Wildfire Evacuation Simulator Considering Social Vulnerability Factors

MIMS Capstone Project Spring 2021

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1. Executive Summary

1.1 Background

The alarming increases in wildfire frequency and intensity in California bring into question the effectiveness of evacuation plans in situations of unprecedented fire danger. Examining the disastrous 2018 Camp Fire in Paradise, CA reveals that evacuation plans and assessments based purely on historical experiences can result in strategies that simply cannot match the demands of unprecedented fire danger.[1]

Regardless of efforts from the responsible organizations, there are multiple problems in conventional methods of disaster preparation as follows:

- **Unpredictability**: Evacuation plans made without sufficient empirical inputs (e.g., factors relating to the disaster and human behaviors) may not work given the many unforeseen factors that can occur during an extreme event. For instance, in a wildfire, the speed and direction of fire/smoke, and the dynamic behavior of the local community, etc. can be beyond what has been prepared for.

[1] https://www.latimes.com/local/california/la-me-camp-fire-deathtrap-20181230-story.html

- **Cost and resource limitations:** Organizing real evacuation drills can be disruptive and resource consuming.
- **Community Awareness:** Engaging with the community to keep them informed of disaster response and recovery processes can be difficult. It can also be difficult to track how informed a community is to begin with.

Further, it is interesting to note that the traditional approaches to assessing wildfire risk focus on biophysical indicators such as fuel and weather conditions, potentially obscuring the specific challenges experienced by vulnerable communities in the event of environmental disaster. Although research on the specific risks that vulnerable communities face in the event of wildfires is limited, existing research has shown that natural disasters can disparately damage such communities. For example, research by Davies et al. uncovered racial and ethnic disparities in wildfire risks to communities, with census tracts that "were majority Black, Hispanic or Native American experiencing ca. 50% greater vulnerability to wildfire compared to other census tracts.[2]"

The increasing urgency for more robust wildfire preparedness combined with the lack of attention paid to the specific challenges vulnerable communities face during wildfires led us to build a wildfire evacuation simulation tool that incorporates social vulnerability factors. This tool, built using Woodacre, CA (a small town in Marin County) as the pilot site, would ideally be used to facilitate the assessment and planning of evacuation strategies in various wildfire scenarios, while also considering the social makeup of the location.

[2] "The unequal vulnerability of communities of color to wildfire - PLOS." 2 Nov. 2018, https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0205825. Accessed 6 May. 2021.

Project Goals and Outcomes

Our project includes two main components:

- A traffic simulation tool for the evacuation planners at Woodacre that can factor in social vulnerability factors
- An educational web page explaining the motivations for including social vulnerability considerations when evaluating wildfire risk

The **traffic simulation tool** provides visual simulations of road network traffic activity during various evacuation scenarios. It also allows users to alter different parameters that affect evacuation behavior, including the direction of fire, number of cars per household, evacuation compliance rate, time of evacuation notice, and incorporating social vulnerability metrics. The tool would also output a graphic summary tracking how many cars successfully evacuated at various times during the evacuation.

The **educational web page** is meant to educate users about the importance of considering human-centered factors during wildfire risk assessment and evacuation planning. It includes a number of static and interactive visualizations to facilitate understanding.

A **key differentiating facto**r of our solution is its application of an environmental justice perspective to wildfire evacuation. This is important as socially vulnerable groups may experience additional difficulties in these circumstances.

Target Audience

Our tool is mainly targeted towards public safety agencies at various levels of government (e.g., Cal Fire, local fire departments and policy makers) for better preparedness in the event of a large-scale evacuation. All first responders - law enforcement, fire services and emergency medical services - are directly benefited from our fire evacuation tool and information visualizations to make better decisions to ensure safe evacuation under various dynamic conditions. The audience for the educational web page, however, is designed to allow the general public to understand it.

2. Research and Design

2.1 Defining Problems

We began the project by conducting problem space research to understand the practices and attendant challenges of preparing for and responding to wildfire evacuation in California. To do this, we conducted a literature review of research relating to wildfire evacuation and held needfinding meetings with stakeholders invested in wildfire preparedness and response.

2.1.1 Interviews with Stakeholders

For our needfinding meetings, we interviewed five individuals with knowledge of different aspects of wildfire response including three firefighters (a fire chief, deputy fire chief, and battalion fire chief) in Northern California; the director of resident services at an affordable housing agency in Santa Rosa; and a postdoctoral researcher at the University of California, Berkeley with expertise in traffic modeling for evacuation scenarios. Some of our guiding research questions in these meetings were:

- Who are the people involved in responding to and reacting to fires?
- How do residents living in high risk zones receive information?
- What are common evacuation protocols? How much do they vary by town or region?

The interview guides for these meetings can be found in the appendix. These conversations revealed the following key findings around wildfire evacuation:

- Most evacuation planning happens when firefighters and other emergency response officials confront rapidly escalating incidents. Pre-incident planning aids are generally static informational artifacts such as county-wide mapbooks.
- Although firefighters have historically relied on training and familiarity with their areas of service to make informed decisions about evacuation, there is a growing recognition of the opportunities afforded by technology for access to data that can increase response time and efficacy. Many of these technologies are still, however, in the nascent stages of development.
- In planning for evacuations, fire chiefs must account for the road network of their communities. For example, to prevent traffic back-ups on two-lane highways commonly found in rural areas of California, first responders implement contraflow lane reversals to increase the speed of evacuation.
- Senior citizens may face additional challenges when adapting to wildfire risks because they may not have ready transportation or support systems in place in the event of evacuation. Seniors may also be less connected technologically, which reduces the probability of receiving alerts about wildfire threats, or they may not have a plan in place for evacuation.

- Evacuation alerts may only be shared in English, which poses issues for residents for whom English is not their primary language.
- Firefighters recognize that different social factors may affect evacuation response among residents, but there are currently few tools or systematic means for identifying these vulnerabilities within a community.

2.1.2 Review of Existing Solutions and Literature

Beloglazov et al[3] introduce a comprehensive approach to modeling wildfire evacuation scenarios enabling emergency services to better understand, plan and prepare for wildfires. Traditional approaches don't adequately account for what this paper deems as dynamic factors. They define dynamic factors as "the events connecting the evolution of fire to the warnings issues, and consequently to the actions of people and evacuation outcomes". These factors are accounted for using an end-to-end workflow consisting of a wildfire simulator, warning generator, behaviour model, traffic simulator, and analytics engine. Based on these factors, they also introduce a new metric, exposure count, which represents the number of vehicles that were near the fire during the evacuation. Further, the approach introduced in this paper has been implemented in IBM Evacuation Planner which is offered as a Software as a Service(Saas) system to stakeholders.

[3] "Simulation of Wildfire Evacuation.. - IBM Research" https://researcher.watson.ibm.com/researcher/files/au1-kent.steer/techreport-AU-8-4-2015.pdf Accessed 6 May. 2021.

Traditional approaches to assessing wildfire risk focus on biophysical indicators such as fuel and weather conditions, but this approach obscures the specific challenges experienced by vulnerable communities in the event of environmental disaster. Davies et al.[4] addressed this gap by examining wildfire vulnerability from an environmental justice perspective that explored relationships between race, geography, and wildfire (2018). Their research uncovered racial and ethnic disparities in wildfire risks to communities, with census tracts that "were majority Black, Hispanic or Native American experiencing ca. 50% greater vulnerability to wildfire compared to other census tracts" (Davies et al., 2015).

Dulebenets et al[5] identify factors influencing the driving ability of individuals under emergency evacuation and the occurrence of crashes along the evacuation routes. Additionally, apart from considering factors like driver and traffic flow characteristics, this study also investigates the effects of a wide range of different factors (including driver characteristics, evacuation route characteristics, driving conditions, and traffic characteristics) on the major driving performance indicators under emergency evacuation. The results they obtained indicated that age, gender, visual disorders, number of lanes, and space headway may substantially impact the driving ability of individuals throughout the emergency evacuation process. Given that a significant percentage of the population of Woodacre can be considered to be vulnerable since approximately 46% of the population is 65 years of age, we found this study to be very helpful in building our model.

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[4] "The unequal vulnerability of communities of color to wildfire - PLOS." 2 Nov. 2018, https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0205825. Accessed 3 May. 2021.
[5] "Development of statistical models for improving ... - ScienceDirect." https://www.sciencedirect.com/science/article/abs/pii/S095183201830437X. Accessed 3 May. 2021.

For the traffic simulation model, we have drawn inspiration from the agent-based macroscopic traffic simulation model built by Zhao et al[6] for the city of San Francisco which enables real-time decisions in response to natural disasters or disruptive events. The traffic simulation described here is designed to balance the abstractions and details in modelling with the goal of achieving efficient city-scale analysis. The simulation is conducted under the agent-based modelling (ABM) framework, where traffic is intuitively simulated as the movements and interactions between large numbers of agents, each representing an individual vehicle. The ABM allows individual characters to be incorporated, enabling the inclusion of complex human behaviour observed in the real world . However, agent mobility is based on the simplified assumption of volume-delay relationship between macroscopic variables (flow and average speed). This simplification allows simulation to be carried out more efficiently to suit the needs of real-time modelling, forecast and decision making. This model uses a cleaned network from the OpenStreetMap and the agent-level disaggregate travel demand from travel surveys with aggregated data. Further, the traffic modelling framework is presented after implementing an efficient priority-queue based Dijkstra algorithm.

Existing Tools

Many small towns in California are actively reaching out to its residents regarding wildfire risks. Apart from the traditional verbal or written ways of communication, we are seeing a few companies providing services for visual communication. These include

- ***Zonehaven*** uses intelligent algorithms and data-driven methods to draw real-time evacuation zones that minimizes the fire risk or traffic congestion during the evacuation.

[6] "Agent-Based Model (ABM) for City-Scale Traffic ... - ICE Virtual Library." https://www.icevirtuallibrary.com/doi/full/10.1680/icsic.64669.203. Accessed 3 May. 2021.

However, it seems to be a one-way, top-down approach that is more applicable during the evacuation process, rather than a planning and preparation tool.

- ***Santa Fe Simtable*** uses a sandbox exercise to show the fire evacuation process. Currently, it is mainly a tool to train emergency responders and firefighters and does not seem to have the resident behavior element.

2.1.3 Location Selection

We choose to focus on Woodacre as a case study because of the following reasons:

- Populated areas in Woodacre have, on average, greater wildfire likelihood than 76% of communities in California.
- A significant percentage of the population of Woodacre can be considered to be vulnerable since approximately 46% of the population being above 65 years of age
- Woodacre's population size and road network posed favorable conditions for modeling, compared to other site locations. The small size of town was also suitable for mesoscopic traffic modelling, in which we want to control finer details about individuals' behavior.

2.2 Design Iterations

Based on research we conducted through stakeholder interviews and literature review, we identified the following opportunities:

- Although emergency planners increasingly recognize the need to plan for wildfire evacuations, technologies for modeling different types of fire scenarios are not widely used. The technologies that do exist fail to account for the differing needs and behaviors of socially vulnerable populations within a community. To address this gap, we propose

building a **traffic evacuation simulator** that could serve as a proof of concept for including social vulnerability as a factor within the model.

- We also saw an opportunity to use **information visualization** to help educate users of the traffic simulator of the importance of taking a human-centered approach to pre-disaster planning. This would help spread awareness of risk differentials across communities in California that might otherwise be obscured when examining wildfire hazard from a purely biophysical standpoint.

2.2.1 Evacuation Simulator

User Flow & Concept Testing

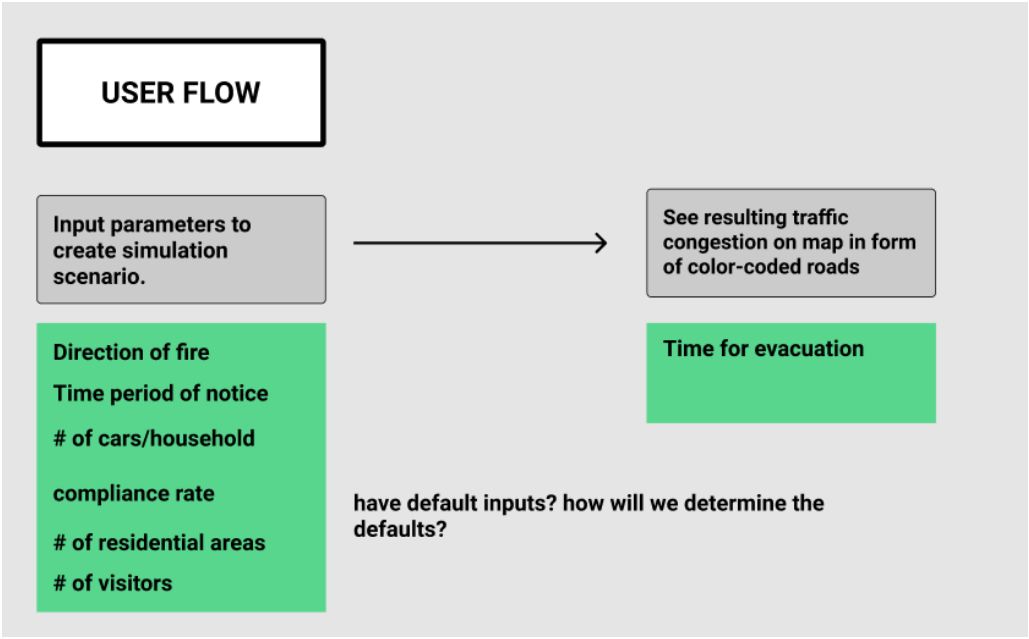

Fig 1 - Early user flow for evacuation simulator

We began the design process by drafting a simple user flow with potential inputs and outputs for the traffic simulator. These initial parameters were largely guided by what was technically

feasible, but we knew we needed user input to understand the types of information that would be valuable for our intended audience. To do this, we conducted concept testing with a fire chief by showing him an image representing the idea of a traffic simulator and gathering feedback on what he found useful and not useful about potential features.

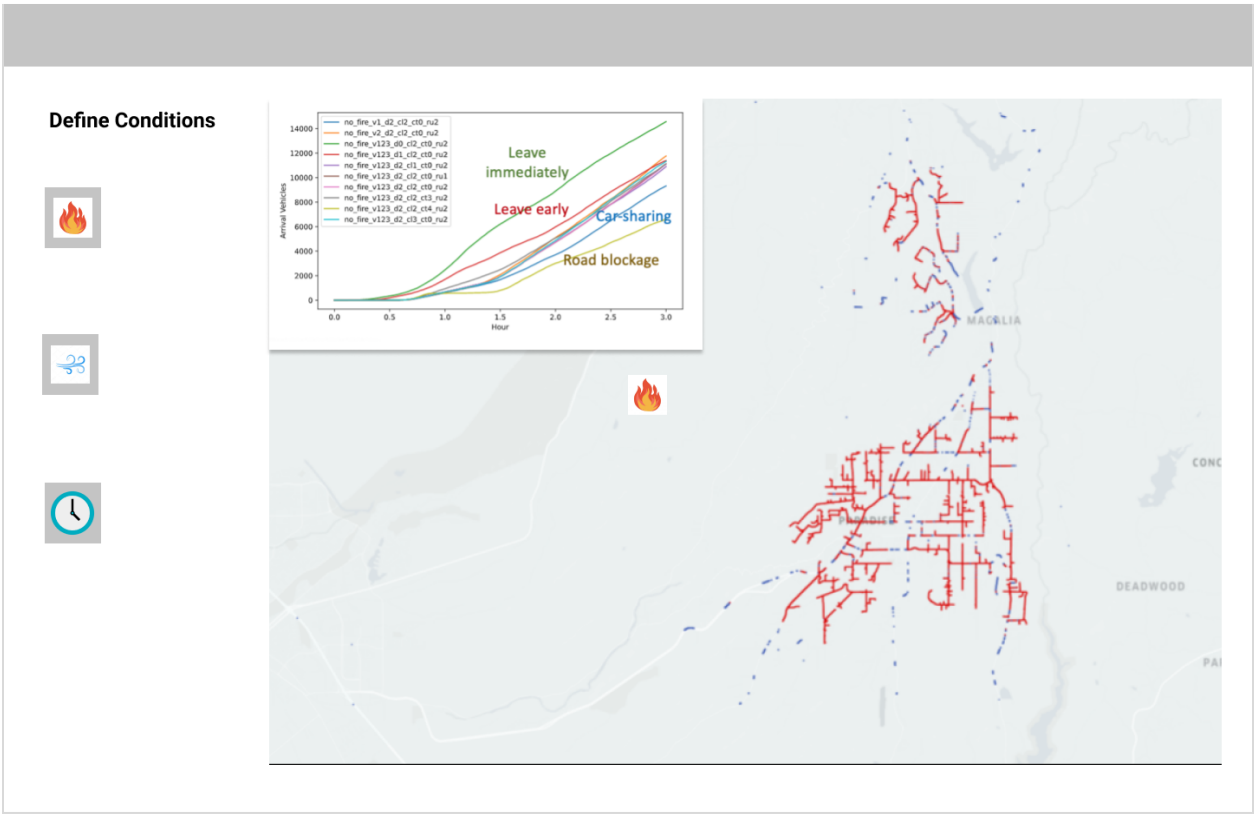

Fig 2 - Image used for concept testing

Key takeaways from this session were:

- It would be helpful to be able to simulate different scenarios and understand the time necessary to evacuate a community.
- It would be helpful for the simulator to recognize social-demographic factors that may impact evacuation.

Parallel Prototyping to Create Low-Fidelity Designs

Once we validated the idea for our design through the concept test, we proceeded to develop low-fidelity sketches for the input and output interfaces. We took a parallel prototyping approach to generate a greater diversity of ideas (Dow et al., 2011)[7]. Three group members created low-fidelity designs separately before reconvening as a group to share their work.

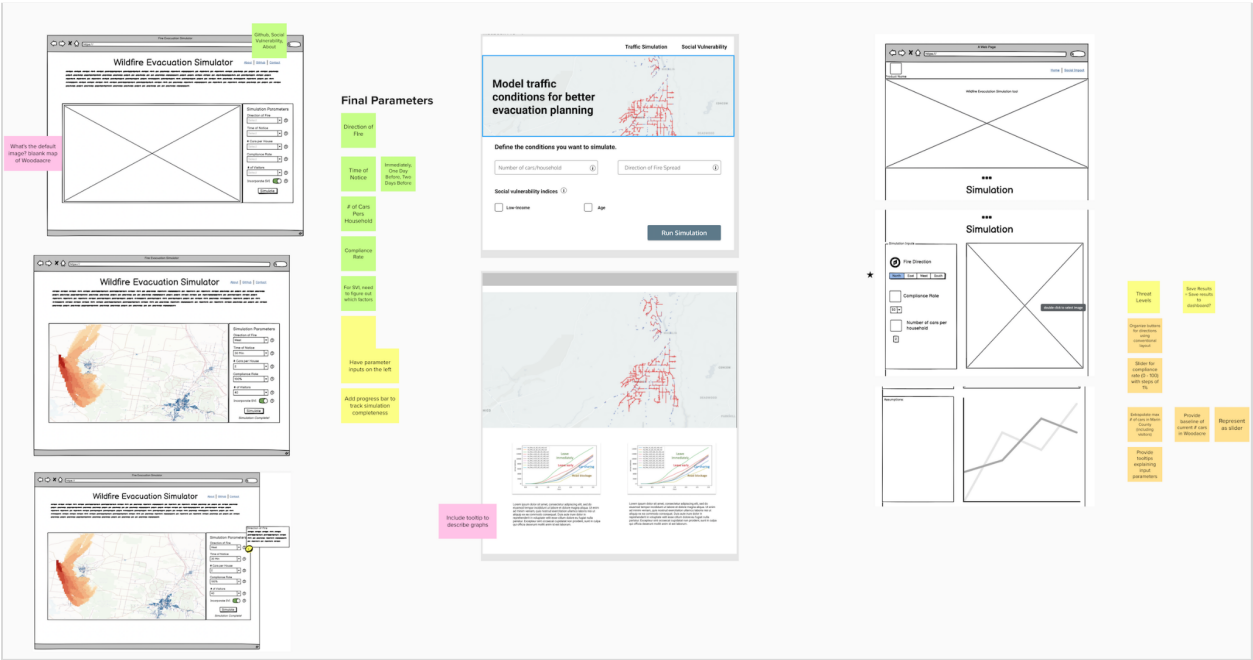

Fig 3 - Mural canvas containing three different designs and comments documenting ideas for convergence.

After discussing the different design variations, we incorporated the ideas we liked the best into one prototype. This version of the design included a banner image that provided immediate information to the viewer about the topic of the site, explanatory text about the traffic simulator, a panel for input parameters to the left of the map, and a progress bar that would provide the user with information about the status of the simulation as it was being generated.

[7] Dow, S., Fortuna, J., Schwartz, D., Altringer, B., Schwartz, D., & Klemmer, S. (2011, May). Prototyping dynamics: sharing multiple designs improves exploration, group rapport, and results. In Proceedings of the SIGCHI conference on human factors in computing systems (pp. 2807-2816)

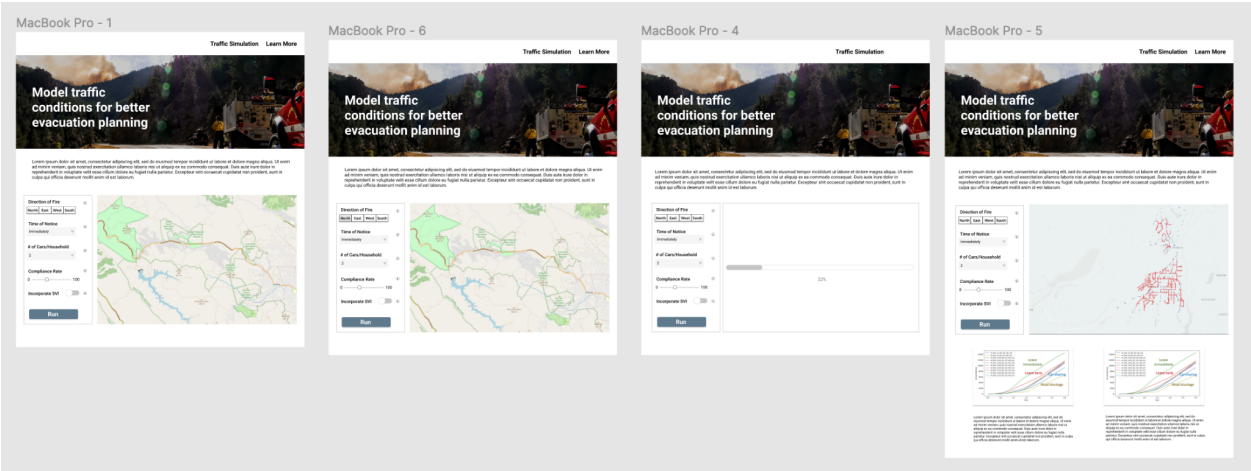

Fig 4 - Medium fidelity prototype incorporating ideas from our three initial designs.

Final Web Application Design

For the initial design of the web application, we mostly replicated the medium fidelity prototype using front end web development tools. After integrating the front end design with the backend, we conducted three usability tests with the fully functional web application to gauge (1) If input parameters were legible/understandable to users (2) how users might interact with traffic simulator (3) how users might interpret traffic simulation visualization (4) If the results were interpretable. The usability tests were conducted with experts who had some experience with the wildfire space but not necessarily wildfire evacuation simulations. The key takeaways from the tests included:

- It would be helpful to have more context about what the tool does with simple, concise and clear messaging.
- It would be helpful to make the simulations and results more interpretable with the following:
    - Proper and clear labeling
    - Effective color coding to clear identify the roadblocks

    - Including a compass and scale in the map
- It would be helpful to compare results across different simulations and especially between a simulation without social vulnerability factors and one with them.

Based on the takeaways, we iterated on the initial web application design to come up with the final design as shown below:

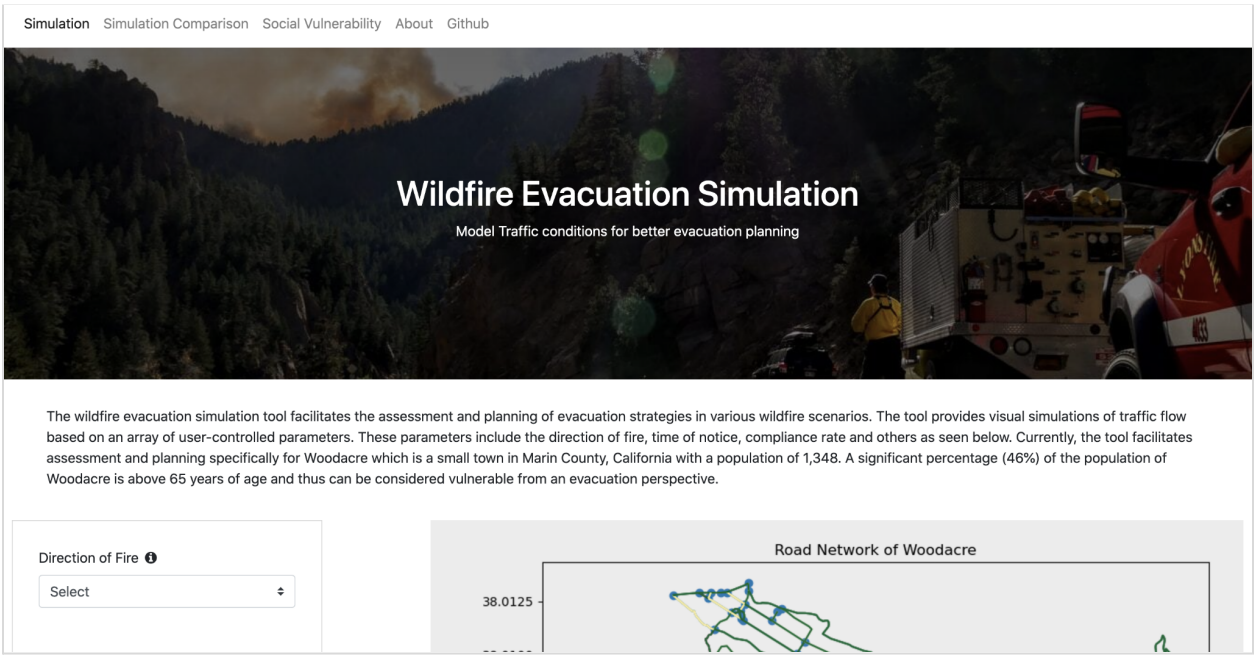

Fig 5 - Final website design landing page main section

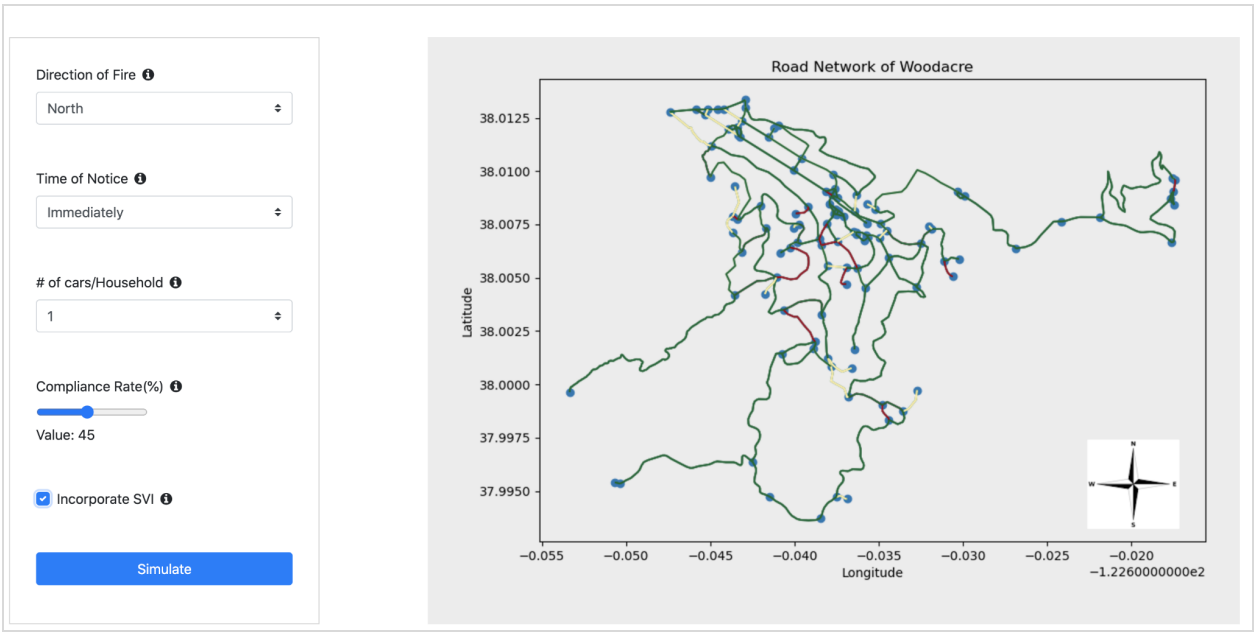

Fig 6 - Final website design input and simulation section

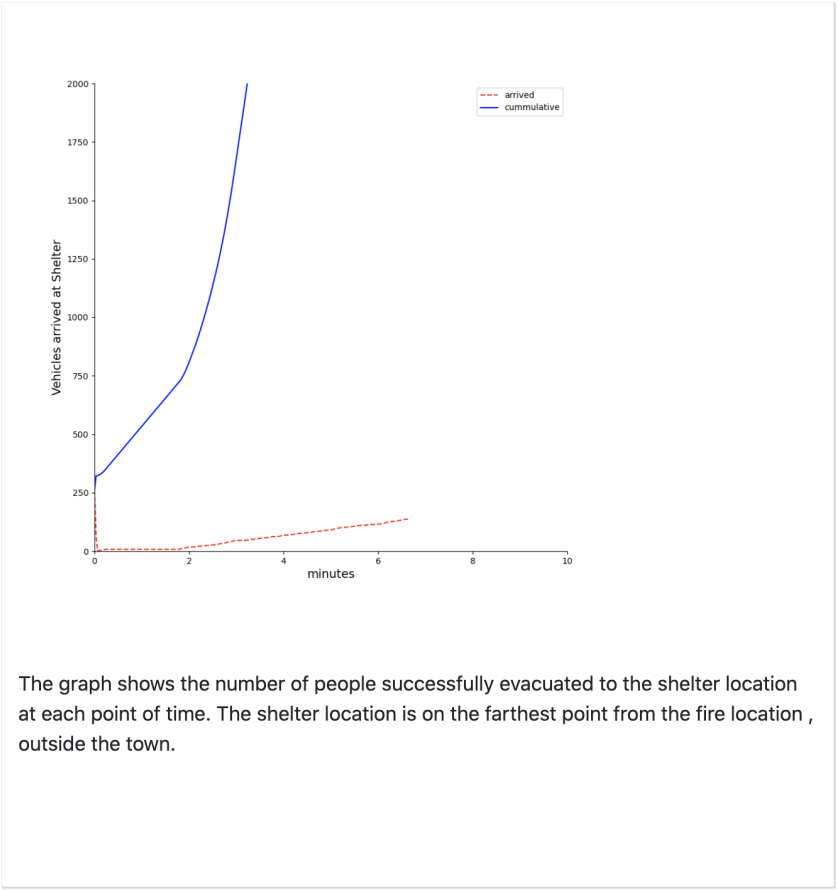

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Fig 7 - Final website design results section

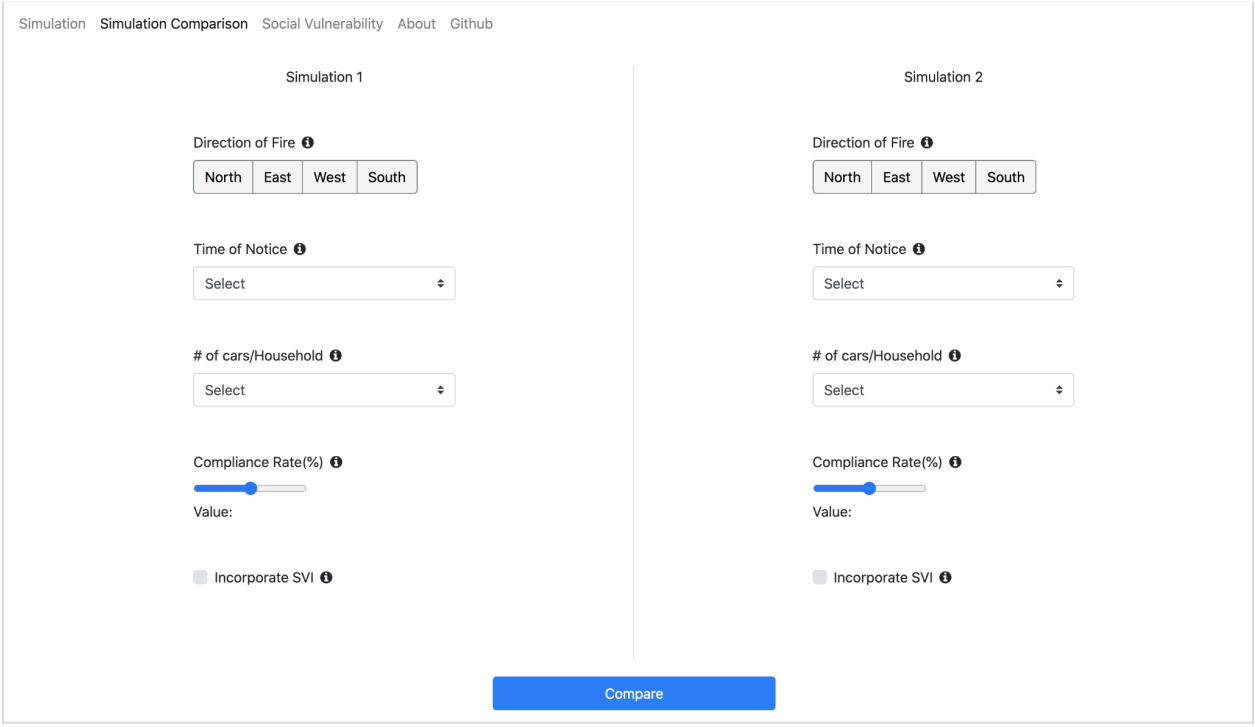


Fig 8 - Final website design comparison page

2.2.2 Educational Web Page

We began the design process for the educational web page by conducting exploratory data analysis of a data set used by Davies et al. (2018) to better understand which regions of California appear to have their wildfire risk the most accentuated by social vulnerability and identify which vulnerability traits seem to carry the most weight in affecting said risk. In conducting this analysis, we created choropleths and scatter plots in Tableau that served as initial designs for some of the visualizations on the web page.

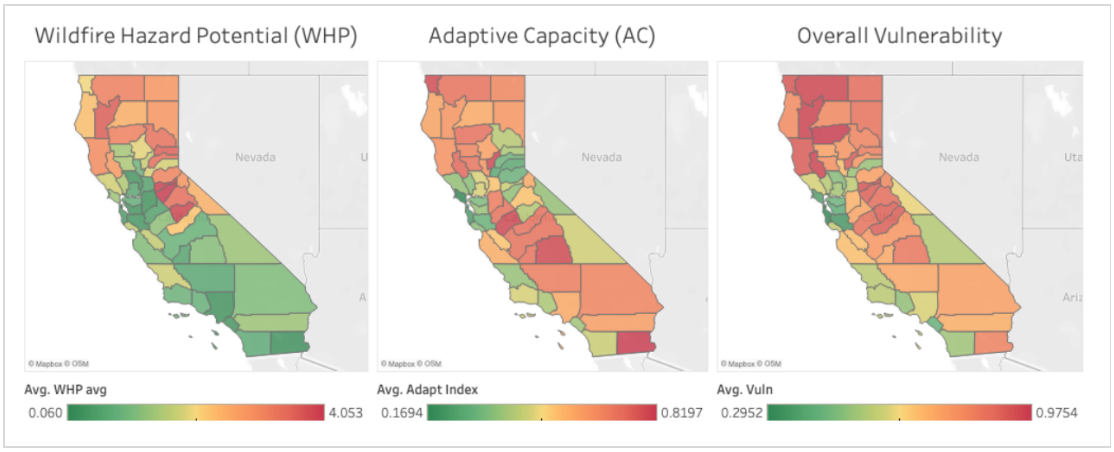


Fig 9 - Choropleths of Wildfire Hazard Potential (WHP), Adaptive Capacity, and Overall Vulnerability

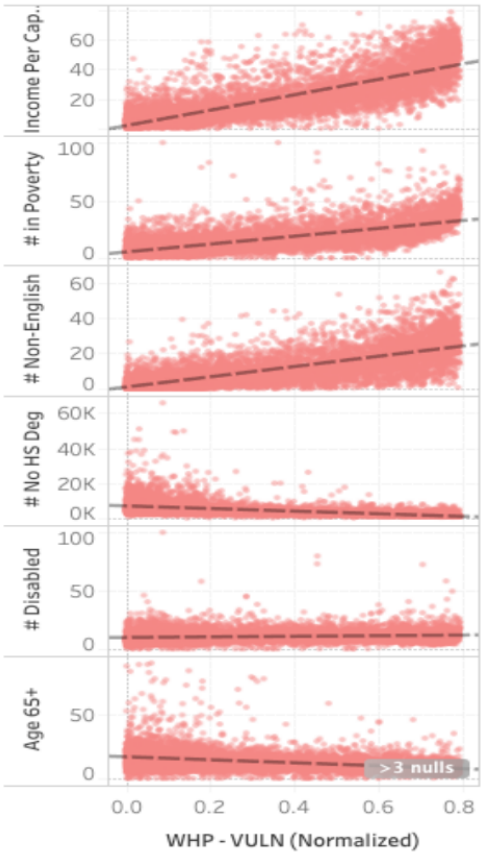


Fig 10 - Scatter plots relating vulnerability metrics

After this initial analysis, we began prototyping versions of the design that incorporated storytelling. We created an infographic that highlighted statistics relating specific vulnerabilities experienced by certain populations in Northern California in previous fires.

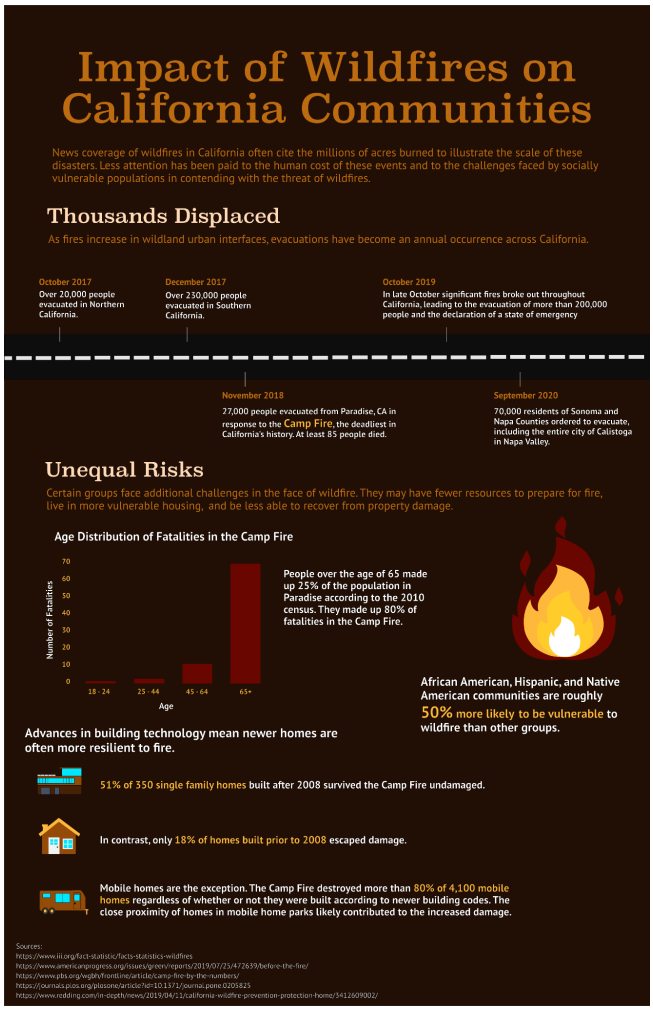


Fig 11 - First iteration of infographic

Fellow students and a graduate student instructor in Marti Hearst's class on information visualization helped conduct a heuristic evaluation of the design. They provided the following feedback, which informed our final website design:

- Increase the size of the housing unit icons

- Using isotypes of the housing units might help us tell a better visual story and reduce the amount of text

We incorporated this feedback into an updated version of the design, which included isotypes of the housing icons and improved color contrast and highlighting of key text.

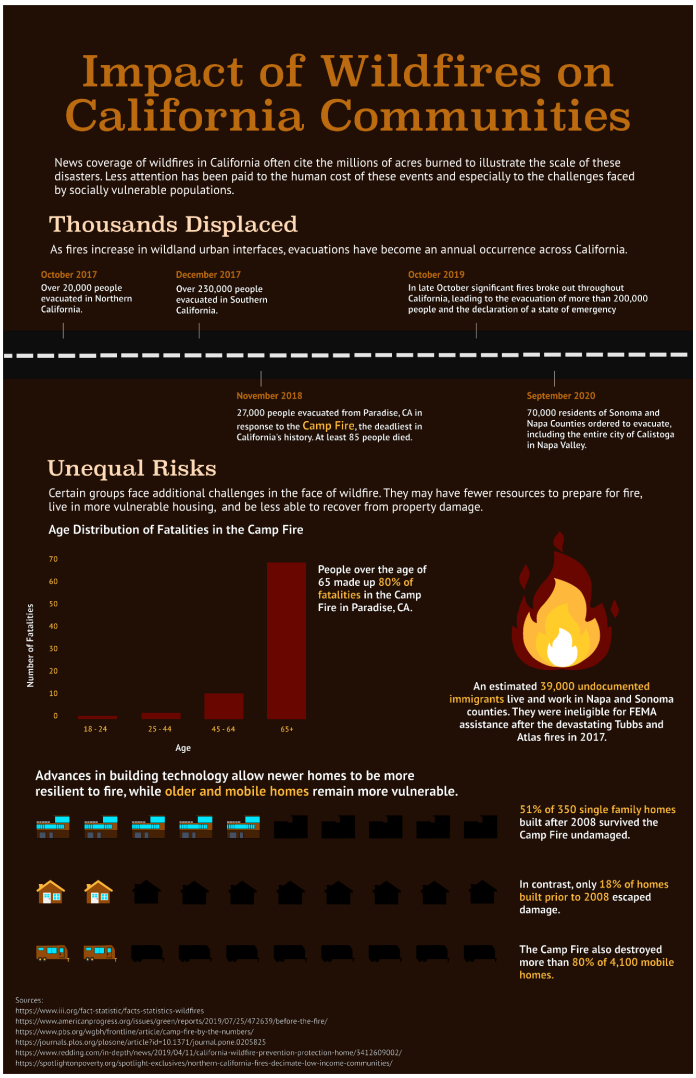


Fig 12 - Second iteration of infographic

We also used the Story feature within Tableau to pair select visualizations with accompanying text. This allowed us to introduce key concepts communicated by the choropleths and provide additional context for how to interpret these indices.

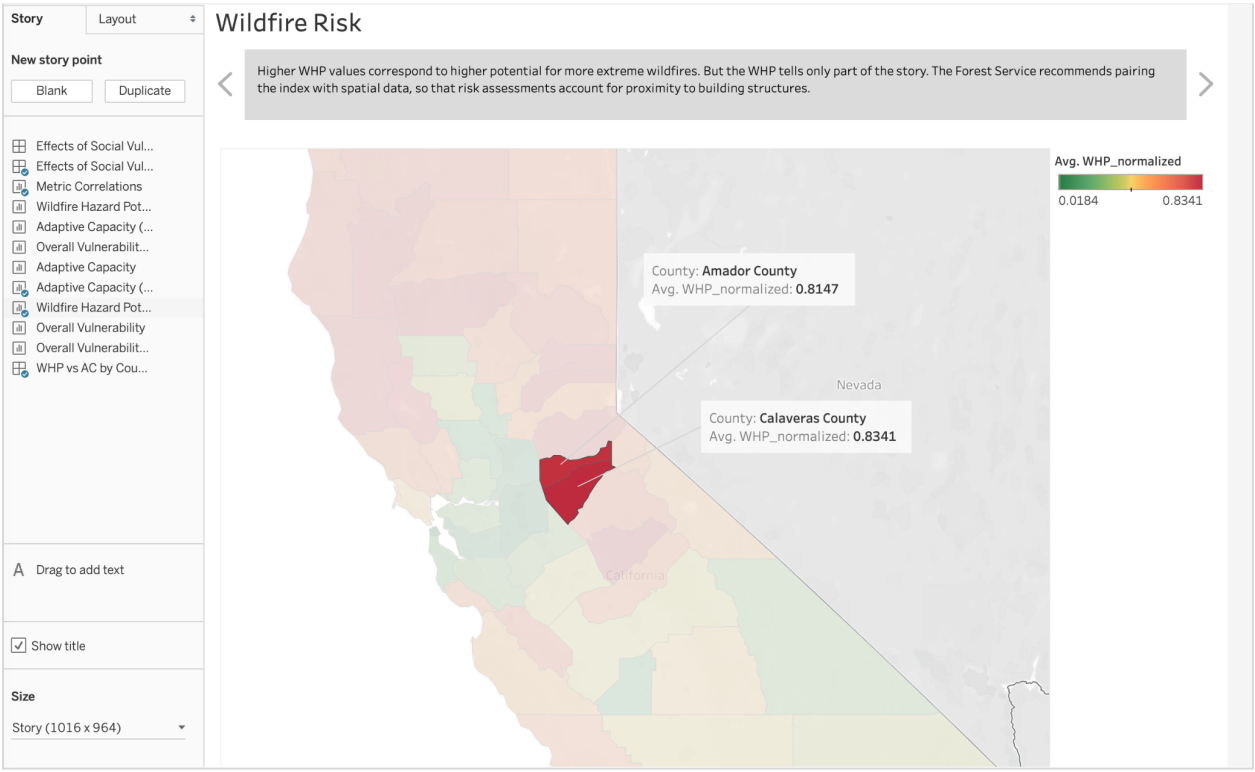
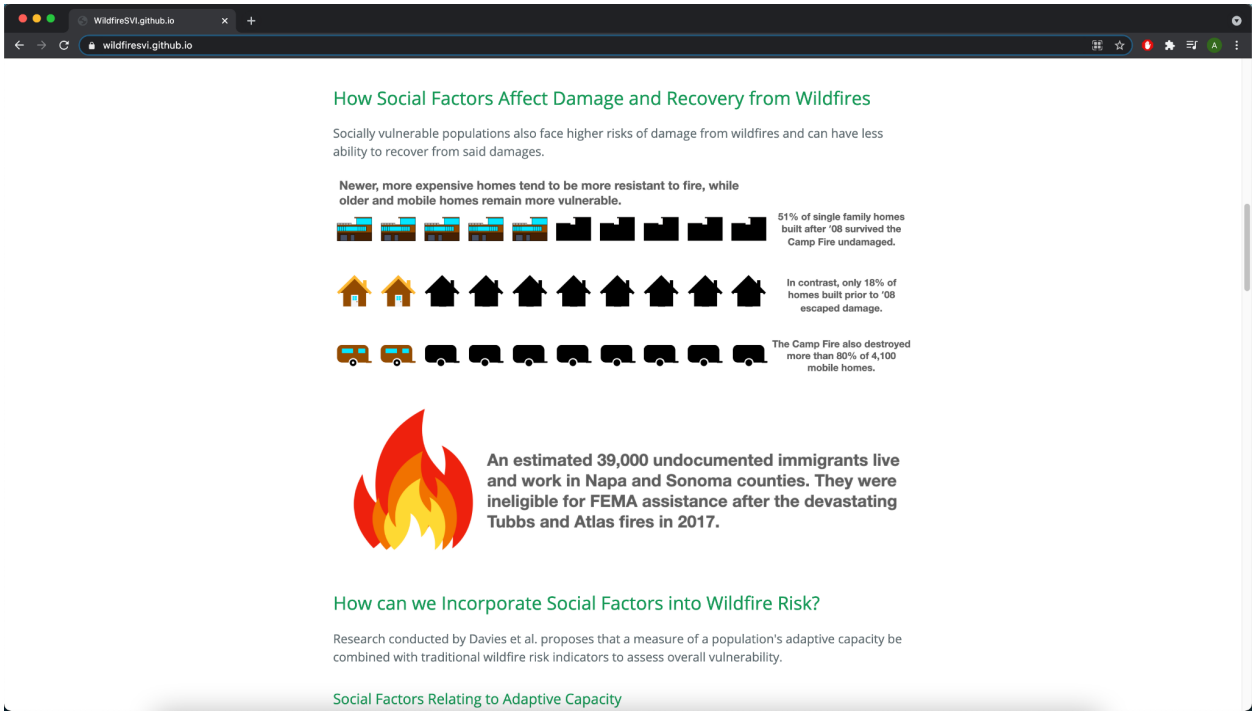


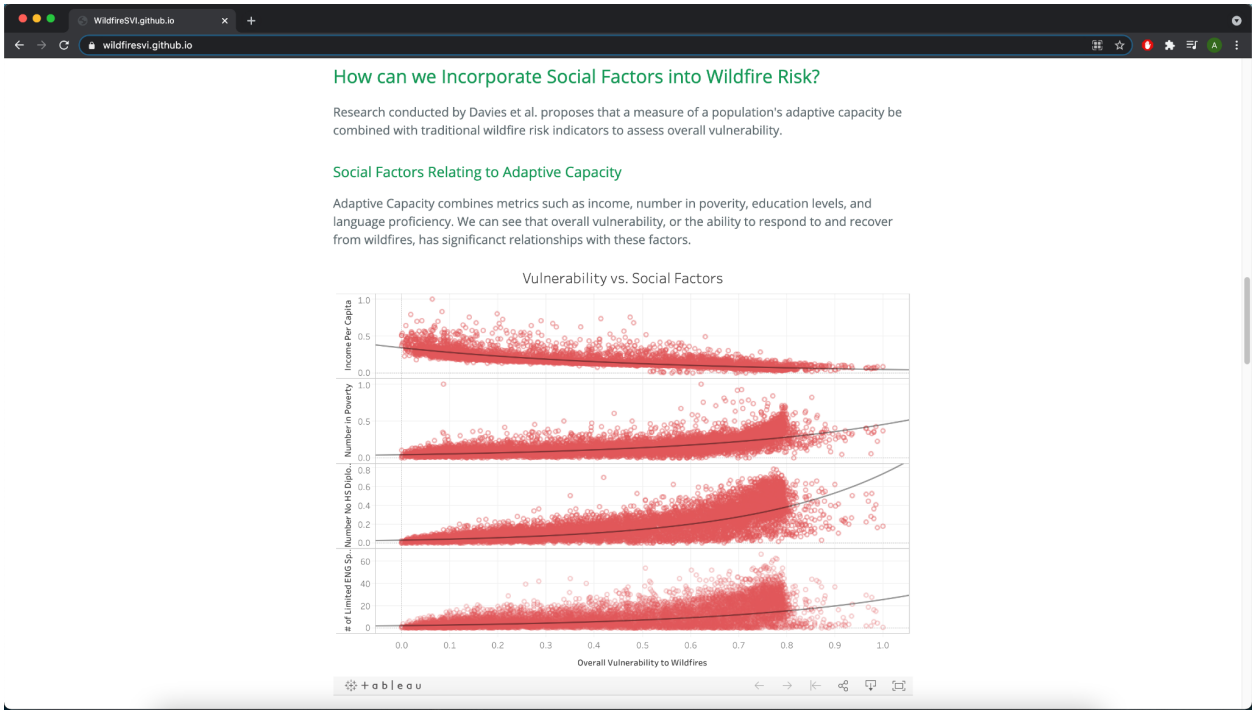
Fig 13 - A panel in our Tableau Story introducing the concept of Wildfire Hazard Potential

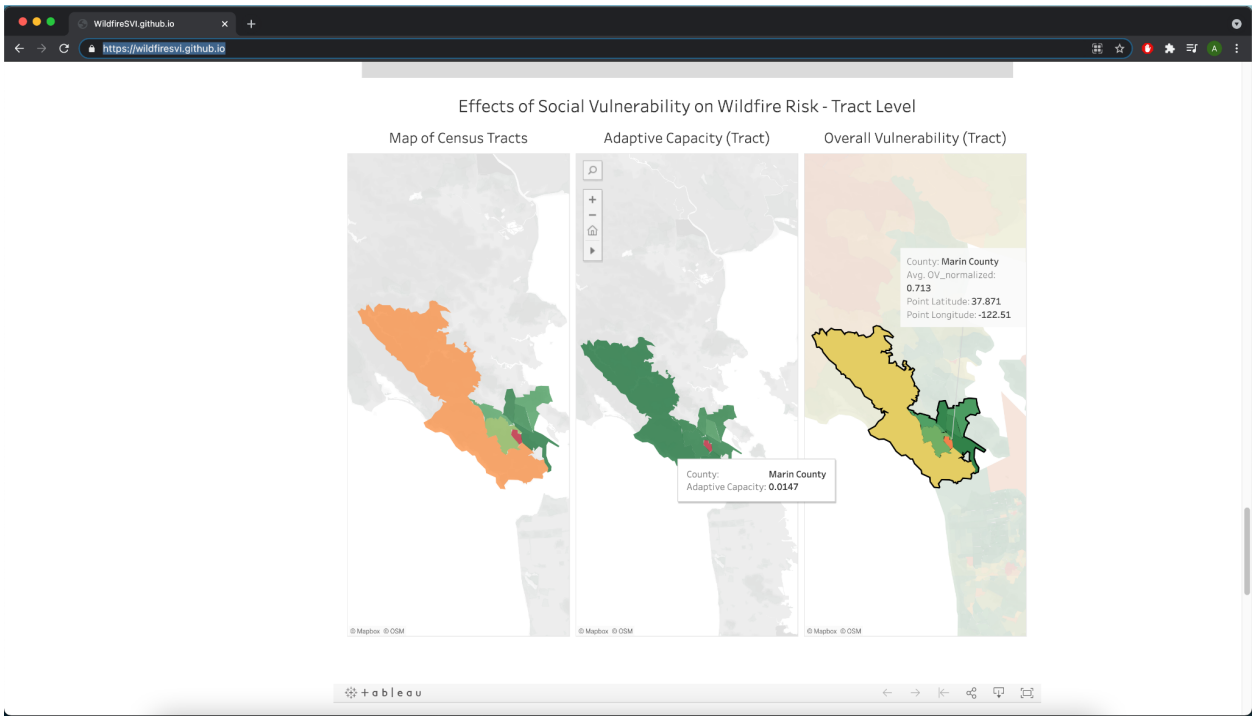
Usability Testing

To evaluate the designs of our visualizations and their accompanying narrative, we incorporated elements from our infographic and Tableau Story into a webpage hosted by Github Pages and conducted usability tests with three participants. The purpose and rationale of this study was to gauge how well the visualizations achieved their primary goals of (1) educating users on what social factors affect wildfire vulnerability and (2) how these social factors affect vulnerability. The study of social factors in the context of wildfires is relatively nascent, leading to frameworks and terminology that can be esoteric in nature. Therefore, the focus of our usability study (and our visualizations as a whole) stayed on more fundamental goals of comprehension.

Fig 14 - Screenshots of first iteration of education web page




WildfireSVI.github.io
wildfiresvi.github.io
How can we Incorporate Social Factors into Wildfire Risk?
Research conducted by Davies et al. proposes that a measure of a population's adaptive capacity be combined with traditional wildfire risk indicators to assess overall vulnerability.
Social Factors Relating to Adaptive Capacity
Adaptive Capacity combines metrics such as income, number in poverty, education levels, and language proficiency. We can see that overall vulnerability, or the ability to respond to and recover from wildfires, has significanct relationships with these factors.
Vulnerability vs. Social Factors
Income Per Capita
Number in Poverty
Number No HS Diplo..
# of Limited ENG Sp..
Overall Vulnerability to Wildfires
tableau


WildfireSVI.github.io
https://wildfiresvi.github.io
Effects of Social Vulnerability on Wildfire Risk - Tract Level
Map of Census Tracts
Adaptive Capacity (Tract)
Overall Vulnerability (Tract)
County: Marin County
Avg. OV_normalized: 0.713
Point Latitude: 37.871
Point Longitude: -122.51
County: Marin County
Adaptive Capacity: 0.0147
tableau

Method

The usability tests were carried out and recorded over Zoom. Each session lasted 35 - 40 minutes, and participants shared their screens while examining a series of visualizations on a website. We began each session by asking participants about their experience with information visualization, how often they looked at information visualizations, and their interest in learning about wildfires. We then provided participants with six brief tasks and asked them to think out loud while completing them. After each task, the test facilitator asked participants four questions. One of these questions was task specific while the other three sought to elicit information about what participants liked or disliked about each design; their reasons for liking or disliking something; and the questions they had after viewing each visualization. As participants completed each task, the notetaker captured quantitative data about task performance such as task time to completion as well as qualitative data from the participant's think-aloud or question responses.

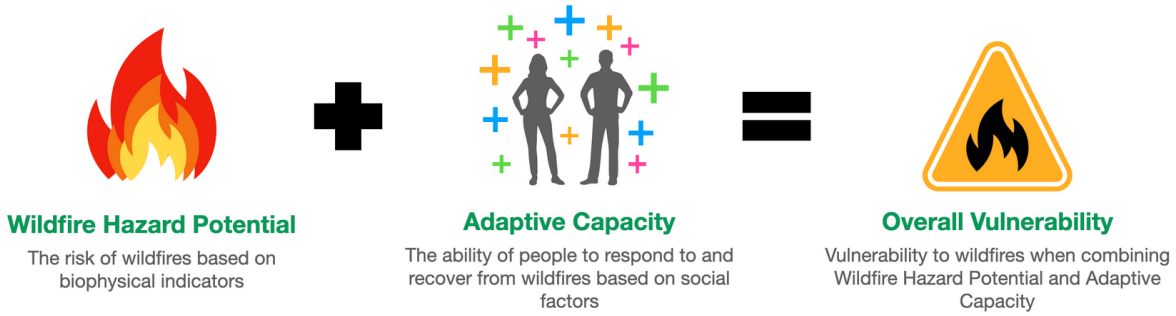
Results

Based on our study results, we identified 5 major takeaways to guide future development of our visualization:

- Provide More Contextual Clarity / Background Information
- Define Terminology Earlier
- Clearly Indicate the Interactive Elements within Visualizations
- Simplify the Scatter Plots for Interpretability

We incorporated this feedback into our design by making the following changes:

- To provide greater contextual clarity upfront, we edited the first paragraph of the website to be more concise and provided more explicit labeling for some of the visualizations.
- To define key terms earlier, we provided a list of social factors as examples at the top of the page. We also visualized the relationship between key concepts of wildfire hazard potential, adaptive capacity, anad overall vulnerability.



- Since we used Tableau to host our visualizations, we were limited by the platform's affordances for indicating interactivity. We attempted to provide additional guideposts for viewers by stating explicitly in the surrounding text when there might be opportunities to further interact with the designs.

> Here, we see the Wildfire Hazard Potential (WHP), Adaptive Capacity, and Overall Vulnerability for Marin, Sonoma, and Napa Counties. You can scroll over each county to see more information on each county.
>
> On each map, green indicates more favorable values, and red indicates less favorable values. For example, we can see that these counties have moderate to severe WHP risk.

- We decided to remove the scatter plots, since they were not easily interpretable and did not add much insight into understanding Adaptive Capacity. Additionally, since Adaptive Capacity is included in the calculation of Vulnerability, it did not make sense to plot them against each other, as they would certainly show strong relationships.

3. Wildfire Evacuation Simulator

The traffic data in catastrophic events like wildfires, floods, hurricanes is not easily available. Also, development of new policies around city-scale infrastructure, resiliency tools, enabling real-time decisions in response to natural disasters or disruptive events and traffic management during emergency situations needs analyzing the past situations and weighing the consequences of proposed changes. This makes traffic simulation a viable alternative that provides a convenient way to empirically study traffic policies.

Traffic modelling for a city is often seen as analogous to modelling fluid flow in a pipe. The traffic models can be classified as macroscopic models and microscopic models based on the level of details given to the behavioural rules used during the modelling. Microscopic models simulate individual cars by calculating each vehicle's speed and location using car-following and lane-changing modules. Macroscopic models depict the traffic stream as continuum flows and apply equations similar to those in fluid dynamics to describe the traffic density dynamics, traffic speed and traffic flow. Microscopic models provide a detailed representation of the traffic process, which makes them most suitable for evaluation of complicated traffic facilities. We used a mesoscopic traffic simulation model that simulates traffic at a city level in case of wildfires, through a combination of individual agent level travel demand/route choice and macroscopic road link dynamics with volume-delay relationships.

We used an agent-based macroscopic traffic simulation model for the city of Woodacre, CA. Agent-based modelling (ABM) is an approach that encapsulates the philosophy that instead of treating the problem as one entity, the behavior of each of the smaller elements (agents) within the system is modeled. It is a bottom-up approach where macro outcomes are derived from the

activities of individual micro actors. ABM allows individual behavior to be incorporated, enabling the inclusion of complex human behaviour observed in the real world[8]. In this model, agent mobility is based on the assumption of a volume-delay relationship between macroscopic variables.

3.1 Traffic Simulation

3.1.1 Data

Two types of data are required for the agent-based macroscopic traffic simulations: the network properties (topology, capacity, speed limit etc.) and the travel demand (origin, destination, departure time etc.). This section details the process of data collection from openly available data sources as well as the assumptions involved in data processing.

OpenStreetMap is an initiative to create and provide free editable geographic data of the world, such as street maps to anyone. Users may collect data using manual survey, GPS devices, aerial photography, and other free sources, or use their own local knowledge of the area. This crowdsourced data is then made available under the Open Database License. The OSM road network was initially populated by the public domain TIGER maps in 2007 - 08 and has been gradually updated by the community over the years in the US. Since then OpenStreetMap data has been used in various scientific studies to study spatial development and socio-economic factors in a developing country.

Downloading the OSM road network

[8] "An agent-based approach to modelling driver route choice ...." https://espace.library.uq.edu.au/view/UQ:38812/Dia-_Paper_2.pdf. Accessed 6 May. 2021.

The OpenStreetMap data has also been used in various traffic simulation studies[9] alongside microscopic traffic simulation package SUMO[10] and other tools like netconvert to convert the OSM data to SUMO specific representations. We obtained the road network data using OSMnx library, a comprehensive Python tool for downloading geospatial data from OpenStreetMap and modelling, projecting, visualizing, and analyzing real-world street networks and any other geospatial geometries. Figure 15 shows the Python script used to download the road network for Woodacre, Marin, CA. We choose then to use a classic format for the roads and nodes. Each road is a polyline composed of road sections. Each road has a target node and a source node. Each node knows all its input and output roads. A road is considered as directed. For bidirectional roads, 2 roads have to be defined corresponding to both directions. A road can be composed of several lanes. The vehicles are able to change at any time it's lane and even use a lane of the reverse road. Legal speed is another property of the modeled road. Different roads are defined in the output by a feature named "Highway" which can take values as residential, service, path etc. This data also contains useful information about different attributes of the road network like the max speed limit for each road, the number of lanes, the length of each road. But, there were few missing and redundant values which needed to be taken care of like the max speed limit for the roads was missing for 50% of the data points. Also, the number of lanes was missing for 96% of roads. As Woodacre is a small town in Marin county the crowd sourced data on Open Street Maps is not complete and we used the US census data[11] to impute a few of the missing features for Woodacre. This road network data is then converted to directed graph to run

[9] "Simulation pipeline for traffic evacuation in urban areas and ...." https://www.sciencedirect.com/science/article/pii/S2590198220301214. Accessed 4 May. 2021.
[10] "Eclipse SUMO - Simulation of Urban MObility." https://www.eclipse.org/sumo/. Accessed 4 May. 2021.
[11] "• Number cars per household in the U.S. | Statista." 4 Mar. 2021, https://www.statista.com/statistics/551403/number-of-vehicles-per-household-in-the-united-states/. Accessed 6 May. 2021.

subsequent traffic simulations and also find the best path from location A to location B. For calculation of road capacities we used the link speed limit and the number of lanes. Figure 16 shows a cleaned network for the study area, with 112 nodes and 300 edges.

```
place_name = "Woodacre, CA, USA"
graph = ox.graph_from_place(place_name)
nodes, edges = ox.graph_to_gdfs(graph)
fig, ax = ox.plot_graph(graph)
for _, edge in ox.graph_to_gdfs(graph, nodes=False).fillna('').iterrows():
    c = edge['geometry'].centroid
    text = edge['name']
    ax.annotate(text, (c.x, c.y), c='w')
plt.show()
# nodes, edges = ox.graph_to_gdfs(graph)
```

Fig 15 - Script to download the road network for Woodacre from OSM, using OSMX

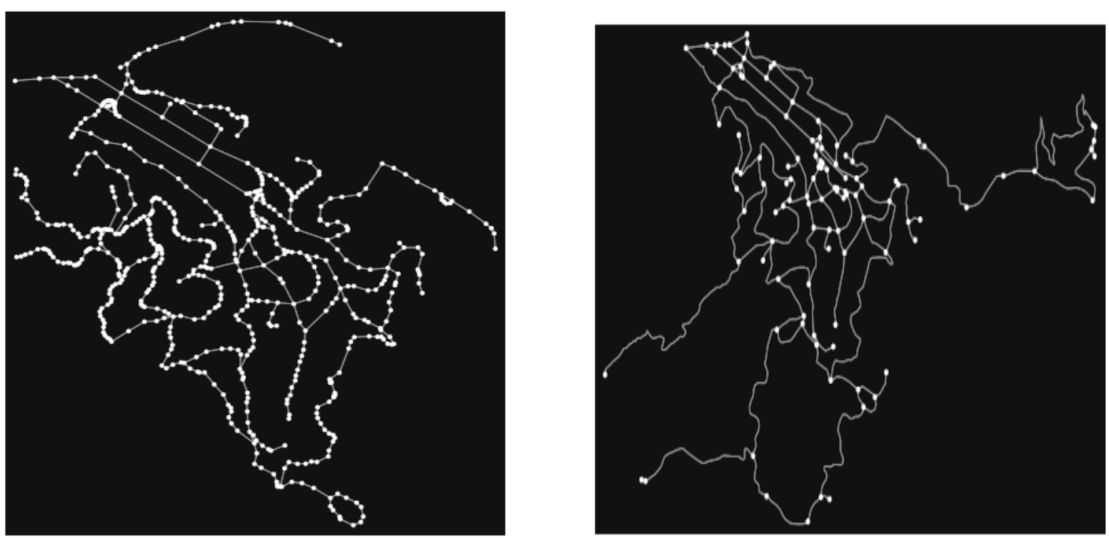


Fig 16 - The road network of Woodacre, downloaded from OSM

Left - without cleaning for redundant nodes

Right - simplified road network for woodacre after cleaning (removing redundant nodes and imputing missing values)

The physical features of the road network and the city are easy to get from OSM but the demand data on the number of vehicles in the town and household is difficult to obtain from OSM. We used the parcel data which is made open source by Marin County[12], which defines each parcel as a piece of land which can be owned, sold, and developed as a proxy for individual households. We then used the input parameter from the user on the number of cars per household to generate the total demand in terms of vehicles in the city. The input parameter in terms of the direction of fire and compliance rate are also considered while changing the demand. We assign the origin location (node) and destination node to each vehicle and create an OD (origin - destination) pair for each vehicle.

3.1.2 Modeling

Demand

The demand is assigned to the Woodacre road network by creating an agent representing a vehicle for each OD (origin - destination) pair and finding the shortest path between the origin and destination in terms of the series of edges which needs to be traversed to reach the shelter place (destination node). Temporarily, we update the agent based model every second and for each step we update the location of all the agents in the graph. The framework for traffic simulation is shown in Figure 17.

[12] "GIS Data Download - MarinMap." https://www.marinmap.org/dnn/DataServices/GISDataDownload.aspx. Accessed 5 May. 2021.

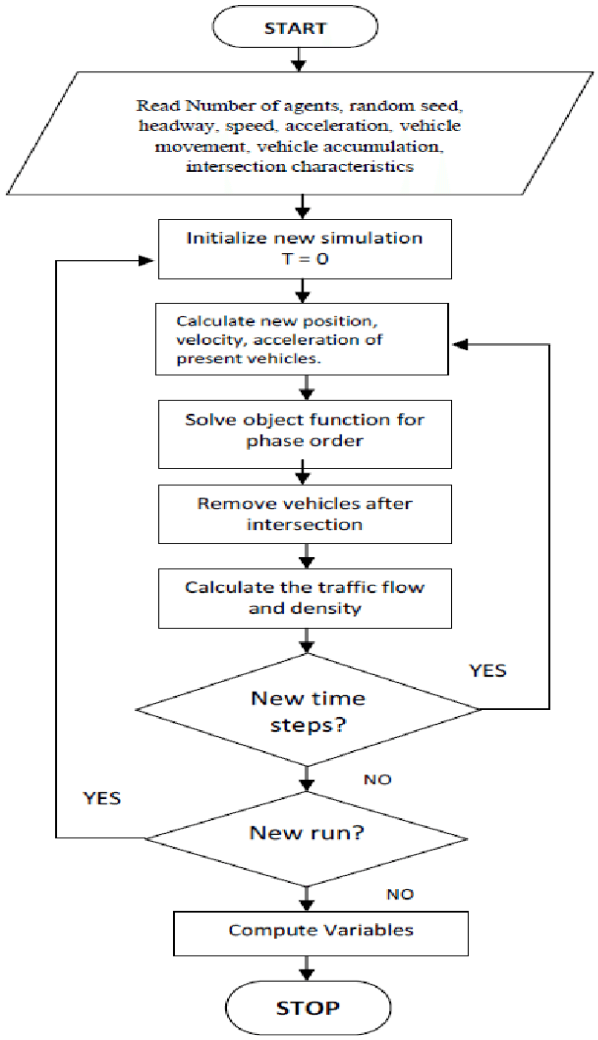


Fig 17 - Agent Based Modelling Framework for Traffic Simulation

The outer loop controls the progression of time for the traffic simulation. Inside the loop all the variables concerning traffic are updated for 1 second time slice. For calculating the new position of each agent in the model we use a priority-queue based Dijkstra shortest path algorithm which will be described further. A route or path is a sequence of graph edges that connect the origin node to the destination node (shelter place). For this, we made an assumption that each agent will try to follow the fastest path when travelling from point A to B ignoring few other factors such as

the financial cost and quality of the roads. This assumption can be justified in our scenario as during wildfires, the highest priority for people is to save their lives and get out of the fire affected region instead of worrying about the other financial losses. This is done in 3 steps:

1. The time to travel each link (edge) in the graph (road network) is updated as the weight.
2. We find the best path with smallest total weight (minimum time) for an agent to travel from point A to B
3. Next is updating the link-level travel time based on the traffic flow calculated based on the simulation from previous step

Update of link-level travel time

Link-level travel time is also updated every second based on the well-known Bureau of Public Roads (BPR, 1964) volume-delay curves. It has the following form "estimated_travel_time" the link-level travel time with traffic on the link is defined as function of traffic on the link(number of vehicles queued) and the capacity of the link. The calibration factor **α**(25) and the max allowed speed for the link are considered.

estimated_travel_time = len(self.queue_vehicles)/ (self.capacity + 0.1) * 25 / self.maxmph + self.fft

Within one time step(every second), the volume of the network and link travel time are updated by the iterative assignment process.

Shortest-path finding - Dijkstra shortest path algorithm

We used a priority-queue based Dijkstra shortest path algorithm to find the shortest and fastest route for all the agents to travel to the shelter location. Dijkstra's algorithm is an iterative algorithm that provides the shortest path from one particular starting node to all other nodes in

the graph and is based on the popular graph traversing algorithm Breadth First Search in Computer Science. We applied Dijkstra algorithm to the road network graph for Woodacre by weighing in the link-level travel time and finding the weighted shortest path from agent's source node to destination node which in our case is the shelter location.

3.1.3 Results

As an output of the Agent based simulation we received the traffic volume, that is number of vehicles running on each road, and also number of vehicles queued at each time stamp t (sec). Figure 18 shows such results on a day in Woodacre when the fire is moving from North to South and the evacuation notice to immediately evacuate is given to the people of Woodacre. Also, we considered that the number of cars per household is 2 (US census) and people will have 100% compliance rate. Here the social vulnerability index is not factored in while modelling the traffic flow. Woodacre has a considerable population above 60 and this influences the driving behavior of people of Woodacre. We see that without considering SVI in the traffic Model it takes, approximately 7 minutes given the above parameters to evacuate and reach the shelter place. We also see that the hair pin bend road, which is connecting the northern part of the Woodacre with the southern part is the main point of congestion during the evacuation.

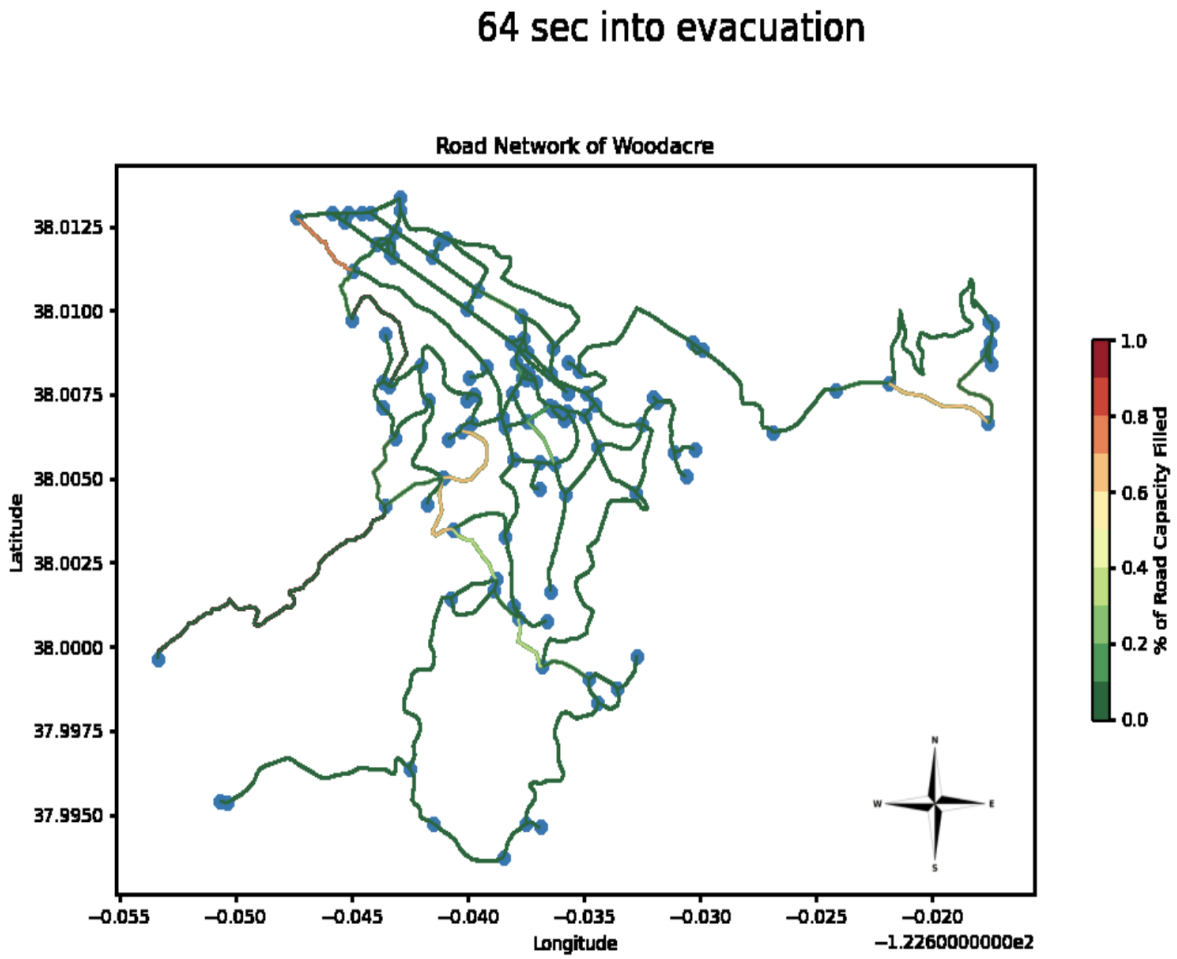


Fig 18 - Traffic Simulation for Woodacre in case of fire from Northern direction without considering the Social Vulnerability Index in the model

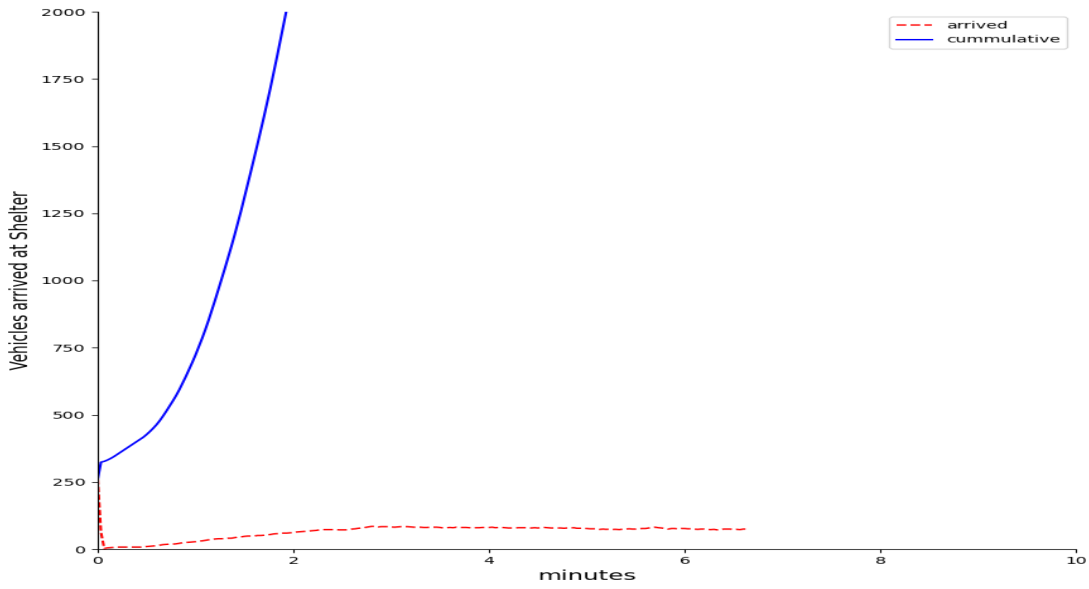


Fig 19 - The graph shows the time taken for evacuating all the vehicles when SVI (social vulnerability Index) is not considered when modelling the traffic flow for Woodacre.

Below figure shows the result on a day in Woodacre when the fire is moving from North to South and the evacuation notice to immediately evacuate is given to the people of Woodacre. Keeping all the parameters as same we just incorporated the SVI (Social Vulnerability Index) in the model and see the evacuation is different in terms of the demand at different points of time. When SVI is not incorporated in modelling the evacuation demand is more normalized. This indicates the effect of incorporating SVI in the modelling. This validates our assumption that the

traffic simulation output changes and when this SVI is factored in.

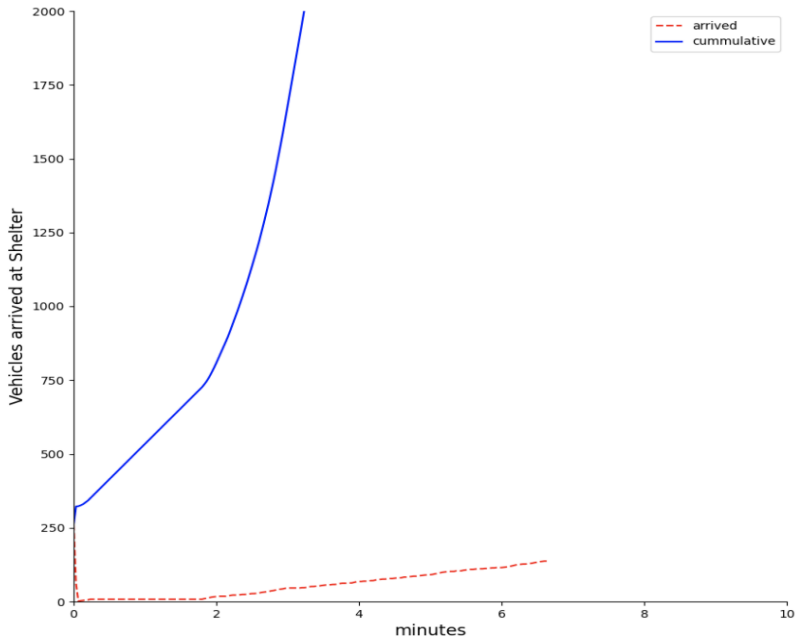


Fig 20 - The graph shows the time taken for evacuating all the vehicles when SVI (social vulnerability Index) is considered while modelling the traffic flow for Woodacre.

3.1.4 Technology

Web Application

We developed the front end of the web application using HTML, CSS, Bootstrap framework and Javascript. For the backend, we used Flask which is a Python micro framework.

3.2 Incorporating Social Vulnerability Factors

Incorporating social vulnerability factors into our simulation posed a number of questions. First, we needed to define what we meant by social vulnerability. Second, we needed to determine how

to translate these social vulnerability factors into our simulation model in ways that were both justifiable by existing research and compatible with the parameters of our model.

3.2.1 Defining Social Vulnerability

To define social vulnerability, we conducted a survey of existing literature relating to wildfire evacuations, social vulnerability to wildfires, and social inequity relating to wildfire risk to examine what factors were being considered. We placed higher emphasis on the factors included in studies that placed greater focus on understanding wildfire evacuation behavior (e.g., research by Dulebenets et al. on the development of statistical models for improving efficiency of emergency evacuation in areas with vulnerable populations)[13]. Combining research from Dulebenets et al., Fukui et al., Bella et al., Casutt et al., and Davies et al., we generated the following list of social vulnerability factors that closely related to wildfire evacuation[14,15,16,17]:

- Low Income
- Ethnicity (underrepresented minority)
- Old Age (65+)
- Visual Impairment
- Chronic Disease
- Physically Handicapped
- Non-English Speaker

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[13] "Development of statistical models for improving ... - ScienceDirect.com." https://www.sciencedirect.com/science/article/pii/S095183201830437X. Accessed 6 May. 2021.
[14] "Elderly Driver - an overview | ScienceDirect Topics." https://www.sciencedirect.com/topics/social-sciences/elderly-driver. Accessed 6 May. 2021.
[15] "Analysis of driver speeds under night driving ... - ScienceDirect.com." https://www.sciencedirect.com/science/article/pii/S0022437514000255. Accessed 6 May. 2021.
[16] "The relation between performance in on-road ... - ScienceDirect.com." https://www.sciencedirect.com/science/article/pii/S1369847813001368. Accessed 6 May. 2021.
[17] "The unequal vulnerability of communities of color to wildfire - PLOS." 2 Nov. 2018, https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0205825. Accessed 6 May. 2021.

- Limited Education Level (no high school diploma)
- Single parent household (with children under 18)
- Lack of access to transportation
- Lack of access to telecommunication technology
- Mobile home dwellers

3.2.2 Translating Social Vulnerability into Evacuation Behavior

For each social vulnerability factor in our list, we sought to identify a research-backed quantification method that translated into evacuation behavior. Given that the parameters of our simulation model were limited to movement speed, departure time, number of cars, and compliance rate across different nodes (locations) in Woodacre, we needed the quantification methods to be translatable into modifications of these values. Additionally, we needed information on the distribution of such social factors for Woodacre (e.g., the population age distribution), which were multi-layered in some cases (e.g., the number of physically handicapped people, and the severity/types of handicaps).

We found these requirements to be fairly limiting, especially given the relatively nascent state of research in this domain as well as limited detailed information on the distribution of social factors. Of the factors from our list, we found that Old Age satisfied the requirements to be incorporated into our simulator. Below, we outline how we incorporated Old Age into our simulator.

We quantified the impact of age on the speed of driving in emergency evacuation settings using a study conducted by Dulebenets et al[18]. Primarily using an immersive evacuation scenario driving simulator, the study found that every 1 year older a participant was, that participant took 0.0107 minutes (0.64 seconds) longer to drive through a 10-mile route under emergency evacuation conditions. For perspective, in a 10 mile evacuation, a 65 year old would take 25.68 more seconds than a 25 year old, with all else being equal. When considering larger population sizes in the hundreds or thousands, these differences could be substantial. Below is the table of coefficients generated from Dulebenets et al.'s study, which shows that age is a highly significant predictor of travel time.

	Coefficient	S.E.	*t*-stat	*p*-value
Intercept	11.9658	0.5605	21.3473	<0.0001
Age	0.0107	0.0038	2.8175	0.0053
Driving frequency	–0.0649	0.0260	–2.4916	0.0136
Distance driven per week	–0.0286	0.0123	–2.3240	0.0212
Difficulty evacuating	–0.4187	0.2019	–2.0732	0.0395
Ability to make quick decisions	–0.2555	0.0903	–2.8279	0.0052
Simulator experience	–0.0625	0.0119	–5.2682	<0.0001
Average space headway	0.0015	0.0008	1.9069	0.0480

Fig 21 - Regression Model from Dulebenets et al. predicting evacuation travel time

After quantifying the impact of age on driving speed, we found the distribution of ages in Woodacre using census data. We found that more than 45% of Woodacre's population (590 out

[18] "Development of statistical models for improving ... - ScienceDirect.com." https://www.sciencedirect.com/science/article/pii/S095183201830437X. Accessed 6 May. 2021.

of 1303 people) are 65 years or older, which made this a practically relevant factor to consider for the city.

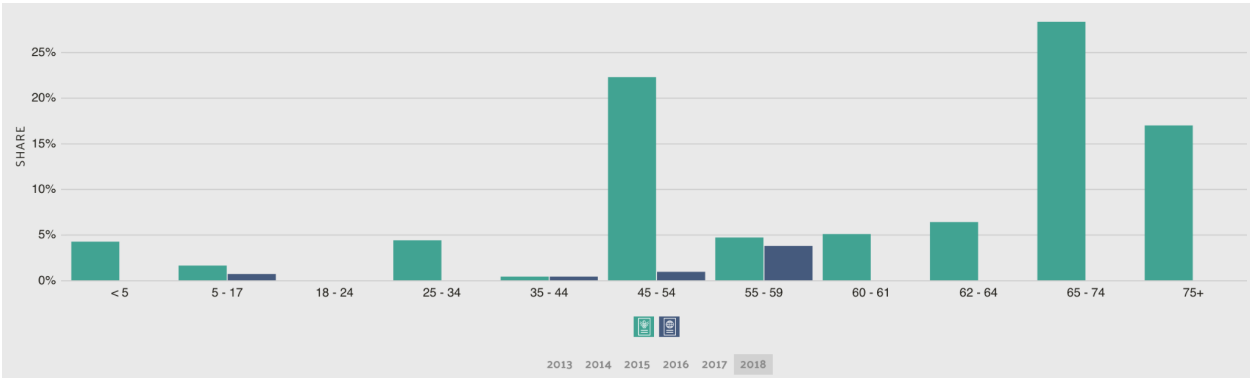

Fig 22 - Age Distribution of Woodacre (population size = 1303)[19]

To integrate these findings into our simulator, we randomly assigned age to the agents in Woodacre, following this age distribution we assigned the average max speed of 25mph to all the lanes of Woodacre to model the traffic simulation. While considering the SVI in the model, based on these ages, we adjusted driving speed for these roads in accordance with the Age coefficient found in the study by Dulebenet et al. For example, if we assigned a road to have a maxspeed of , their overall driving speed would be reduced to 36% of the original to 10 mph.

3.2.3 Results

When comparing simulation results that do and do not incorporate Old Age, we find clear differences in overall evacuation rate and time required to complete evacuation. During our tests using the simulation we found that for a given set of parameters, the SVI-incorporated simulation displays more severe traffic congestion patterns and a longer time to evacuate.

[19] "Woodacre, CA | Data USA." https://datausa.io/profile/geo/woodacre-ca. Accessed 6 May. 2021.

Even when only considering old age, the differences in evacuation results indicate a need to more strongly consider social vulnerability when preparing for evacuations. In the future, we hope to further explore how social vulnerability may introduce previously unseen risks in evacuation planning, both at a greater depth (e.g., how does age affect not only speed, but departure time) and at a greater breadth (e.g., how do family size and structure, English proficiency, and health conditions affect evacuation speed). We discuss possibilities for future exploration at greater length in our conclusion.

4. Educational Web Page

An educational web page was created to educate users about the effects of social vulnerability on wildfire risk and wildfire evacuations. As we conducted our needfinding assessments, we realized that very few responders, authorities, and researchers in the domain of wildfires were knowledgeable of how social factors relate to wildfire risk.

We decided that aggregating and presenting the limited data that does exist regarding social vulnerability and wildfires could be a meaningful educational contribution. Our hope is that this website can (1) educate and influence wildfire evacuation planners to more strongly consider social factors when preparing for evacuations, and (2) encourage other individuals (e.g., researchers, aspiring firefighters, city officials) to conduct their future work with these factors in mind and further contribute to this area.

The website is live and accessible at https://wildfiresvi.github.io/

4.1 Data

The website includes the following data:

Statistics on socially vulnerable populations' responses to wildfires.

- This data was collected from a number of public resources including iii.org, americanprogress.org, pbs.org, plos.org, redding.com, and spotlightonpoverity.org. Statistics on different socially vulnerable populations are sparse and disparately located, requiring a larger number of sources[20,21,22,23,24].

Risk Metrics Detailing Wildfire Potential and Social Vulnerability in California

- This data was collected from the research paper by Davies et al., titled *The Unequal Vulnerability of Communities of Color to Wildfire.* Davies et al. conduct an analysis to measure the vulnerability of communities to wildfires, when considering both biophysical indicators and social factors.
- To understand biophysical risk, they reference the Wildfire Hazard Potential (WHP) of California, broken down into census tracts, which is provided by the United States Forest Service (USFS)[25]. They also normalize WHP to be between 0 to 1.

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[20] "Facts + Statistics: Wildfires | III." https://www.iii.org/fact-statistic/facts-statistics-wildfires. Accessed 6 May. 2021.
[21] "Before the Fire: Protecting Vulnerable Communities From Wildfire ...." 25 Jul. 2019, https://www.americanprogress.org/issues/green/reports/2019/07/25/472639/before-the-fire/. Accessed 6 May. 2021.
[22] "Camp Fire: By the Numbers | Fire in Paradise | FRONTLINE | PBS ...." 29 Oct. 2019, https://www.pbs.org/wgbh/frontline/article/camp-fire-by-the-numbers/. Accessed 6 May. 2021.
[23] "California wildfires: Here's why some homes survive the blaze." 11 Apr. 2019, https://www.redding.com/in-depth/news/2019/04/11/california-wildfire-prevention-protection-home/3412609002/. Accessed 6 May. 2021.
[24] "Northern California Fires Decimate Low-Income Communities ...." 25 Oct. 2017, https://spotlightonpoverty.org/spotlight-exclusives/northern-california-fires-decimate-low-income-communities/. Accessed 6 May. 2021.
[25] "Wildland fire potential: A tool for assessing wildfire risk and fuels ...." https://www.fs.usda.gov/treesearch/pubs/49429. Accessed 6 May. 2021.

- To understand social factors, they estimate the "adaptive capacity" of each census tract using census data. They define adaptive capacity as "the ability of a census tract to absorb and adjust to disturbances, like wildfire, while minimizing damage to life, property, and services" and derive a quantitative metric for each census tract using a method proposed by Flanagan et al., which takes the weighted rank of a census tract across a number of social indices (listed in the table below)[26]. These values are then also normalized to be between 0 and 1. Counties with higher weighted ranking values (i.e., farther from 0) are considered to be less adaptive.
- Finally, Davies et al. calculate a metric for overall vulnerability to wildfires, by combining WHP and Adaptive Capacity into a value pair for each census tract and calculating each pair's Euclidean distance from the minimum WHP and Adaptive Capacity values (formula below).

Domain	Variable
Socioeconomic Status	• Persons below poverty level • Civilians (age 16+) unemployed • Per capita income
Language and Education	• Persons (age 25+) w/out high school diploma • Persons (age 5+) who speak English "less than well"
Housing and Transportation	• Housing in structures w/ 10+ units • Mobile homes • Households with >1 persons per room • Households with no vehicle available • Persons in institutionalized group quarters
Demographics	• Civilian noninstitutionalized population w/ disability • Single parent household w/ children under 18 • Persons age 65+ • Persons age 17-

Fig 23 - Social Factors considered for calculating Adaptive Capacity

[26] "A Social Vulnerability Index for Disaster Management - De Gruyter." https://www.degruyter.com/document/doi/10.2202/1547-7355.1792/html. Accessed 6 May. 2021.

$$V = \sqrt{(AC - AC_{min})^2 + (WHP - WHP_{min})^2}$$

Fig 24 - Formula for calculating overall vulnerability

- The resulting dataset is one where each row represents a census tract, its WHP, Adaptive Capacity, Overall Vulnerability, and accompanying census tract data used to calculate Adaptive Capacity. While Davies et al. created a heatmap comparing WHP to Overall Vulnerability, it is difficult to interpret and does not facilitate future exploration well. We found this type of visualization to be potentially very informative and memorable and thus sought to redesign and expand on it as a component of our webpage.

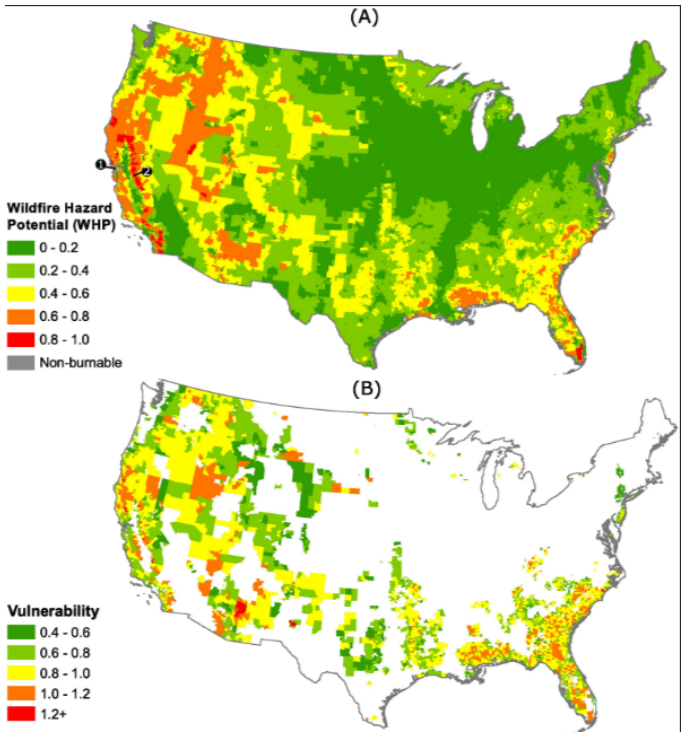


Fig 25 - Map by Davies et al. comparing WHP to Vulnerability

4.2 Website Overview

Below we walk through the different sections of the educational webpage, created using Github Pages and the Jekyll web theme.

4.2.1 Introduction

The header and introductory section of the webpage introduce the main topic of incorporating social factors into wildfire risk. It also defines social factors (Note that the list of social factors is condensed compared to the list presented in Section 3.2.1. This was done to keep the page more readable).

Fig 26 - Introduction of Web Page

4.2.2 Examples of how Social Factors Affect Wildfire Response and Recovery

This section provides examples of how some socially vulnerable populations are affected by wildfires, in comparison to normal populations. The information and iconography here were adapted from the infographic presented in Section 2.2.2., with updates based on our usability tests to make the icons more representative of their accompanying statistics, as well as updated spacing and sequencing to make the examples more easily digestible. While it would have been ideal to include additional statistics spanning across more types of vulnerable populations, it was difficult to find additional data in this space.

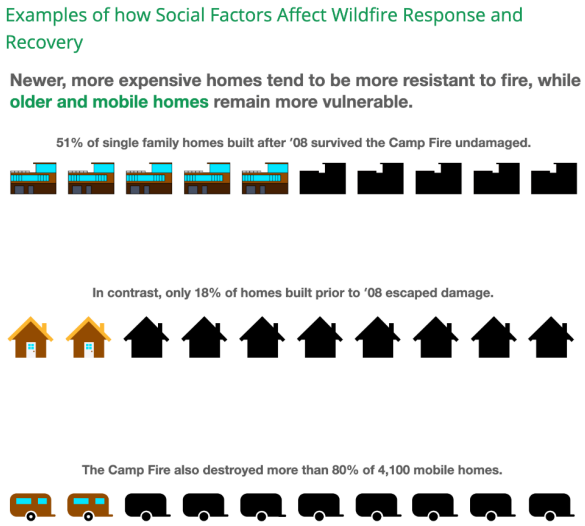


Fig 27 - Examples of how Social Factors Affect Wildfire Response and Recovery

4.2.3 How can we Incorporate Social Factors into Wildfire Risk?

This section begins to outline the approach used by Davies et al. to calculate overall vulnerability to wildfire, incorporating social factors. Compared to previous iterations that immediately

presented users with interactive heat maps, this section now starts with term definition with icons, as well as a link to the original research paper for more information.

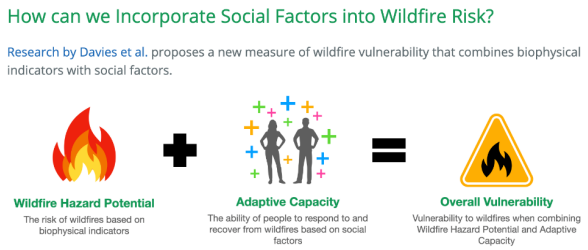
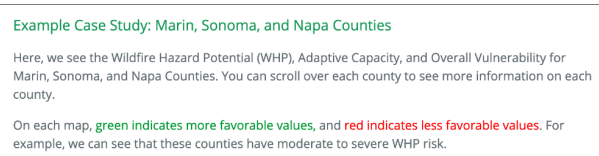
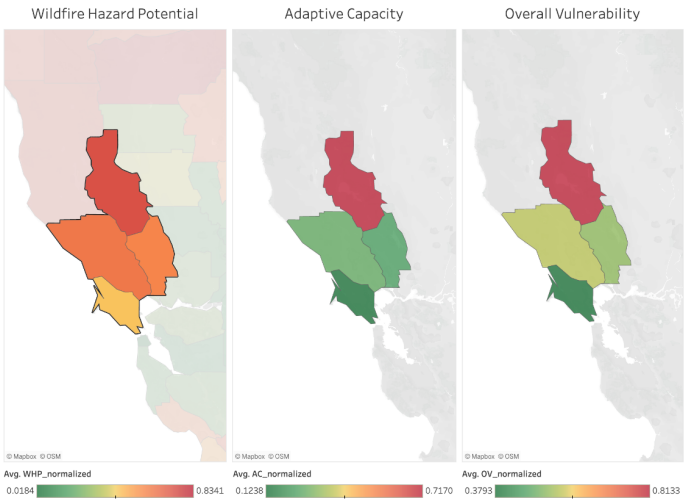


Fig 28 - Risk Metric Definitions

The site then introduces interactive maps showing WHP, Adaptive Capacity, and Overall Vulnerability using a case study that focuses on Sonoma, Napa, Marin, and Lake Counties. The supporting text describes how considering the Adaptive Capacity of a county can reveal that even if WHP is high, overall ability to respond and recover from fire can be quite high as well. The maps also support tool tips, so when users scroll over counties, they can see County names and relevant metrics. Below this section, a similar case study at the census tract level is explained, emphasizing the importance of having varying granularity when examining regions for vulnerability.



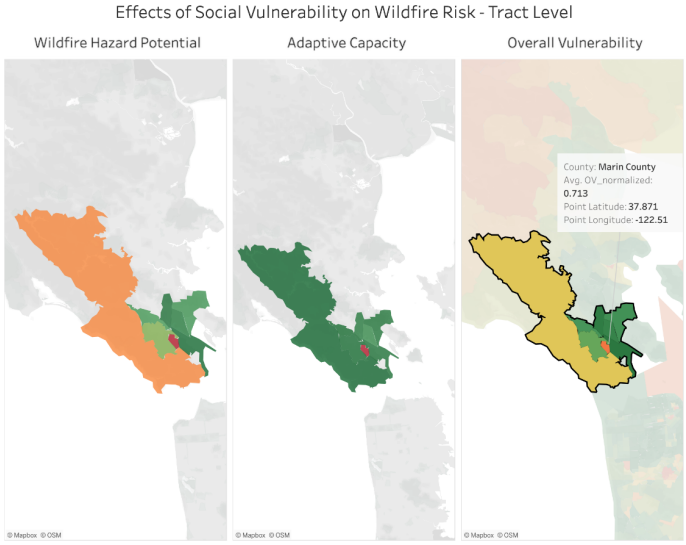


When we examine these communities' adaptive capacity, we see that Sonoma, Napa, and Marin counties are more resilient to disasters, while Lake County is less reslient.

The overall vulnerability of the first 3 counties is thus tempered, while Lake County's vulnerability to fire is increased.

Digging Deeper: Census Tracts in Marin County

We can zoom further into Marin County, which appears to have a strong adaptive capacity, and find that **pockets of vulnerability still exist.** In this case, we find such pockets at the census tract level.

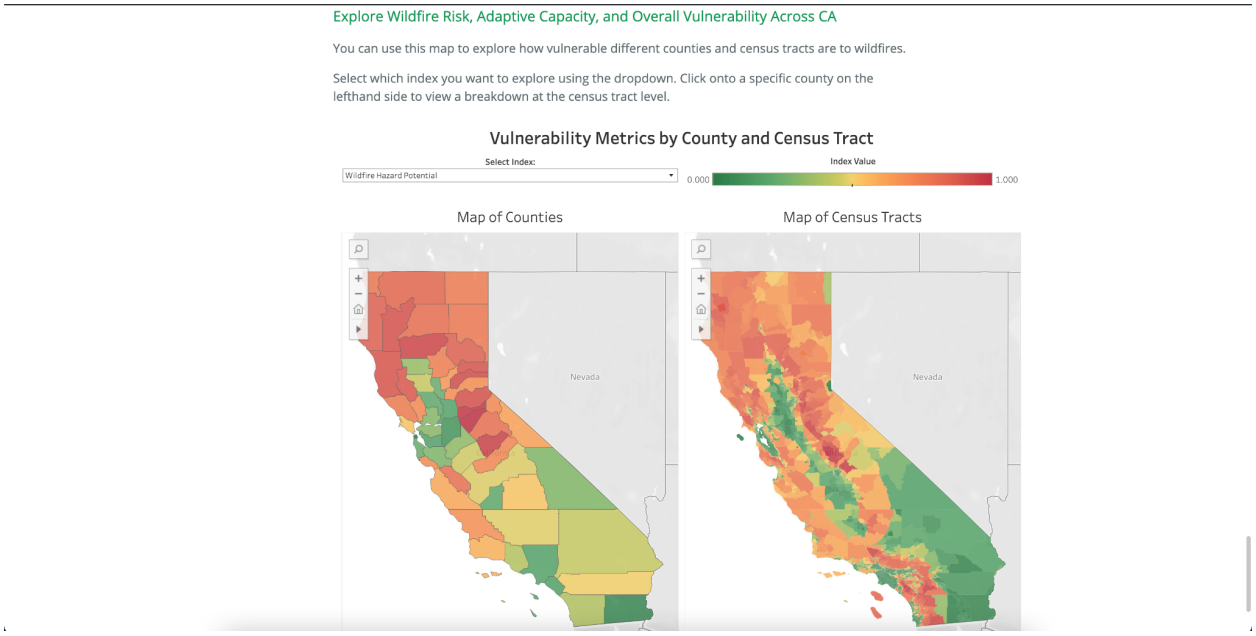


Identifying these communities and helping them respond to wildfires will be an important part of readying regions for a future of in which fire becomes an increasing part of the landscape.

Fig 29 - Incorporating Social Factors into Wildfire Risk

4.2.4 Exploratory Map of California

The final section shows an interactive map of California at the county and census tract levels. Users can select which index they would like to explore (WHP, Adaptive Capacity, Overall Vulnerability), select a county to "zoom" into, and compare index values using a tool tip. This visual is presented after providing initial context and definitions for understanding social vulnerability and wildfire risk, so that users are equipped to further explore areas they are curious about. Our hope is that this visual will reveal interesting insights on how vulnerability varies across counties and census tracts, such that users can gain an appreciation of how nuanced each community's risk can be.



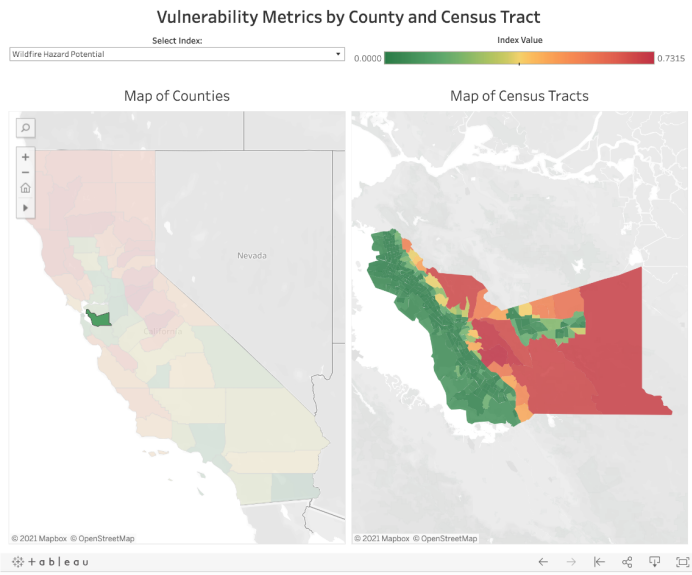


Fig 30 - Exploratory Map of California

5. Conclusion and Future Work

Wildfires are inevitable and with factors like climate change their frequency and severity is only expected to increase[27]. As a result, California needs to be better prepared. However, given the complexity of the problem, it is easier said than done. There are both reactive and proactive approaches which are under the purview of different jurisdictions and at multiple scales thereby involving a lot of planning and coordination. Proactive approaches may include city planning, evacuation planning, and educating people, while reactive approaches may include firefighting and evacuation. Our project explored a proactive approach which aims to help emergency responders and policy makers to facilitate the assessment and planning of evacuation strategies. While we do acknowledge that wildfire evacuation in itself includes a lot of components, our model is a proof-of-concept demonstrating the importance of factoring in the socially vulnerable

27 https://www.gov.ca.gov/wp-content/uploads/2019/04/Wildfires-and-Climate-Change-California%E2%80%99s-Energy-Future.pdf

population while planning evacuation strategies. Furthermore, we believe that it will inform future work in this area.

Future work may expand on different aspects of our project. There is a potential to include more input parameters like destination, need for contraflow etc. as well as other social vulnerability factors like income levels, family structures, and health conditions, as discussed above. Further, some of the parameters and social factors in the model can be further validated by qualitative research with the people of Woodacre and the target users. Additionally, the predictions of the simulation can be further optimized by incorporating more data sources such as social media and satellite data. For a more comprehensive analysis, the modelling can also include dynamic factors like the wildfire spread. Furthermore, on the product side, there is scope to further enhance the experience of users and include game theory elements to make the simulations more engaging and compelling for the target audience. More generally, the simulation can be adapted for different locations in California to better inform their evacuation strategies. Lastly, we believe that this approach can be tightly coupled with some of the reactive approaches thereby creating a feedback loop and further enhancing the credibility of the simulation.

6. Appendix

Interview Guide - Residents

Interview Guide - Firefighters

Usability Test Script - Traffic Simulator

Usability Test Script - Educational Web Page