffic monitoring stations (loops, microloops and radar)); traffic analysis guidelines; and other modeling information are accessible from this web page.

Related Resources:

> **ClearGuide**, Iteris, undated.
> https://www.iteris.com/products/performance-analytics/clearguide
> *From the web page*: Iteris’ ClearGuide mobility intelligence solution helps city, state, regional and national agencies make the best traffic operations and planning decisions in an intuitive and easy-to-use interface. ClearGuide analyzes large amounts of complex transportation data to produce real-time and historical visualizations that help identify problem areas before traffic congestion worsens.

Intelight MAXVIEW ATMS, Q-Free, undated.
https://www.intelight-its.com/products/intelight-maxview-atms/
From the web page: Q-Free Intelight MAXVIEW ATMS (advanced traffic management system) is a sophisticated tool that delivers an integrated, real-time view of an agency's traffic signal network and ITS [intelligent transportation system] infrastructure. Successfully deployed by 90+ agencies, it is a proven workhorse to help agencies gain control of their entire traffic signal network in a single application.

Performance Measurement System (PeMS), Version 20.1.1, Utah Department of Transportation, undated.
https://udot.iteris-pems.com/
From the web page: The traffic data displayed on the map is collected in real-time from roadway detectors. PeMS is also an Archived Data User Service (ADUS) that provides tools for historical data analysis.

PTV Vissim, PTV Group, undated.
https://www.ptvgroup.com/en/solutions/products/ptv-vissim/
From the web page: PTV Vissim is proven to be the world's standard for traffic and transport planning and for a good reason: It gives you a realistic and detailed overview about the status quo of the traffic flow and impacts, with the possibilities to define multiple what-if scenarios. With our links and connectors concept in PTV Vissim, you can map your network in detail and model different geometries—from a standard node to complex intersections.

Related Research and Resources

A literature search of domestic and international in-progress and published research examined wildfire evacuation route planning and modeling. The literature search also sought information about evacuation behavior. Findings from this literature search are presented below in the following topic areas:

- State guidance and research.
- Evacuation modeling.
- Evacuation behavior.
- Modeling tools.
- Related resources.

State Guidance and Research

Road Design

California

Evacuation Route Design Guidance, Design Information Bulletin 93, Division of Design, California Department of Transportation, December 2020.
https://dot.ca.gov/-/media/dot-media/programs/design/documents/signed-dib-93-evacuation-route-a11y.pdf
From the introduction:

> This Design Information Bulletin (DIB) provides guidance on design procedures and recommendations for developing projects on evacuation routes. The guidance is primarily for rural communities where access to and from the community is limited and where a [s]tate highway will be used as an evacuation route. While the guidance focuses on wildfire evacuation routes, it can be applied to other events that require the evacuation of a community through a limited number of available routes. This guidance should be considered during the project initiation phase when working with local agencies in identifying potential evacuation routes or how a [s]tate highway project on an evacuation route may enhance that route's effectiveness during an emergency. During the Project Approval and Environmental Document (PA&ED) phase, the guidance assists in setting study limits, developing project details, and identifying and balancing elements that serve a dual purpose during normal and emergency operations.

The bulletin addresses a number of road features to consider to facilitate evacuations, including geometric considerations; travel lanes, shoulders and turn lanes; intersections; Complete Streets features; barriers and guardrails; and bridges, tunnels and other structures.

Planning Policies and Practices

California

Fire Hazard Planning Technical Advisory, General Plan Technical Advice Series, Public Review Draft, Governor's Office of Planning and Research, State of California, November 2020.
https://opr.ca.gov/docs/20201109-Draft_Wildfire_TA.pdf
From the introduction:

> The goal of this technical advisory is to provide a robust planning framework for addressing fire hazards, reducing risk and increasing resilience across California's diverse communities

and landscapes. To accomplish this goal, it is essential that local jurisdictions develop and incorporate effective policies and implementation programs in their general plans and integrate their general plans with other relevant hazard and risk reduction policies, plans and programs. This advisory provides guidance on those policies and programs, and is also intended to assist city and county planners in discussions with professionals from fire hazard prevention and mitigation, disaster preparedness, and emergency response and recovery agencies as they work together to develop effective fire hazard policies for the general plan.

Guidance for fire hazard planning policies begins on page 25 of the plan. Case studies featuring planning policies from local jurisdictions begin on page 66 (also see *Related Resources* below).

Related Resources:

Disaster Preparedness and Safety Element, Department of Planning and Development, City of Berkeley, undated.
https://www.cityofberkeley.info/Planning_and_Development/Home/General_Plan_-_Disaster_Preparedness_and_Safety_Element.aspx
Policies are presented to make developed areas more accessible to emergency vehicles and reliable for evacuation, including utility and transportation systems (Policy S-12), fire preventive design standards for structures (Policy S-21) and firefighting infrastructure (Policy S-22).

Town of Mammoth Lakes General Plan, Community and Economic Development Department, Town of Mammoth Lakes, September 2019.
https://www.townofmammothlakes.ca.gov/DocumentCenter/View/9579/General_Plan-Updated-Sep-2019?bidId
Included are policies that aid emergency evacuation and access to emergency vehicles.

City of Westlake Village General Plan, City of Westlake Village, January 2019.
https://www.wlv.org/DocumentCenter/View/1836/WLV-General-Plan
Wildfire policies and implementation actions are presented beginning on page 207 of the PDF.

Mass Evacuation Plan, City of Malibu, August 2020.
https://www.malibucity.org/DocumentCenter/View/26832/FINAL-Evacuation-Plan-8192020
Evacuation, traffic management and communication strategies are presented in this plan to safely and effectively evacuate members of the community during life-threatening emergencies. Five traffic control plans are included (beginning on page 8) that describe the various types of traffic control equipment that may be used and the agencies responsible for implementing each plan.

Evacuation Modeling

Domestic

"A Spatial Optimization Model for Resource Allocation for Wildfire Suppression and Resident Evacuation," Siqiong Zhou and Ayca Erdogan, *Computers and Industrial Engineering*, Vol. 138, December 2019.
Citation at https://www.sciencedirect.com/science/article/abs/pii/S0360835219305704
From the abstract:

This paper presents an integer two-stage stochastic goal programming model for comprehensive, efficient response to a wildfire including firefighting resource allocation and

resident evacuation. In contrast to other natural disasters, the progression of wildfires depends on not only the probabilistic fire-spread scenarios but also decisions made during firefighting. The proposed model optimizes the resource preparations before the fire starts and resource allocation decisions during the fire event. The model takes into account different wildfire-spread scenarios and their impact on high-risk areas. The two objectives considered are minimizing the total cost of operations and property loss and minimizing the number of people at risk to be evacuated. A case study based on Santa Clara County in California, United States of America, is presented to demonstrate the model performance. Numerical experiments show that this model works well to find solutions by considering a trade-off between two objectives; and varying cell size based on scenarios reduces problem dimension and improves solution time.

Below are highlights from the article:

- The model considers residents at risk and resource allocation for wildfires.
- Scenarios consider wind direction, wind speed and humidity.
- Constant problem size regardless of geographical area affected in scenarios.
- Short computation time to solve large-size wildland urban interface (WUI) wildfire cases.
- Experiments demonstrate trade-offs to provide insights to decision-makers.

"Setting Wildfire Evacuation Triggers by Coupling Fire and Traffic Simulation Models: A Spatiotemporal GIS Approach," Dapeng Li, Thomas J. Cova and Philip E. Dennison, *Fire Technology*, Vol. 8, Issue 5, pages 617-642, September 2018.
https://content.csbs.utah.edu/~pdennison/reprints/denn/2019_Li_etal_FT.pdf
From the abstract: Wildfire evacuation triggers refer to prominent geographic features used in wildfire evacuation practices, and when a fire crosses a feature, an evacuation warning is issued to the communities or firefighters in the path of the fire. The existing wildfire trigger modeling methods consider evacuation time as an input from a decision-maker and employ fire spread modeling and GIS to create a trigger buffer around a threatened asset. This paper substantially improves on previous methods by coupling fire and traffic simulation models to set triggers, which allows us to estimate evacuation time using a traffic simulation model rather than relying on expert judgment. Specifically, we propose a three-step method within a spatiotemporal GIS framework to couple these models and to evaluate the value of the generated trigger buffers. The first step uses traffic simulation to estimate the total evacuation time for a threatened community. The second step derives the cumulative probabilities for distinct evacuation times from multiple simulations and generates corresponding probability-based trigger buffers. In the last step, we evaluate the value of the generated buffers by coupling fire and traffic simulation models to examine the spatial configurations of fire perimeters and evacuation traffic. A case study of Julian, California[,] is used to test the proposed method. The results from two evacuation scenarios with different travel demand indicate that a larger trigger buffer (more lead time) will be needed for higher levels of evacuation travel demand. For example, the time required to guarantee that 95% of the evacuating residents arrive at the safe area as a fire approaches a community is estimated at 160 min[utes] for one scenario but 292 min[utes] if the travel demand is doubled. The resulting framework advances the dynamic representation of evacuation traffic in wildfires and improves our understanding of wildfire evacuation timing and decision making. The paper concludes with a discussion of the strengths and limitations of the proposed method, as well as future research directions.

"Scalable Evacuation Routing in a Dynamic Environment," Kaveh Shahabi and John Wilson, *Computers, Environment and Urban Systems*, Vol. 67, pages 29-40, January 2018. https://johnwilson.usc.edu/wp-content/uploads/2018/03/Scalable-evacuation-routing-in-a-dynamic-environment.pdf
From the abstract: Natural disasters can create unpredicted traffic congestion or can temporarily block urban or rural roads. Evacuating a large area in an emergency situation is not possible without prior knowledge of the road network and the ability to generate an efficient evacuation plan. An ideal evacuation routing algorithm should be able to generate realistic and efficient routes for each evacuee from the source to the closest shelter. It should also be able to quickly update routes as the road network changes during the evacuation. For example, if a main road is blocked during a flood, the evacuation routing algorithm should update the plan based on this change in the road network. In this article major works in evacuation routing have been studied and a new algorithm is developed that is faster and can generate better evacuation routes. Additionally, it can quickly adjust the routes if changes in the road network are detected. The new algorithm's performance and running time are reported.

Wildfire Evacuation Modeling, City of Colorado Springs and Pikes Peak Area Council of Governments, 2010.
https://icma.org/sites/default/files/302857_Colorado%20Springs%2C%20CO.pdf
From the introduction:

> Evacuation protocols, communication/notification procedures, evacuation routes and traffic control plans must be established well in advance of actual wildfire events to support rapid-response evacuation of neighborhoods under wildfire threat. Evacuation protocols (e.g., no-entry, evacuation of special populations, etc.) and communication/notification procedures for this plan were established based on local policies and procedures, supported by national standards and experience. Regional simulation analysis was used to develop localized evacuation routes and traffic control plans for the [21] WUI neighborhoods identified by the Colorado Springs Fire Department (CSFD) Wildfire Mitigation Plan. The PPACG [Pikes Peak Area Council of Governments] Travel Model was used to support the regional simulations. PPACG is the designated [m]etropolitan [p]lanning [o]rganization (MPO) for the Colorado Springs Urbanized Area, and the PPACG model is the official MPO travel demand model. The model is used to support federally-mandated transportation and air quality planning. The basic structure and function of the model includes a demand side (traffic defined as internal one to zone trips) and a supply side (the roadway network). The model database includes model year scenarios for 2005, 2010, 2015, 2020, 2025, 2030 and 2035. Within each model year scenario, eight time-of-day submodels represent peak and off-peak travel conditions.

The following factors were considered in the analysis:

- Evacuation route capacity (an hourly carrying capacity of the route roadway segments).
- Volume-to-capacity ratio (to screen evacuation route adequacy based on an evacuation duration target of one hour).
- Evacuee destinations (official shelters, other households in the area, motels or out of the county entirely).
- Number of cars permitted to evacuate.
- Background traffic (p.m. peak hour was used).

Note: A participant in the development of the wildfire evacuation modeling plan cited above (also a co-author of the *Transportation Research Record (TRR)* article cited as a *Related Resource* below) publicly posted the August 2013 TRB Annual Meeting paper submission that was the basis for the *TRR* article.

The full text of the author-submitted TRB conference paper—"The Test of Fire: A Comparison of Adapted Four-Step MPO Modeling Results and Planning Process Findings to Actual Experience"—is available at https://tmip.org/sites/freightmodelimprovementprogram.localhost/files/attachments/TRB%202014_A%20Test%20of%20Fire-Wildfire%20Evacuation%20Modeling_0.pdf.

Related Resource:

"Wildfire Evacuation Scenario in Colorado: Comparison of Adapted Four-Step Metropolitan Planning Organization Modeling Results and Planning Process Findings With Actual Experience," Maureen Paz de Araujo, Mary R. Lupa, Craig T. Casper and Bret Waters, *Transportation Research Record 2430*, Issue 1, 2014.
Citation at https://journals.sagepub.com/doi/10.3141/2430-14
From the abstract: In late 2010, the City of Colorado Springs and the Pikes Peak Area Council of Governments in Colorado completed a cooperative wildfire evacuation planning process. The process was supported by the simulation of wildfire evacuation scenarios with an adaptation of the Council of Governments' four-step travel model. The adapted model was used to assess times to evacuate, identify choke points and develop traffic control plans for identified at-risk neighborhoods. Evacuation simulations used a worst-case scenario in which the wildfire event took place during the p.m. peak traffic hour, and affected households were included in both background commuter traffic and neighborhood evacuation traffic. Link-based hourly volume-to-capacity ratios were used as a metric to estimate times to evacuate and to identify egress bottlenecks. Route closures, route restrictions, no-entry restrictions and contraflow operations were evaluated as measures for inclusion in neighborhood-level traffic control plans. On Tuesday, June 26, 2012, the simulated worst case became reality. More than 34,000 persons were evacuated during the event, including 26,000 during the 6-h[our] period between 15:30 and 21:30. Before the wildfire was fully contained, 18,247 acres had burned, 347 homes and other structures had been destroyed, and two people had died. That the no-notice, mandatory evacuation was as successful as it was can be attributed to extensive advance planning, the accuracy of modeled evacuation simulations, and the effectiveness of the final traffic control plans. This study examined how the model results were borne out by actual experience. Recommendations to improve no-notice evacuation planning from the perspective of lessons learned are presented.

International

"Traffic Modeling for Wildland-Urban Interface Fire Evacuation," Paolo Intini, Enrico Ronchi, Steven Gwynne and Adam Pel, *Journal of Transportation Engineering, Part A: Systems*, Vol. 145, Issue 3, pages 1-15, March 2019.
https://pdfs.semanticscholar.org/2879/ca4ce7adfd1957388945150c3536ecca7425.pdf?_ga=2.64267755.572904345.1614117955-1496768185.1610660331
From the abstract: Several traffic modeling tools are currently available for evacuation planning and real-time decision support during emergencies. This paper reviews potential traffic-

modeling approaches in the context of wildland-urban interface (WUI) fire-evacuation applications. Existing modeling approaches and features are evaluated pertaining to fire-related, spatial and demographic factors; intended application (planning or decision support); and temporal issues. This systematic review shows the importance of the following modeling approaches: dynamic modeling structures, considering behavioral variability and route choice; activity-based models for short-notice evacuation planning; and macroscopic traffic simulation for real-time evacuation management. Subsequently, the modeling features of 22 traffic models and applications currently available in practice and the literature are reviewed and matched with the benchmark features identified for WUI fire applications. Based on this review analysis, recommendations are made for developing traffic models specifically applicable to WUI fire evacuation, including possible integrations with wildfire and pedestrian models.

e-Sanctuary: Open Multi-Physics Framework for Modelling Wildfire Urban Evacuation, Enrico Ronchi, Steven Gwynne, Guillermo Rein, Rahul Wadhwani, Paolo Intini and Albin Bergstedt, Fire Protection Research Foundation, December 2017.
https://nfpa.org/-/media/Files/News-and-Research/Fire-statistics-and-reports/WUI/RFWUIEvacuationModelingFramework.ashx
From the abstract:

> The present work describes a novel framework for modelling wildfire urban evacuations. The framework is based on multi-physics simulations that can quantify the evacuation performance. The work argues that an integrated approached requires considering and integrating all three important components of WUI evacuation, namely: fire spread, pedestrian movement and traffic movement. The report includes a systematic review of each model component and the key features needed for the integration into a comprehensive toolkit.

A review of traffic models is presented in Section 5.4 (page 186 of the report) and Appendix 3 (page 317 of the report). Additional details about vehicle transport models for the simulation of WUI fire evacuation is provided in Appendix 4 (page 368 of the report).

"Joint Evacuation and Emergency Traffic Management Model With Consideration of Emergency Response Needs," Maria Konstantinidou, Konstantinos Kepaptsoglou, Matthew Karlaftis and Antony Stathopoulos, *Transportation Research Record 2532*, pages 107-117, 2015.
Citation at https://journals.sagepub.com/doi/10.3141/2532-13
From the abstract: This study investigates the joint planning of evacuation operations and emergency traffic management while accounting for emergency response needs. Extended wildfires across a highway network are the assumed disaster setting. Population evacuation takes place by using part of the network, whereas emergency traffic management strategies are applied outside the evacuation zone. Network performance enhancement is pursued through the implementation of lane reversal. The problem is formulated as a two-stage optimization model; minimization of total evacuation time (TET) and minimization of total network travel time (TNTT) are the upper-level objectives for the evacuation area and the rest of the network, respectively. The lower level corresponds to a traffic assignment model on the basis of user equilibrium. Demonstration of the model on a real-world network proves the computational efficiency of the algorithm. The model systematically produces robust results in terms of TET-TNTT minimization and thus addresses the operational needs arising and enhances overall transportation network performance.

Evacuation Behavior

Domestic

Understanding California Wildfire Evacuee Behavior and Joint Choice-Making, Stephen D. Wong, Jacquelyn C. Broader, Joan L. Walker and Susan A. Shaheen, Transportation Sustainability Research Center, May 2020.
https://escholarship.org/content/qt4fm7d34j/qt4fm7d34j_noSplash_1c947cbcaa8da177fead87b982ce2c1b.pdf
From the abstract: For evacuations, people must make the critical decision to evacuate or stay followed by a multidimensional choice composed of concurrent decisions of their departure time, transportation mode, route, destination and shelter type. These choices have important impacts on transportation response and evacuation outcomes. While extensive research has been conducted on hurricane evacuation behavior, little is known about wildfire evacuation behavior. To address this critical research gap, particularly related to joint choice-making in wildfires, we surveyed individuals impacted by the 2017 December Southern California Wildfires (n=226) and the 2018 Carr Wildfire (n=284). Using these data, we contribute to the literature in two key ways. First, we develop two simple binary choice models to evaluate and compare the factors that influence the decision to evacuate or stay. Mandatory evacuation orders and higher risk perceptions both increased evacuation likelihood. Individuals with children and with higher education were more likely to evacuate, while individuals with pets, homeowners, low-income households, long-term residents and prior evacuees were less likely to evacuate. Second, we develop two portfolio choice models (PCMs), which jointly model choice dimensions to assess multidimensional evacuation choice. We find several similarities between wildfires including a joint preference for within-county and nighttime evacuations and a joint dislike for within-county and highway evacuations. To help build a transportation toolkit for wildfires, we provide a series of evidence-based recommendations for local, regional and state agencies. For example, agencies should focus congestion reducing responses at the neighborhood level within or close to the mandatory evacuation zone.

Research in Progress

Evacuation Behavior and Its Mobility Impacts in Coastal Communities From Across the Nation, Office of the Assistant Secretary for Research and Technology, U.S. Department of Transportation, start date: July 2020, expected completion date: June 2021.
Project description at https://rip.trb.org/view/1740687
From the project description: Several recent evacuations have occurred in the [United States]. Hurricane evacuations have been ordered in the state of Florida while wildfires and impending dam failures have led to evacuations in the state of California. It has generally been accepted that the evacuation from a regional hurricane is fundamentally different than the evacuation from a wildfire. Hurricane evacuations generally encompass larger areas when compared to wildfire evacuations and provide several days of advanced warning[,] [w]hereas, wildfires impact smaller areas with significantly shorter warning time. However, at the broadest level, evacuees and their vehicles move in both time and space. This research seeks to develop a better understanding of the travel flow principles that govern the evacuation process and its impact on the mobility of a community for different hazard types. This knowledge can be leveraged to better plan for and respond to evacuations, regardless of the event.

International

"A Modelling Framework for Householder Decision-Making for Wildfire Emergencies," Ruggiero Lovreglio, Erica Kuligowski, Steve Gwynne and Ken Strahan, *International Journal of Disaster Risk Reduction*, Vol. 41, December 2019.
Citation at
https://www.sciencedirect.com/science/article/abs/pii/S221242091930041X?via%3Dihub
From the abstract: In this paper, we propose a mathematical framework aimed at simulating how householders perceive the risk associated to wildfires and how they take protective actions in response to such threats. A conceptual Wildfire Decision Model, based on nine assumptions derived from existing literature on human behaviour in wildfires, is introduced. A mathematical framework is then proposed to implement such a model within a simulation tool. The proposed modelling solution can help identify the information required to generate new dynamic and behavioural travel demand models for wildfire evacuation.

"Should We Leave Now? Behavioral Factors in Evacuation Under Wildfire Threat," Jim McLennan, Barbara Ryan, Chris Bearman and Keith Toh, *Fire Technology*, Vol. 55, pages 487-516, 2019.
Citation at https://link.springer.com/article/10.1007/s10694-018-0753-8
From the abstract: This paper reviews North American and Australian research into wildfire evacuation behavior published between January 2005 and June 2017. Wildfire evacuation policies differ across the two regions: [I]n North America mandatory evacuations are favored, in Australia most are advisory. Research from both regions indicates that following a wildfire evacuation warning some threatened residents will wish to remain on their property in order to protect it, many will delay evacuating, and some residents who are not on their property when an evacuation warning is issued may seek to return. Mandatory evacuation is likely to result in greater compliance[;] enforcement policies are also likely to be influential. Self-delayed evacuation is likely if warnings are not sufficiently informative: [R]esidents are likely to engage in information search rather than initiating evacuation actions. The wildfire warning and threat histories of a location may influence residents' decisions and actions. The complexities of behavioral factors influencing residents' actions following an evacuation warning pose challenges for wildfire evacuation modeling. Suggestions are offered for ways in which authorities might reduce the numbers of residents who delay evacuating following a wildfire warning.

"Simulation of Wildfire Evacuation With Dynamic Factors and Model Composition," Anton Beloglazov, Mahathir Almashor, Ermyas Abebe, Jan Richter and Kent Charles Barton Steer, *Simulation Modelling Practice and Theory*, Vol. 60, pages 144-159, January 2016.
Full-text author preprint available at https://beloglazov.info/papers/2016-smpt-wildfire-evacuation.pdf
From the abstract:

> Wildfires cause devastation on communities, most significantly loss of life. The safety of at-risk populations depends on accurate risk assessment and emergency planning. Evacuation modelling and simulation systems are essential tools for such planning and decision making. During a wildfire evacuation, the behaviour of people is a key factor; what people do, and when they do it, depends heavily on the spatio-temporal distribution of events in a scenario. In this paper, we introduce an approach that enables the behaviour of people and the timing of events to be explicitly modelled through what we term dynamic factors. Our approach composes several simulation and modelling systems, including a wildfire simulator, behaviour modeller, and microscopic traffic simulator, to compute detailed projections of how scenarios unfold. The level of detail provided by our modelling approach

enables the definition of a new risk metric, the exposure count, which directly quantifies the threat to a population. Experiments for a wildfire-prone region in Victoria, Australia, resulted in statistically significant differences in clearance times and exposure counts when comparing our modelling approach to an approach that does not account for dynamic factors. The approach has been implemented in a high performance and scalable system—the architecture of which is discussed—that allows multiple concurrent scenarios to be simulated in timeframes suitable for both planning and response use cases.

Evacuation response is simulated using the IBM Evacuation Planner, a web interface that allows users to run evacuation simulations using environmental variables such as the location and starting time of the fire, the placement and capacity of shelters, and wind velocity.

Related Resource:

IBM Evacuation Planner, IBM Research, IBM, undated
https://researcher.watson.ibm.com/researcher/view_group.php?id=4709
From the web page: IBM Evacuation Planner makes it possible to conduct detailed investigations of hypothetical bushfire scenarios. Through these scenarios users can assess the impact of a bushfire at multiple levels; from a broad region down to individuals. Furthermore, with our scenario building tools users can quantify and compare the effectiveness of various risk mitigation strategies.

Behind the scenes we employ state-of-the-art modeling and simulation subsystems to predict the spread of the fire, the behaviour of the population and the flow of traffic throughout the evacuation. Together these systems fill in the blanks for evacuation planners. ….

Current configuration options include ignition points, wind speed and direction, fire danger index [and] shelters/evacuation [centers]. Results include dynamic fire spread, dynamic traffic conditions, regional clearance times, regional egress times, regional departure profiles [and] at-risk individual identification.

"A Review on Travel Behaviour Modelling in Dynamic Traffic Simulation Models for Evacuations," Adam J. Pel, Michiel C. J. Bliemer and Serge P. Hoogendoorn, *Transportation*, Vol. 39, pages 97-123, 2012.
https://link.springer.com/article/10.1007/s11116-011-9320-6
From the abstract: This contribution reviews the different (mathematical) model formulations underlying these traffic simulation models used in evacuation studies and the behavioural assumptions that are made. The appropriateness of these behavioural assumptions is elaborated on in light of the current consensus on evacuation travel behaviour, based on the view from the social sciences as well as empirical studies on evacuation behaviour. The focus lies on how travellers' decisions are predicted through simulation regarding the choice to evacuate, departure time choice, destination choice and route choice. For the evacuation participation and departure time choice we argue in favour of the simultaneous approach to dynamic evacuation demand prediction using the repeated binary logit model. For the destination choice we show how further research is needed to generalize the current preliminary findings on the location-type specific destination choice models. For the evacuation route choice we argue in favour of hybrid route choice models that enable both following instructed routes and en-route switches. Within each of these discussions, we point at current limitations and make corresponding suggestions on promising future research directions.

Modeling Tools

Domestic

Evacuations: Wildfire and Emergency Management, Simtable, 2021.
https://www.simtable.com/emergency-management/evacuations/
From the web page: The Simtable Evacuation module creates agent-based models of your local populations. Households can show the probability of occupancy, number of residents and multiple vehicles. Demographics can include retiree, tourist/visitor and school-aged populations. ….

Agent drivers navigate the road network based on their knowledge of the incident and of the roadways. Our approach allows for emergent congestion patterns and heterogeneous driver behavior. Similar models can be adapted for pedestrian evacuations from special events, festivals and large sporting matches.

Let Simtable create custom traffic models to help you with your public safety evacuation planning.

- See traffic flows in relation to fire simulations and the time of their progression.
- Locate potential traffic congestion points.
- Identify key escape routes and plan for resource allocation.
- Use population modeling to estimate vehicle and foot traffic.
- Integrate rich real-time data with remote sensor gathering.

"Out of Harm's Way: Enabling Intelligent Location-Based Evacuation Routing," Kaveh Shahabi, *ArcUser*, Summer 2012.
https://www.esri.com/news/arcuser/0612/files/arcasper.pdf
From the article: Traditionally, evacuation planners use either simulation software (like agent-based modeling) or basic shortest path routing methods to predict and visualize emergency situations. The results are relatively static, one-size-fits-all evacuation plans.

ArcCASPER (Capacity-Aware Shortest Path Evacuation Routing) is a custom [ArcGIS] Network Analyst tool that uses a state-of-the-art routing algorithm to produce evacuation routes to the nearest safe area for each evacuee or group of evacuees. The CASPER algorithm determines realistic traversal speeds for each road segment based on road capacity and number of evacuees. It intelligently and dynamically takes into account road capacity and travel time to create routes that minimize traffic congestion and evacuation times.

Developed as an evacuation routing extension to ArcGIS Network Analyst, ArcCASPER is available from the ArcGIS Resource Center. [*Note*: It appears that ArcCASPER is no longer available through the Esri web site. See *Related Resources* below for another access point.] The Network Analyst extension handles management of the transportation network dataset and computation of road attributes. Visualization of input points and final routes is done through ArcMap. ArcCASPER provides its three routing methods (shortest path, capacity constrained route planner [CCRP] and CASPER) as additional options to the standard Network Analyst capabilities.

Note: The January 2018 journal article "Scalable Evacuation Routing in a Dynamic Environment" (see page 16) explores the use of CASPER (see page 3 of the article for the citation). More CASPER-related resources are cited below.

Related Resources:

Spatial-computing/CASPER, GitHub, Inc., 2021.
https://github.com/spatial-computing/CASPER
From the web site: The CASPER project is a plug-in for Esri ArcGIS Desktop to do evacuation routing.
….

CASPER (Capacity-Aware Shortest Path Evacuation Routing) is a custom Network Analyst tool that uses a state-of-the-art routing algorithm to produce evacuation routes to the nearest safe area for each evacuee or group of evacuees. It is an innovative new ArcGIS tool that can help city officials, public safety and other emergency departments to perform evacuation planning more intelligently and efficiently.

"CASPER: Intelligent Capacity-Aware Evacuation Routing," Kaveh Shahabi and John P. Wilson, *Computers, Environment and Urban Systems*, Vol. 46, pages 12-24, April 2014.
https://johnwilson.usc.edu/wp-content/uploads/2018/03/CASPER-Intelligent-capacity-aware-evacuation-routing.pdf
From the abstract: We propose a new method to perform urban routing efficiently under capacity constraints. This new method helps with evacuation routing as well as other urban transportation challenges. Traditionally, simulation software or shortest path routing combined with zonal scheduling have been used to solve routing problems. Our method utilizes a state-of-the-art algorithm to connect each source node to its nearest destination. It also intelligently takes into account transportation network capacity and traffic flow to minimize congestion and systemwide transportation times. We have compared our method with previous routing algorithms and a common simulation method. We show that our algorithm generates reliable and realistic routes and decreases global transportation time by at least an order of magnitude, without any loss of performance.

"Clarifying Evacuation Options Through Fire Behavior and Traffic Modeling," Carol L. Rice, Ronny J. Coleman and Mike Price*, Proceedings of the Second Conference on the Human Dimensions of Wildland Fire*, pages 104-111, 2011.
https://www.nrs.fs.fed.us/pubs/gtr/gtr-nrs-p-84papers/14rice-p-84.pdf
From the abstract: Communities are becoming increasingly concerned with the variety of choices related to wildfire evacuation. We used ArcView with Network Analyst to evaluate the different options for evacuations during wildfire in a case study community. We tested overlaying fire growth patterns with the road network and population characteristics to determine recommendations for evacuation routes. We were able to develop time- and distance-based transportation models to identify preferred and alternate evacuation corridors. We also defined and applied network accumulation models to inventory, queue and route evacuees using private and public transportation via the safest and fastest routes, without overloading the transportation system. The output from this type of modeling can be used as a decision support tool. Knowing the pace of the evacuation provides decision-makers with information about the

consequences of timing the decision to evacuate. The analysis can also quantify the effect of including additional residences or neighborhoods on the total evacuation time. This analysis makes it possible to identify information that is of vital importance to communities, such as specific routes and intersections that are appropriate and effective for evacuation and others that should be avoided.

International

"The Simulation of Wildland-Urban Interface Fire Evacuation: The WUI-NITY Platform," Jonathan Wahlqvist, Enrico Ronchi, Steven M.V. Gwynne, Max Kinateder, Guillermo Rein, Harry Mitchell, Noureddine Benichou, Chunyun Ma, Amanda Kimball and Erica Kuligowski, *Safety Science*, Vol. 136, April 2021.
https://www.sciencedirect.com/science/article/pii/S0925753520305415
From the abstract: The purpose of this platform is to enhance the situational awareness of responders and residents during evacuation scenarios by providing information on the dynamic evolution of the emergency. WUI-NITY represents current and predicted conditions by coupling the three key modelling layers of wildfire evacuation, namely[,] the fire, pedestrian and traffic movement. This allows predictions of evacuation behaviour over time. The current version of WUI-NITY demonstrates the feasibility and advantages of coupling the modelling layers. Its wildfire modelling layer is based on FARSITE, the pedestrian layer implements a dedicated pedestrian response and movement model, and the traffic layer includes a traffic evacuation model based on the Lighthill-Whitham-Richards model. The platform also includes a sub-model called PERIL that designs the spatial location of trigger buffers. The main contribution of this work is in the development of a modular and model-agnostic (i.e., not linked to a specific model) platform with consistent levels of granularity (allowing a comparable modelling resolution in the representation of each layer) in all three modelling layers.

Related Resources

Domestic

"Evaluating Rural Pacific Northwest Towns for Wildfire Evacuation Vulnerability," Alex Dye, John Kim, Andrew McEvoy, Fang Fang and Karin Riley, *Natural Hazards*, Vol. 107, pages 911-935, 2021.
Citation at https://link.springer.com/article/10.1007/s11069-021-04615-x
From the abstract: In this paper, we leverage a high-resolution spatial data set of wildfire burn probability and mean fireline intensity to conduct a regional-scale screening of wildfire evacuation vulnerability for 696 Oregon and Washington rural towns. We characterize each town's surrounding road network to construct four simple road metrics related to the potential to quickly and safely evacuate: (1) the number of paved lanes leaving town that intersect a fixed-distance circular buffer; (2) the variety of lane directions available for egress; (3) the travel area that can be reached within a minimum distance while constrained only to movement along the paved road network; and (4) the sum of connected lanes at each intersection for the road network within a fixed-distance circular buffer. We then combine the road metrics with two metrics characterizing fire hazard of the surrounding landscape through which evacuation will occur: (1) burn probability and (2) mean fireline intensity. By combining the road and fire metrics, we create a composite score for ranking all towns by their overall evacuation vulnerability. The most vulnerable towns are those where poor road networks overlap with high fire hazard. Often, these towns are located in remote, forested, mountainous terrain, where topographic relief constrains the available road network and high fuel loads increase wildfire hazard.

"Mapping Wildfire Evacuation Vulnerability in the Western US: The Limits of Infrastructure," Thomas Cova, David Theobald, John B. Norman and Laura K. Siebeneck, *GeoJournal*, Vol. 78, Issue 2, pages 273-285, April 2013.
Publication available at
https://www.researchgate.net/publication/226074609_Mapping_wildfire_evacuation_vulnerability_in_the_western_US_The_limits_of_infrastructure
From the abstract: The goal of this research is to perform a comprehensive geographic search of the western U.S. for communities in wildfire-prone areas that may represent difficult evacuations due to constrained egress. The problem is formulated as a spatial search for fire-prone communities with a high ratio of households-to-exits and solved using methods in spatial optimization and geographic information systems (GIS). The results reveal an initial inventory and ranking of the most difficult wildfire evacuations in the West. These communities share a unique vulnerability in that all residents may not be able to evacuate in scenarios with short warning time. For this reason they represent prime candidates for emergency planning, and monitoring their development is a growing need.

"Evacuation Transportation Modeling: An Overview of Research, Development and Practice," Pamela Murray-Tuite and Brian Wolshon, *Transportation Research Part C: Emerging Technologies*, Vol. 27, pages 25-45, February 2013.
Citation at
https://www.sciencedirect.com/science/article/abs/pii/S0968090X12001386?via%3Dihub
From the abstract: This paper presents a review of highway-based evacuation modeling and simulation and its evolution over the past decade. The review includes the major components of roadway transportation planning and operations, including the current state of modeling in the forecasting of evacuation travel demand, distribution and assignment of evacuation demand to regional road networks to reach destinations, assignment of evacuees to various modes of transportation, and evaluation and testing of alternative management strategies to increase capacity of evacuation networks or manage demand. Although this discussion does not cover recent work in other modes used in evacuation such as air, rail and pedestrian, this paper does highlight recent interdisciplinary modeling work in evacuation to help bridge the gap between the behavioral sciences and engineering and the application of emerging techniques for the verification, validation and calibration of models. The manuscript also calls attention to special considerations and logistical difficulties, which have received limited attention to date. In addition to these concerns, the following future directions are discussed: further interdisciplinary efforts, including incorporating the medical community; using new technologies for communication of warnings and traffic condition information, data collection, and increased modeling resolution and confidence; using real-time information; and further model refinements and validation.

International

"Guidance on Design and Construction of the Built Environment Against Wildland Urban Interface Fire Hazard: A Review," Paolo Intini, Enrico Ronchi, Steven Gwynne and Noureddine Benichou, *Fire Technology*, Vol. 56, pages 1853-1883, 2020.
https://link.springer.com/article/10.1007/s10694-019-00902-z#Sec29
From the abstract: This work presents a wide systematic review of standards, codes and guidelines for the design and construction of the built environment against WUI fire hazard from North American, European [and] Oceanic countries, alongside with transnational codes. The main information reviewed includes the definition of WUI hazards, risk areas and related severity classes, the influence of land and environmental factors, the requirements for building

materials, constructions, utilities, fire protection measures and road access. Some common threads among the documents reviewed have been highlighted. They include similar attempts at (a) defining WUI risk areas and severity classes, (b) considering land factors including the defensible space (also known as ignition zones), [and] (c) prescribing requirements for buildings and access. The main gaps highlighted in the existing standards/guidelines include lack of detailed and widespread requirements for resources, fire protection measures and lack of taking into account environmental factors in detail. The main design and construction principles contained in the reviewed documents are largely based on previous research and/or good practices. Hence, the main contributions of this paper consist in (a) systematically disseminat[ing] these guidance concepts, (b) setting a potential basis for the development of standards/guidelines in other jurisdictions lacking dedicated WUI fire design guidance, [and] (c) highlighting gaps in existing standards/guidelines to be addressed by current and future research.

"New Approaches to Evacuation Modelling for Fire Safety Engineering Applications," Enrico Ronchi, Alessandro Corbetta, Edwin Galea, Max Kinateder, Erica Kuligowski, Denise McGrath, Adam Pel, Youssef Shiban, Peter Thompson and Federico Toschi, *Fire Safety Journal*, Vol. 106, pages 197-209, June 2019.
Citation at https://www.sciencedirect.com/science/article/abs/pii/S0379711218305526
This article presents findings from the New Approaches to Evacuation Modelling workshop at the June 2017 Symposium of the International Association for Fire Safety Science. *From the abstract*:

> The workshop gathered international experts in the field of fire evacuation modelling from 19 different countries and was designed to build a dialogue between the fire evacuation modelling world and experts in areas outside of fire safety engineering. The contribution to fire evacuation modelling of five topics within research disciplines outside fire safety engineering (FSE) have been discussed during the workshop, namely 1) [p]sychology/[h]uman [f]actors, 2) [s]ociology, 3) [a]pplied [m]athematics, 4) [t]ransportation, 5) [d]ynamic [s]imulation and [b]iomechanics. The benefits of exchanging information between these two groups are highlighted here in light of the topic areas discussed and the feedback received by the evacuation modelling community during the workshop. This included the feasibility of development/application of modelling methods based on fields other than FSE as well as a discussion on their implementation strengths and limitations. Each subject area is here briefly presented and its links to fire evacuation modelling are discussed.

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Appendix A: Survey Questions

The following survey was distributed to members of the American Association of State Highway and Transportation Officials (AASHTO) Committee on Design, Committee on Planning and Committee on Traffic Engineering.

Survey on Traffic Modeling of Potential Emergency Wildfire Evacuation Routes

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Note: The response to the question below determined how a respondent was directed through the survey.

(Required) Does your agency use modeling tools and other practices to evaluate potential emergency wildfire evacuation routes when designing road improvements for highways in areas with high fire potential?

Response Options:

- No, and we have no plans to do so. (Directed the respondent to **the Agencies Not Modeling Wildfire Evacuation Routes** section of the survey.)
- No, but we have plans to do so. (Directed the respondent to the **Agencies Considering Modeling Wildfire Evacuation Routes** section of the survey.)
- Yes, we use tools to evaluate impacts to these evacuation routes. (Directed the respondent to the **Agencies Modeling Wildfire Evacuation Routes** section of the survey and the sections that follow it.)

Agencies Not Modeling Wildfire Evacuation Routes

Please briefly describe why your agency is not using modeling tools during the design phase to evaluate impacts to potential emergency wildfire evacuation routes.

Note: After responding to the question above, the respondent was directed to the **Wrap-Up** section of the survey.

Agencies Considering Modeling Wildfire Evacuation Routes

Please briefly describe your agency's discussions, research or plans to use modeling tools during the design phase to evaluate impacts to potential emergency wildfire evacuation routes.

Note: After responding to the question above, the respondent was directed to the **Wrap-Up** section of the survey.

Agencies Modeling Wildfire Evacuation Routes

Modeling Tools

1. Please provide the name of the traffic modeling or other tool(s) your agency uses to evaluate potential emergency wildfire evacuation routes and briefly describe how each tool is used.
    - Tool 1 Name:
    - Tool 1 Vendor (if applicable):

- Tool 1 Use:
- Tool 2 Name:
- Tool 2 Vendor (if applicable):
- Tool 2 Use:
- Tool 3 Name:
- Tool 3 Vendor (if applicable):
- Tool 3 Use:

2. What data sources supply the data needed for the modeling tool(s)?
3. On how many road improvement projects has your agency used one or more modeling tools to examine emergency wildfire evacuation routes?
4. Please briefly describe how the use of the modeling tool(s) affected the design choices your agency made to the following elements of a roadway improvement project on an emergency wildfire evacuation route.
    - Nonstandard geometric features
    - Barriers and guardrails
    - Bridges, tunnels and structures
    - Clear recovery zones and horizontal clearances
    - Complete Streets features
    - Intersections
    - Shoulders
    - Signs
    - Traffic signals
    - Travel lanes
    - Turn lanes
    - Other (Please describe.)

Evaluating Human Behavior

(Required) Has your agency evaluated the evacuation behavior (evacuation likelihood, evacuation choices, departure time) of the people impacted by wildfire and used those results to inform design choices on roadway improvement projects?

- No (Directed the respondent to the **Other Practices** section of the survey.)
- Yes (Directed the respondent to the **Evaluating Human Behavior** section of the survey.)

Evaluating Human Behavior

1. In what situations do residents choose to shelter in place versus evacuate?
2. What are the factors that influence that behavior, such as communities that have livestock that need to be protected or transported?
3. Are certain groups more or less likely to evacuate (families with children versus elderly)?
    - No
    - Yes (Please identify these groups and their likelihood of evacuation.)
4. Are residents more likely to evacuate if they know there is a road that supports the demand?
    - No
    - Yes

Other Practices

1. How does your agency identify designated or anticipated emergency evacuation routes in areas where the fire potential is high?
2. To supplement modeling results, does your agency conduct any outreach to gather additional information about potential emergency wildfire evacuation routes?
    - No
    - Yes (Please describe this outreach.)
3. Please describe any other practices your agency has employed to inform design choices for road improvements on highways that are expected to serve as emergency wildfire evacuation routes.

Assessment and Recommendations

1. What successes has your agency experienced when using modeling to evaluate impacts to emergency wildfire evacuation routes?
2. What has been particularly challenging for your agency when using modeling to evaluate impacts to emergency wildfire evacuation routes?
3. What are your top three recommendations for other agencies considering the use of modeling when designing road improvements on emergency wildfire evacuation routes?
    - Recommendation 1
    - Recommendation 2
    - Recommendation 3
4. Please provide links to documents associated with your agency's use of modeling during the design of road improvements on emergency wildfire evacuation routes. Send any files not available online to carol.rolland@ctcandassociates.com.

Wrap-Up

Please use this space to provide any comments or additional information about your previous responses.