Report GIRS-2022-03 | DOI:10.34948/G4159S

Wildfire Egress Model and Simulation Platform

Mohammad Pishahang, Enrique Droguett, Marilia Ramos, Ali Mosleh

Prepared for
Pacific Gas and Electric Company

Wildfire Egress Model and Simulation Platform

Mohammad Pishahang, Enrique Droguett, Marilia Ramos, Ali Mosleh

Report GIRS-2022-03
DOI:10.34948/G4159S

Prepared for
Pacific Gas and Electric Company

The B. John Garrick Institute for the Risk Sciences
University of California Los Angeles

February 2022

Published by: The B. John Garrick Institute for the Risk Sciences, UCLA
www.risksciences.ucla.edu

Abstract

Wildfire is a significant threat to many communities in Wildland Urban Interface (WUI) areas and ensuring an efficient evacuation of these communities in case of wildfire is a pressing challenge. Efficient evacuation planning needs a comprehensive understanding of human decision-making, fire dynamics, and transportation aspects. This report documents the results of a PG&E sponsored project to develop a framework for realistically modeling WUI evacuation for planning and decision-making. The resulting model, WISE – Wildfire Safe Egress – Platform, integrates critical egress elements through a unique risk-based approach for estimating the probability of safe evacuation of a community. WISE is implemented as a web platform, allowing users to perform egress assessment for a given community in a visual GIS-based environment.

Keywords: Wildfire, Egress, Evacuation Planning

Acknowledgments

The WISE research and development team would like to express their special gratitude to Pacific Gas and Electric Company (PG&E) for sponsoring and technically supporting the project. Particularly, we thank Mr. Jon Eric Thalman and Mr. Paul McGregor for their availability and detailed technical discussions, insightful comments, and suggestions. We also would like to thank the PG&E fire safety specialists (Mike Weaver, Rob Cone, Mike Webb, David Hawks, and Donovan Lee) for the priceless experiences shared with our team. The meetings with these experts provided important insights on identifying the relevant attributes impacting the WUI communities evacuation and calibrating the model.

Contents

List of Figures

List of Tables

Executive Summary

Ensuring an efficient evacuation of Wildland Urban Interface (WUI) communities in case of wildfire is a pressing challenge. Wildfire evacuation modeling can be characterized by three main aspects: fire model, human decision-making, and traffic models. An efficient evacuation planning needs a comprehensive understanding of these aspects and their mutual interactions. A number of methods have been proposed for wildfire evacuation assessment focusing on each of these components, but few address the issue considering all these layers.

This report presents the Wildfire Safe Egress (WISE) framework for probabilistic evacuation planning in the case of wildfires. The WISE framework integrates a human decision model, a traffic model, and wildfire dynamics model for estimating the probability that a community safely evacuates when in danger by a wildfire. The likelihood of safe evacuation is calculated by probabilistically comparing two competing parameters: (i) the Available Safe Egress Time (ASET), which determines the total amount of time before the fire reaches a community's border; and (ii) the Required Safe Egress Time (RSET), that determines the time a community needs to safely evacuate. These variables are modeled through a Bayesian Belief Network (BBN). WISE adopts an agent-based approach for estimating the time for community members to evacuate, based on their socio-demographic profile. The different times are inputted to the agent-based traffic model through a Monte Carlo simulation of a Poisson distribution. Then, a traffic model considers routes the evacuee may choose, while considering every road segment. Finally, the RSET is estimated as the summation of the pre-evacuation time and the travel time for each agent (member of the community). These elements are integrated into the BBN along with the Available Safe Egress Time (ASET) for calculating the likelihood of safe evacuation of the community. WISE is implemented as a web-based software platform, allowing users to have a practical egress assessment in a visual GIS-based environment.

WISE was calibrated using the Camp Fire as a test case. The results were compared to published reports on the Camp Fire progress and evacuation process, and PG&E experts firsthand experience with the fire. The results were considerably similar to the real case. A sensitivity analysis demonstrates the impact of different aspects on a successful evacuation, such as an efficient evacuation warning system.

The project’s unprecedented integration of fire dynamics, traffic model, and human behavior model for WUI evacuation into one platform is an essential step towards more realistic evacuation models. The model and software application aimed at predicting, at this stage, the success of an evacuation. Granularity could be increased in many parts of the model and software so that they can be used for additional decision-making prior and during evacuations, such as i) localization of the most vulnerable populations for reinforcement of evacuation efforts, ii) decision on when to warn certain communities considering the time it takes for the community to evacuate, iii) identification of the best routes for evacuation, iv) comparison between different evacuation strategies, e.g. phased evacuation and total evacuation.

1. Introduction

Wildfires pose a significant threat to many communities in Wildland Urban Interface (WUI) areas worldwide. According to the National Interagency Fire Center, in 2021 there were 58,985 wildfires in the U.S., burning about 7.1 million acres [1]. Wildfires cause property damage, assets loss, human casualties, and environmental destruction every year and can be considered one of the most significant natural hazards affecting many communities in California. In the last decade, extreme drought combined with other factors have caused more frequent and severe wildfire incidents in California. Indeed, more than 2 million properties in California were considered at high to extreme wildfire risk in 2021, the largest number of properties of any U.S. state [2].

Wildfires represent a significant concern for electric utilities. On the one hand, utilities' infrastructure can be at the origin of a wildfire. On the other hand, wildfires can damage physical structures leading to service disruption. Pacific Gas and Electric (PG&E) Company is highly affected by these hazards: more than half of the PG&E's service territory is in High Fire Threat Districts (HFTD) Tiers 2 and 3 as recognized by the California Public Utilities Commission (CPUC) in 2018 [3]. Roughly one-third of all PG&E's overhead assets lie in such HFTD areas. These assets include approximately 5,500 line-miles of electric transmission and 25,500 line-miles of distribution assets [3].

Wildfire risk management comprises several aspects, ranging from wildfire prevention, mitigating wildfires consequences, to ensuring communities' safe evacuation when in danger of a wildfire. The latter, wildfire egress planning, is an active multi-disciplinary research area. Yet, ensuring the safety of WUI communities in case of wildfires is a complex task. It requires a deep understanding of the wildfire dynamics and spread mechanisms, human decision-making processes, transportation systems capacity and availability, among many other related subjects. These topics have been extensively studied by researchers. Transportation engineers tend to focus on vehicular traffic modeling of evacuation. They mainly concentrate on the available roads network to predict the travel time for the community members during evacuation. Agent-based modeling [4, 5, 6] is the most common methodology used to simulate traffic systems. Such algorithms provide the researchers with a foundation to compare different evacuation strategies [7], simulate multi-modal evacuation models [8], and offer new technologies like cellular data collection to track the evacuees [9]. In contrast, social scientists have focused on human behavior and decision-making processes in emergencies [10, 11, 12]. Despite recent efforts to converge these two essential aspects of wildfire evacuation [13, 14], no framework implements all elements into a complete wildfire egress planning process in a unified and probabilistic manner.

This project aims at developing and implementing a framework for probabilistic prediction of successful egress of a community in case of a wildfire. The framework was developed through the following steps:

- Literature review on the existing methodologies and approaches to addressing the problem,

- Design of a general "workflow" that analysts could follow in egress planning,
- Research and integration of required open datasets for every step of the workflow (i.e., population distribution, demographic data, road network),
- Development and implementation of a Bayesian Belief Network (BBN)-based framework for probabilistic predictions of required times in the evacuation process,
- Selection of a stack of technologies required to implement the framework in a visual and intuitive manner,
- Software implementation of the BBN model,
- Model calibration based on a real-life wildfire incident.

Developing and implementing a wildfire egress planning framework is a complex problem that requires a wide range of expertise. The project leveraged a multi-disciplinary research team from the Garrick Institute for the Risk Sciences at the University of California, Los Angeles (UCLA-GIRS), and wildfire experts from PG&E. UCLA-GIRS team combines expertise in probabilistic risk analysis and management, reliability engineering, human behavior modeling, spatial data analytics, and software development. The project's final product is a web-based application named WISE (Wildfire Safe Egress planning), which models wildfire evacuation by integrating fire dynamics, human behavior, and traffic models in a GIS-based environment. WISE offers a solid infrastructure for further in-depth studies.

The rest of this report is organized as follows. Chapter 2 discusses the basic concepts and explains the platform structure and workflow. Chapter 3 describes how the model was calibrated with an actual wildfire event. As one of the most destructive fires in California, the Camp Fire was used for model calibration. Chapter 4 discusses opportunities for extensions and enhancements of WISE. Finally, Appendix A provides a step-by-step tutorial of WISE software platform.

2. Wildfire Safe Egress Model and Simulation Platform

Wildfire egress planning consists of three main layers: fire dynamics, human decision-making, and traffic model. Wildfire dynamics are mainly affected by the available vegetations as fuel, weather conditions, and topography of the area. The human decision layer includes the population distribution, demographic characteristics of the society, and the quality of the warning systems. Finally, the traffic model is a function of road network configurations, the available transportation modes, and weather conditions, among many other factors.

Together, these three layers form a complex system in which the components have tight interactions. Wildfires can directly affect the human decision layer. For instance, the visual sighting of the fire or the smoke may encourage people to evacuate faster, or to seek shelter in place. The fire can also affect the communication infrastructure and cause delays in the evacuation process. On the other hand, people may decide to take actions to decrease fire expansion rate, or to suppress the fire. Therefore, the fire dynamics can be affected by human decisions. Wildfire can also impact the traffic as it may change the availability of certain roads or transportation modes. Traffic congestion could cause problems in the firefighting efforts. The interaction between human decisions and traffic is also significant: departure time, selected transportation mode, and vehicle occupancy directly impact the traffic. The traffic congestion status in turn impacts the human decision on the evacuation timing and route. Figure 1 illustrates the flow of data among these three layers.

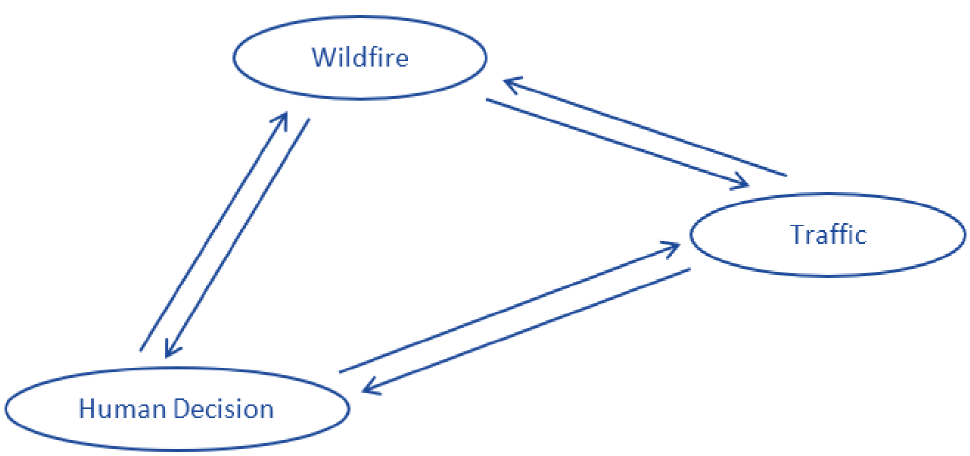

Figure 1: Flow of data and interactions between the three main layers in wildfire egress

A robust evacuation planning framework needs a comprehensive analysis of all these layers as well as their interactions. To address such challenge, WISE framework employs a Bayesian Belief Network (BBN) in which the components and their dependencies are modeled in a probabilistic manner. Figure 2 presents the BBN's main nodes (i.e., uncertain variables). The pre-evacuation time determines the evacuation demand curve (departure times), affecting the traffic model. The traffic model and the pre-evacuation time form the Required Safe Egress Time (RSET). On the other hand, the fire dynamics determine the Available Safe Egress Time (ASET). It also provides flexibility to the analysts should they want to create and compare different evacuation scenarios. Finally, the probability distribution characterizing the likelihood and uncertainty of a successful evacuation scenario is obtained from the RSET and ASET nodes.

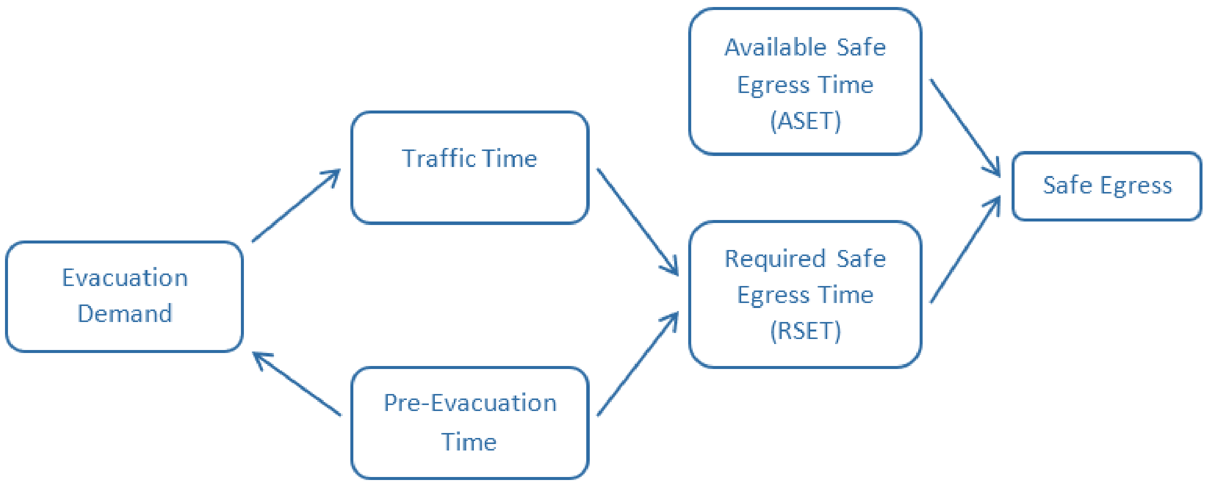

Figure 2: Bayesian Belief Network of the wildfire evacuation process

2.1 Software Platform Architecture

The WISE framework is implemented using web technologies. Figure 3 shows the architecture, components, and modules of the platform. All the datasets are collected in a PostGIS database at the lowest layer. The complete California roads network, gridded population distribution, and demographic tracts are stored in various databases. An Application Programming Interface (API) server is the main “backend” module that interacts with the PostGIS database and a separate computational server.

The frontend is developed as a web application and runs inside a browser. A web GIS environment offers a user-friendly graphical interface to create the evacuation scenarios, run simulations, and visualize the results. Several modules are implemented for different tasks in the application, including probabilistic analysis, human behavior analysis, routing, and traffic modeling. These modules receive user inputs from the GIS environment, communicate with the API server, and generate the results. Most of the heavy computations, such as finding the optimum path (route) between two points, are performed inside the database and the computational server.

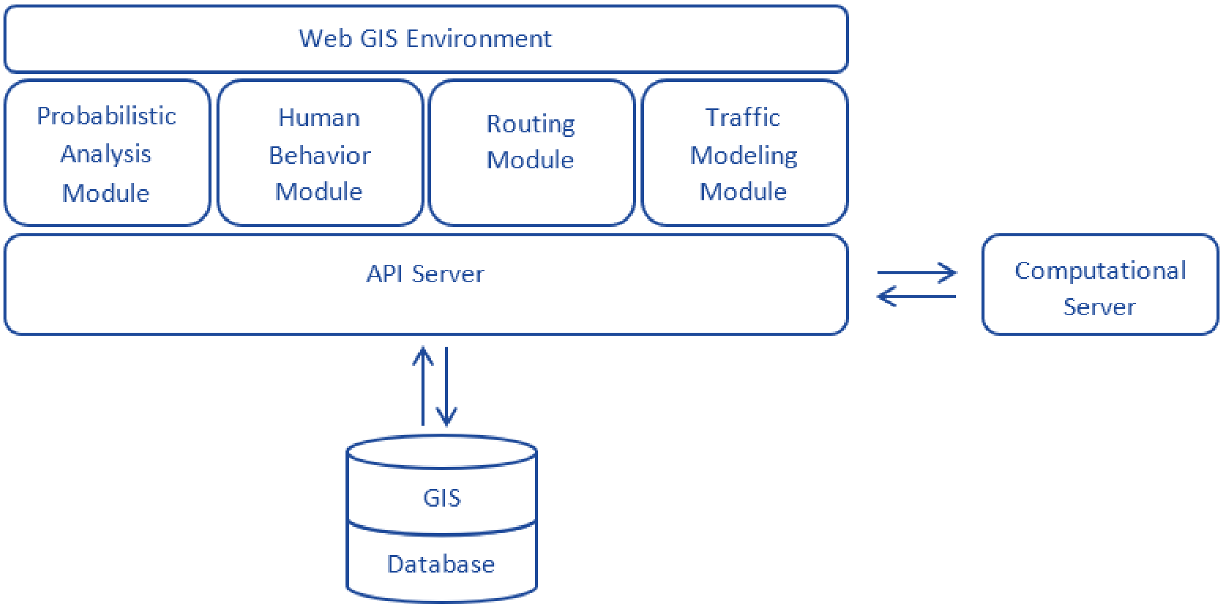

Figure 3: WISE platform architecture

2.2 WISE Modeling and Analysis Flow

In the WISE platform, the user first creates a specific evacuation scenario. Each scenario consists of five main elements: fire, community, safe zone limit, shelter, and warning system. Figure 4 presents the platform workflow, described in this section.

The fire spread model is the first input to the platform. The model is used to calculate the available safe egress time and is required to model the human behavior. After importing the fire spread model, an endangered community can be defined by drawing a map's polygon. This polygon is used for the population extraction in the community and its socio-demographic characteristics from the database. The evacuation warning system is another input required for human behavior modeling. The pre-evacuation stage is then estimated through human awareness, decision, and mobility times.

Knowing the community population and the average pre-evacuation timing for each member, the evacuation demand curve is generated through a Poisson process. In this step, the departure time for each agent (member of the community) is simulated through sampling from a Poisson distribution, which is characterized by the pre-evacuation stage. In addition to the departure times, a shelter point and the safe zone limit are necessary for traffic modeling. The shelter point determines the destination of the agents. However, they can be considered safe when the agents are far enough from the fire (determined by the user-defined polygon defining the safe evacuation zone). The WISE platform uses an agent-based method for traffic time modeling. The pre-evacuation time and traffic time are the two components that determine the required safe egress time for each agent. Finally, the probability of safe evacuation of the community is calculated based on the previous steps.

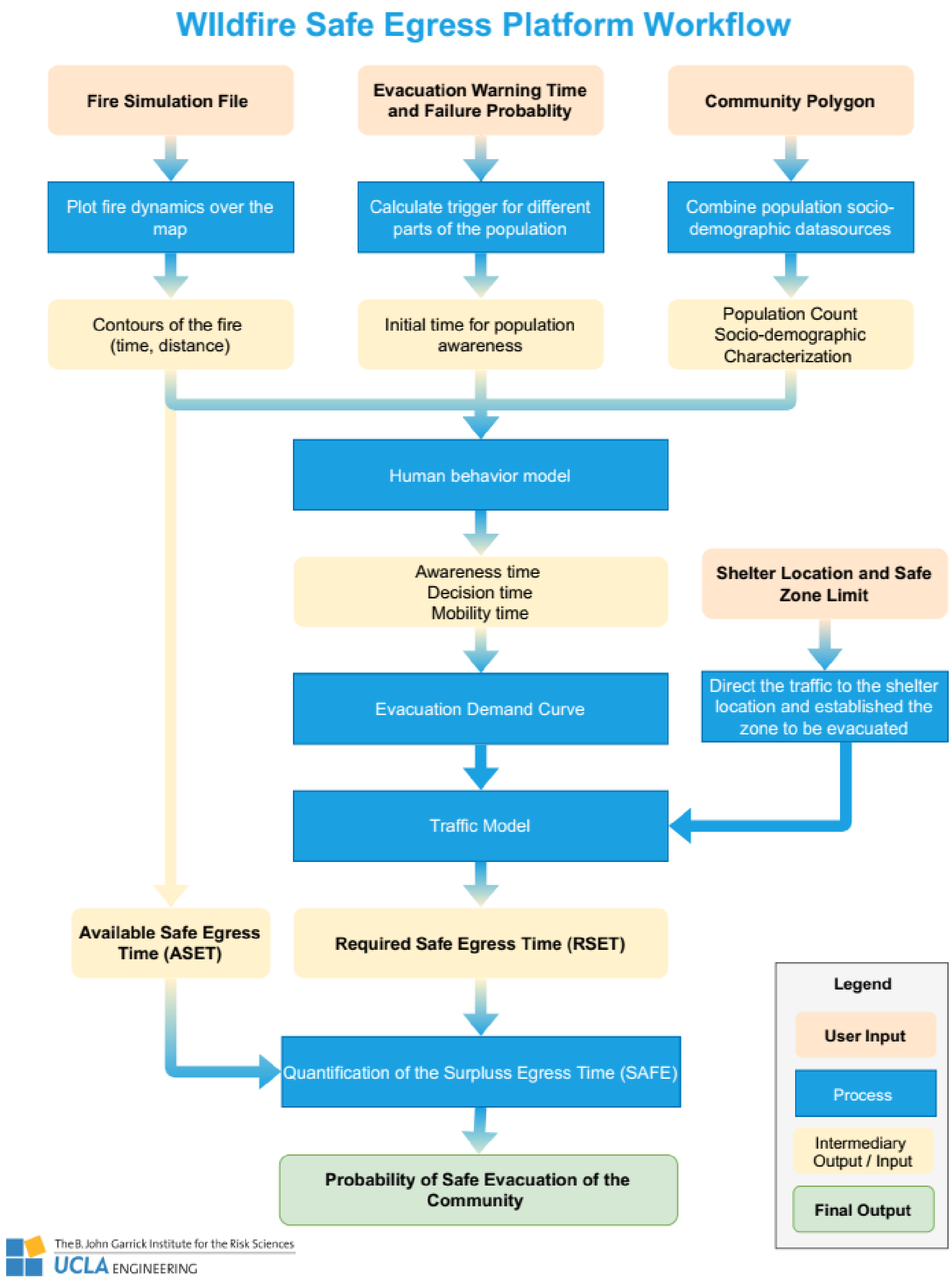

Figure 4: WISE platform analysis flow

2.3 Scenario Creation

2.3.1 Fire Dynamics Simulation

The WISE platform is fire simulator agnostic. Therefore, any wildfire simulation solution which generates the compatible format can be used, i.e., the only required data for fire dynamics is a raster file containing the fire arrival time for each pixel. For example, the pilot and validation process described in this report were obtained based on results from wildfire simulations with FlamMap. By importing the fire dynamics file into the platform, the model is stored in the database, and a representation of the fire will show on the map. This fire model helps the user to define the endangered community. Moreover, the fire model determines ASET parameter.

2.3.2 Community

The community of interest is identified by drawing a polygon on the map. Then, the platform queries the population of grid cells inside this polygon. The characterization of the community merges two data sources for better defining the population count and the profile of the population – which are used to model human behavior. First, U.S. Census tracts are used to define a population. Then, WorldPop [15] is used to estimate the population count within cells of 1km x 1km, plotted on top of the census tract. Figure 5 presents the tracts (in pink), and the cells (in blue). The advantage of using the U.S. Census Tracts is that it allows using the CDC Social Vulnerability Index (SVI) data, as will be discussed in Section 2.4.

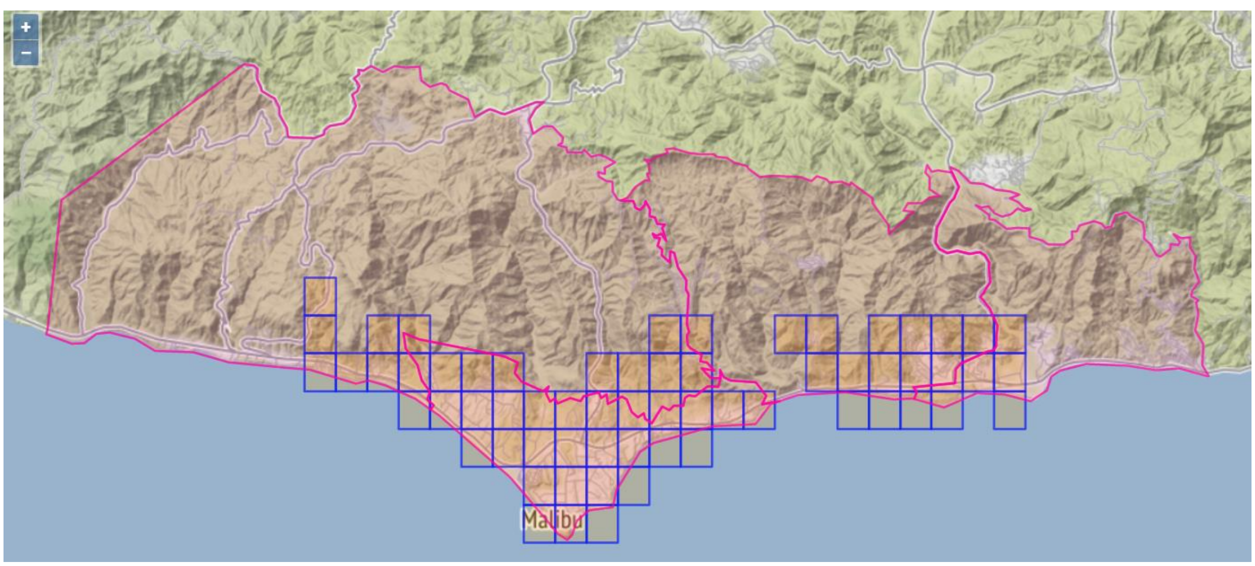

Figure 5: Combination of WorldPop data and U.S. Census tracts

2.3.3 Shelter & Safe Zone Limit

A shelter point is another essential part of the egress scenario. The shelter location indicates to which direction the evacuees will be directed. Thus, the shelter does not need to be a specific place with high capacity to guarantee to accept all the evacuees. The shelter location is combined with a safe zone limit to estimate when and where the evacuees are safe from the dangers of the fire. The user draws a polyline on the map, which separates the *safe zone* from *the endangered zone*. Although the shelter point is still used as the destination for all evacuees, only the travel time before crossing the safe zone limit will be considered part of RSET.

2.3.4 Warning System

As discussed in previous sections, awareness time is a critical part of pre-evacuation time. The initial trigger for community awareness is an evacuation warning, or the fire proximity (whichever happens first). In addition to official evacuation alerts, a community may learn about the upcoming wildfire through different communication channels, including TV programs, social media, telephone, and informing the neighbors face to face.

In case of an official evacuation warning, the notice may fail to reach all the population. In this case, the user can input a failure probability. Figure 6 and Figure 7 illustrate the modeling of the awareness time. In Figure 6, it is considered that an official warning is sent to the population with a probability of failure P_{FW}. In this case, a proportion of the community $Pop_W = 1\text{-}P_{FW}$ is alerted when the warning is sent, T_{Warn}. Figure 7 illustrates the case where there is no official warning.

WISE assumes a linear distribution of the information throughout the community, representing the awareness that is obtained through the visualization of neighbors leaving, neighbors alerting each other, or information obtained by social media and television.

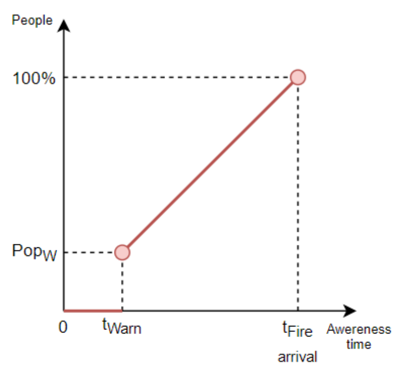

Figure 6: Awareness time with official warning

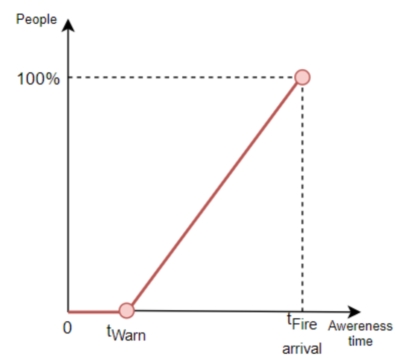

Figure 7: Awareness time without official warning

2.3.5 Evacuation Area

Each agent is modeled as a random point inside the community, and the platform identifies optimum routes between the origin and the shelter point. The routing process is done inside the PostGIS database. Therefore, for each agent, the server needs to perform heavy calculations among every single road segment in California. If the purpose is to do routing and the WUI area around a small city, there is no need to search through all streets in cities far from the area in danger. Therefore, another configuration is added into the scenario creation: the user defines the interested area in which all the egress mission will be performed. Consequently, not only the routing algorithms will perform far faster, but also the evacuation area is explicitly isolated from other places. Figure 8 shows an example of an egress planning scenario.

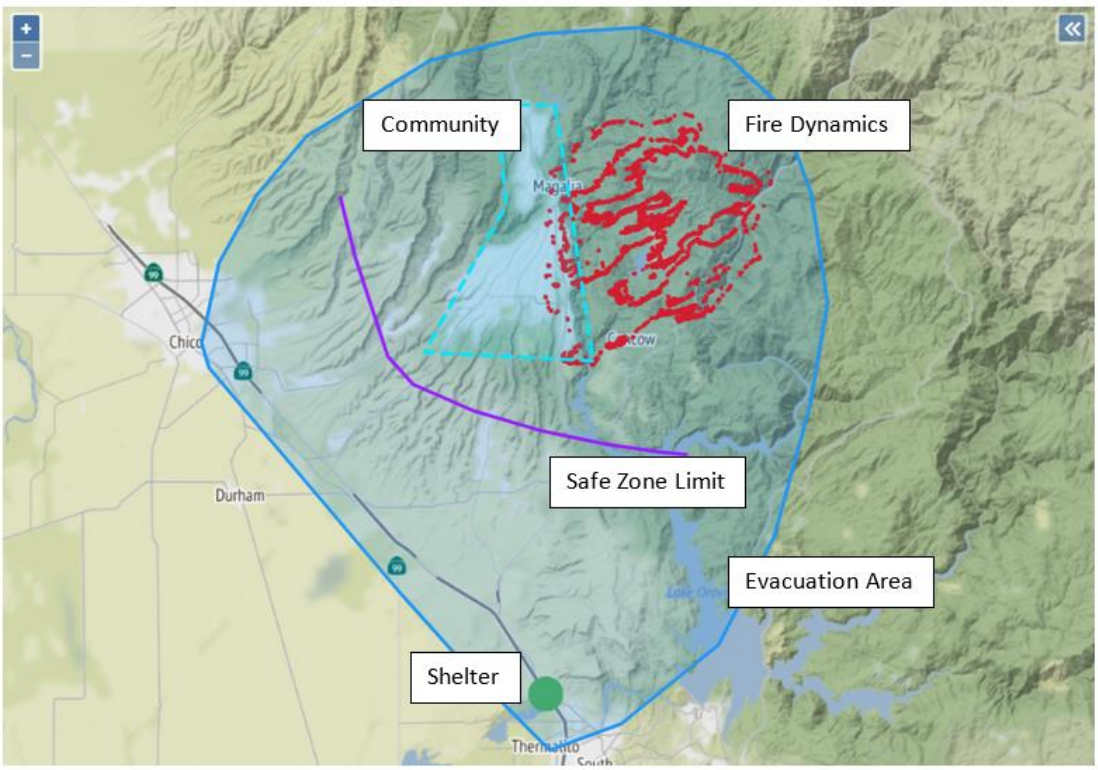

Figure 8: A sample egress planning scenario

2.4 Pre-Evacuation Time (Human Decision-Making)

Human decision-making is modeled for two moments in the evacuation process: the Evacuation Decision Time (EDT) and the Mobilization Time. These time variables constitute the Pre-Evacuation Time to be integrated into the WUI Evacuation Model. During an evacuation, humans decide whether they should evacuate depending on external cues and internal factors. Therefore, the decision to evacuate or stay is not taken at one point in time only. Indeed, as the external factors (such as the approximation of the fire) are dynamic, these decisions are a function of time (Figure 9).

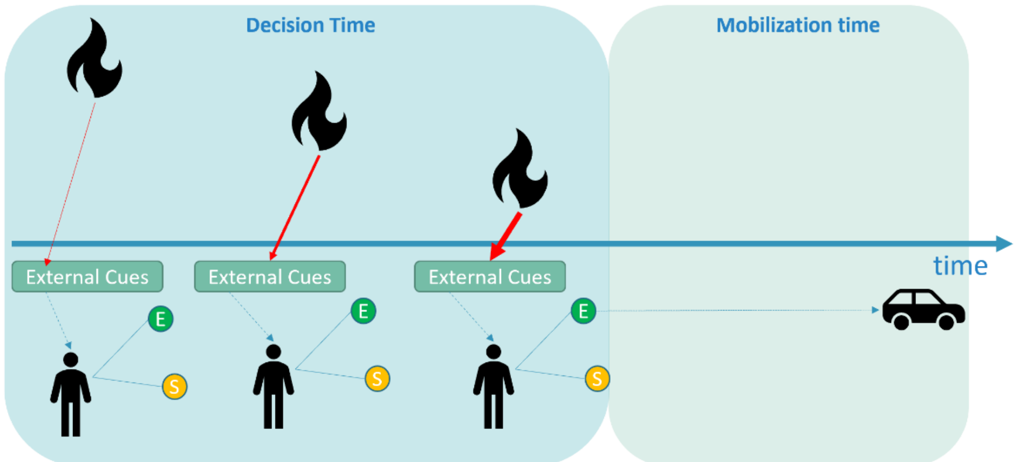

Figure 9: Illustration of decision time and mobilization time

The EDT is the time it takes for an agent to decide to evacuate after receiving and acknowledging a "trigger," which may be an official evacuation alert or visual cues about the need to evacuate (e.g., flames, smoke, neighbors evacuating). The agent may also decide not to evacuate. This situation decision is modeled as an agent that takes "infinite" time to decide to evacuate, i.e., they will not choose to evacuate until the simulation reaches its end.

During an evacuation, an agent may assume different strategies: wait and see, shelter in place (SIP), stay and defend, or evacuate. This model simplifies these strategies as "stay" or "evacuate." Therefore, there is no differentiation between an agent that is sheltering in place and one that is waiting and collecting more information for making a decision.

An agent's decision to evacuate is a function of the agent's Risk Perception (RP) and the Agent's Means (AM). The RP is a function of Internal Factors (IF) and External Factors (EF). The AM is related to the agent's financial and physical means to evacuate, such as car ownership, means for paying for accommodation, and possibilities of missing workdays.

The IFs are related to socio-demographic factors. There is no consensus in the literature about the IFs' impact on the decision to evacuate. For instance, some studies indicate that having children in the household leads to a higher probability of evacuating, while others suggest this is not a significant factor. The EFs include the external cues of the fire proximity and danger posed (flames, smoke), policies in place, and the observation of other agents leaving the area.

The EDT was simplified for the current stage of the egress model development and implementation according to Figure 9. It adopts an agent-based model using the concept of "penalties", and it leverages existing data collected through post-wildfire surveys (Figure 10).

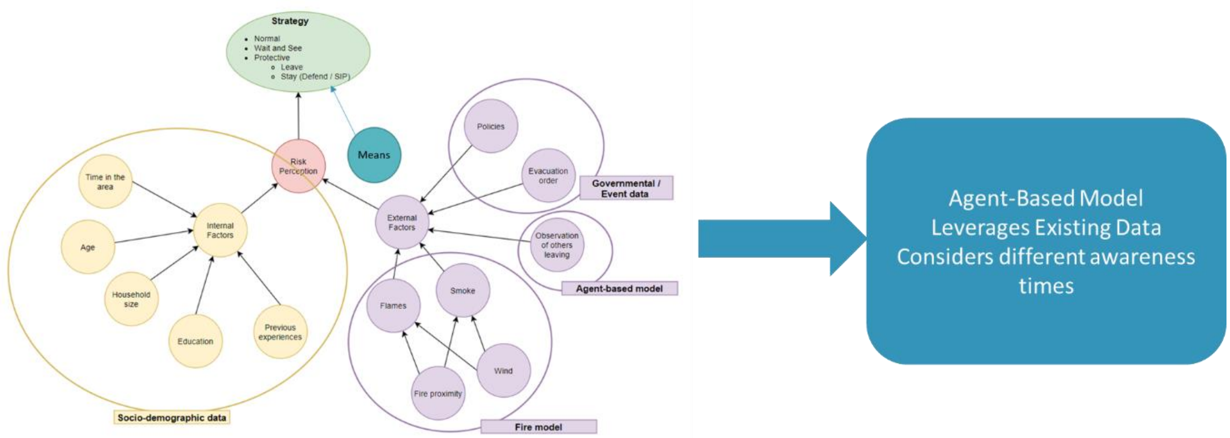

Figure 10: Human decision-making factors

The human behavior model is integrated into WISE through the awareness time, as discussed in Section 2.4.4, and the socio-demographic profile of the community for estimating the “penalties” and the time agents’ take to start evacuating. The SVI indicates the relative vulnerability of every U.S. Census tract. It ranks the tracts on 15 social factors, and further groups them into four related themes (Figure 11). The social factors for which the literature indicates an impact on the evacuation decision and mobilization times, and for which there is data available, are used to estimate the internal factors and the agents’ means.

The tracts are considered homogeneous, i.e., the socio-demographic profile is the same for the agents of the cells within the same tract. The socio-demographic profile of each cell is then estimated using WorldPop and SVI data.

The Pre-Evacuation time is estimated as a function of the time it takes for agents to be aware of the need to evacuate, the time for them to decide on the evacuation, and the time for them to start evacuating:

$$T_{\text{pre-evacuation}} = T_{\text{awareness}} + T_{\text{decision}} + T_{\text{mobility}}$$

For each of these time variables, agents receive a penalty according to socio-demographic profile. The model adopts the times collected data through a post-wildfire survey [12] , as shown in Table 1. Note that these estimates were collected for a rapid fire (Camp Fire). Rapidly advancing fire scenarios pose more challenges concerning the evacuation of the population, and they require a faster decision and evacuation. The validity of these penalties to other scenarios must be further investigated.

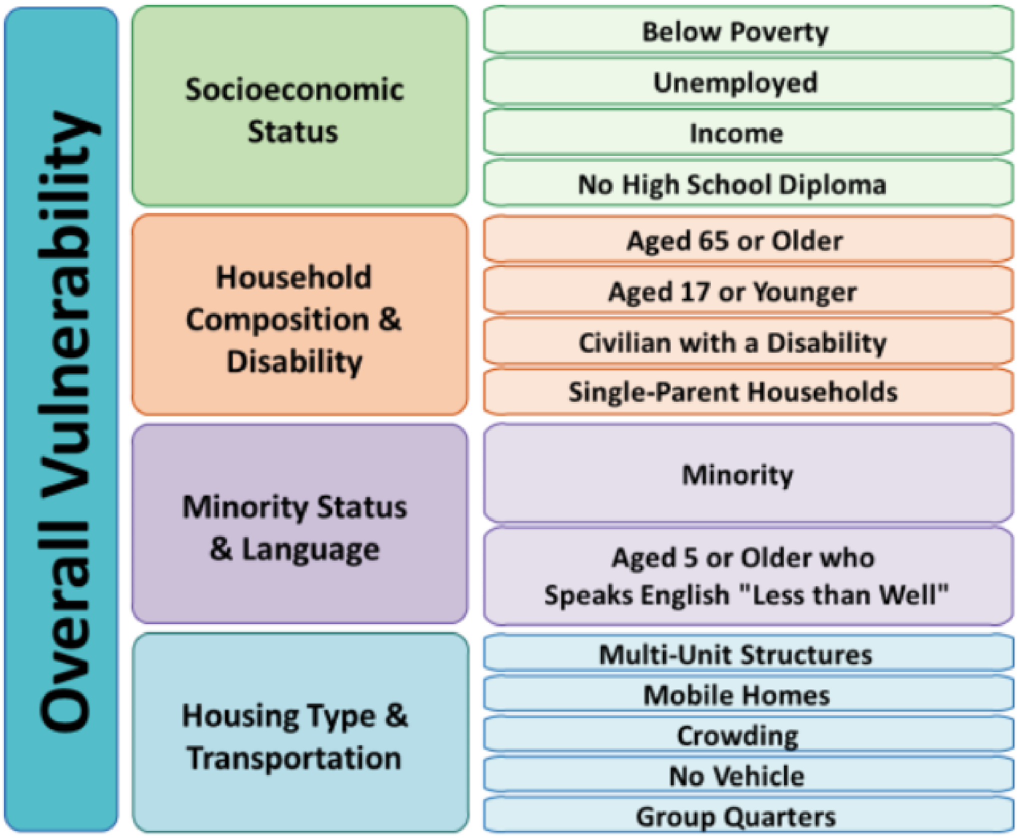

Figure 11: CDC SVI Data

Table 1: Time penalties

Category	Penalty (min)			
	Awareness	Decision	Mobility	total
Elderly (60 years +)	34	37	30	101
Disability			30	30
Income is less than 50k/year	23	37		60
Low English level	29			29
No vehicles on the household				1000

2.5 Evacuation Demand

The pre-evacuation time determines the average amount of time that an agent with a given socio-demographic profile takes before evacuation. However, not all agents start evacuation travel together. Therefore, one must employ a simulation method to generate random departure times for different agents. WISE uses Monte Carlo simulation from a Poisson process for this purpose. Assuming that every agent spends t_0 minutes before evacuation, the evacuation rate is $1/t_0$. This means that for the specific group of agents, one agent starts the travel on average every 1/t0 minutes. The evacuation demand can be modeled through a Poisson distribution with this parameter. For each agent in that group, we can sample a random number from such probability distribution. Thus, every agent will have a random departure time so that the average departure time of the whole group is almost equivalent to t_0.

2.6 Traffic Modeling

The exact origin point of the evacuees is not known, but the destination of all evacuees is the shelter point. WISE generates random points inside the community polygon for every agent. Then, the optimum route the evacuee may choose is calculated using the shortest path routing algorithms. Note that the shortest path does not imply the shortest distance. Every road segment has a traffic cost based on attributes, such as road type, number of lanes, and the segment length. The routing algorithm finds a list of connected road segments from origin to destination with the minimum total cost. *PgRouting* is the routing engine used in WISE, and it performs all the calculations inside the PostGIS database. Although database-level routing is somewhat slower than some other routing options, it provides great opportunities for the platform. The first and the most important benefit of this approach is that the costs of the road segments can be modified dynamically during the simulations. Thus, when some agents are in the same road segment together, WISE automatically increases the traffic cost of that segment, and the next agents will search the optimum routes using the modified costs. Consequently, it is possible to appropriately model traffic congestions. These traffic jams will increase the travel time for corresponding agents and directly affect the probability of a successful egress mission.

2.7 Successful Safe Egress

The last section of the egress planning is a comparison between the Required Safe Egress Time (RSET) and the Available Safe Egress Time (ASET). RSET is the summation of the pre-evacuation time and the traffic time for each agent. On the other hand, ASET depends on the fire dynamics and determines the amount of time the community has before the fire enters the community polygon. Both RSET and ASET are histograms calculated through the previous steps. Comparing these two histograms results in a new histogram which shows the surplus safe egress time. The result explains the proportion of the agents who could evacuate safely, and the agents who needed more time for safe evacuation. The analysts can change parameters in the model and run the simulations to understand the important components and the general mechanism of the evacuation mission.

3. Test Case and Calibration

WISE parameters were calibrated using the Camp Fire as a test case. Camp Fire was a deadly and extremely destructive wildfire in November 2018 and caused at least 85 civilians' fatalities. The Camp Fire was selected as a test case due to its recency and severity, availability of data on the fire progress and communities' evacuation, and PG&E wildfire fire safety experts' knowledge and firsthand experience with this fire.

First, the Camp Fire was simulated in FlamMap [16]. WISE then estimated the probability of safe evacuation of the Paradise community. A first calibration was performed to adjust the model, such that it could realistically represent the wildfire and evacuation process as described in the NIST report and other publications [17]. The results of the calibrated model were discussed with PG&E fire safety experts for validation. The experts provided the WISE development team with many details of the Camp Fire evacuation scenario and their observations. Accordingly, the community was informed about the approaching wildfire almost one hour before the fire reached the city. They reported that nearly 20% of the residents had evacuated when the fire first arrived at Paradise city.

Figure 12 presents the model inputs for the Camp Fire scenario. The trigger time was set to one hour before the fire entered the city. Also, the warning system failure probability is assumed to be one, i.e., the population becomes aware of the need to evacuate following a linear distribution starting one hour before the fire enters Paradise. This is consistent with the real-life events in which the official evacuation warnings failed to reach the population successfully. The simulation of the Camp Fire in WISE shows that, with the defined scenario, almost 16% of the people could evacuate safely before the fire touches the borders of the city, a result close to the 20% indicated by the fire safety experts. Figure 13 shows that a significant portion of the community required almost 150 additional minutes to evacuate safely.

In addition to the results in Figure 13, a sensitivity analysis was performed for different model parameters. The percentage of the community being evacuated was calculated for different time periods, and the results were significantly close to the fire safety experts' reports. The sensitivity analysis is discussed in more detail in the next section.

The calibration process and successful assessment of the model results show that the modular structure of WISE the general workflow, assumptions, and model granularity are good foundations for further research and development of the topic.

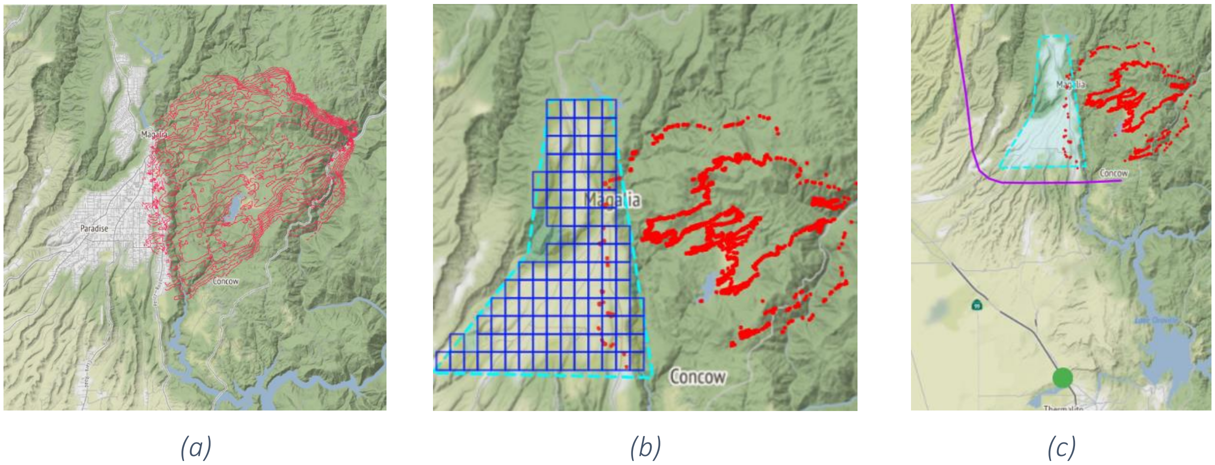

Figure 12: Camp Fire scenario. (a) Fire simulation, (b) community, (c) shelter & safe zone limit

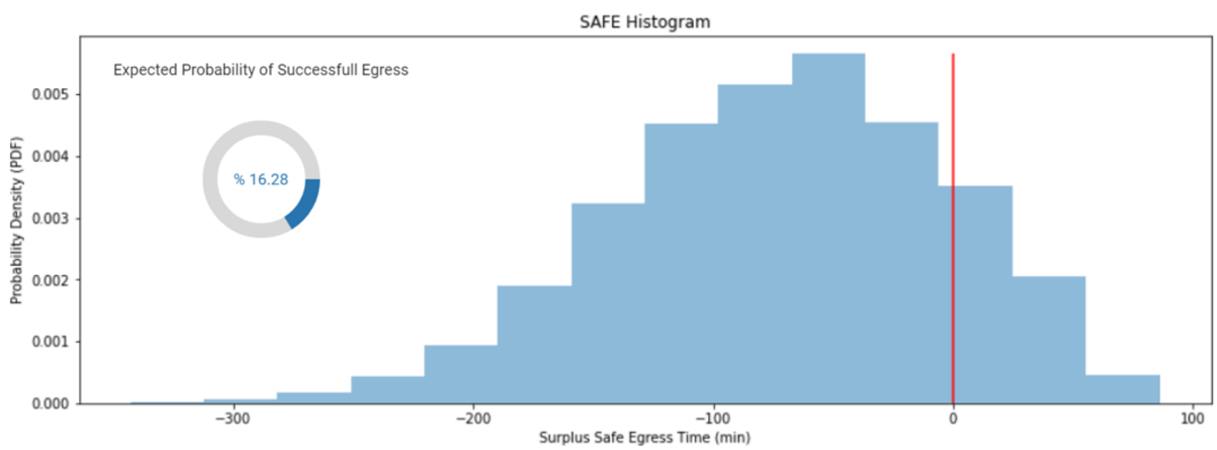

Figure 13: Camp Fire surplus safe egress time histogram

3.1 Sensitivity Analysis

After calibration, many different scenarios were created to evaluate the effect of each parameter in the results. The sensitivity analysis was performed for ASET, different socio-demographic parameters, and the warning system parameters. Figure 14 shows 15 scenarios in which the only changing parameter is ASET. The graph shows that for the given case study, if the community has one hour for egress, only 16% of the population can evacuate safely. However, if the community had 4 hours to egress in the same situation, more than 88% of the population could leave the danger zone before the fire reaches the borders of the city. The same graph demonstrates that in 6.5 hours, almost all the community could be safely evacuated.

These results explain the impact of ASET in a successful evacuation. ASET is tightly linked to the trigger for community evacuation. Although Camp Fire was an extremely fast-moving wildfire, the absence of a successful evacuation warning system played an essential role in losing precious time for evacuation. Proper infrastructure for detecting the fire in its early stages, evaluating the fire dynamics, and informing the citizens, could provide the community with a couple of additional hours for safe egress.

Table 2 provides the sensitivity analysis for time penalties during the pre-evacuation time assessment. This table assumes the same scenarios as Figure 14 with 120 minutes available for Safe Egress Time as the initial condition. The table illustrates that the preparedness of the community can significantly affect the success of an egress mission. Educating the community about probable wildfire threats prior to the catastrophic events, offering public transportation for families without a vehicle, and reducing the warning system failure probability, considerably increase the percentage of the community that can be evacuated safely.

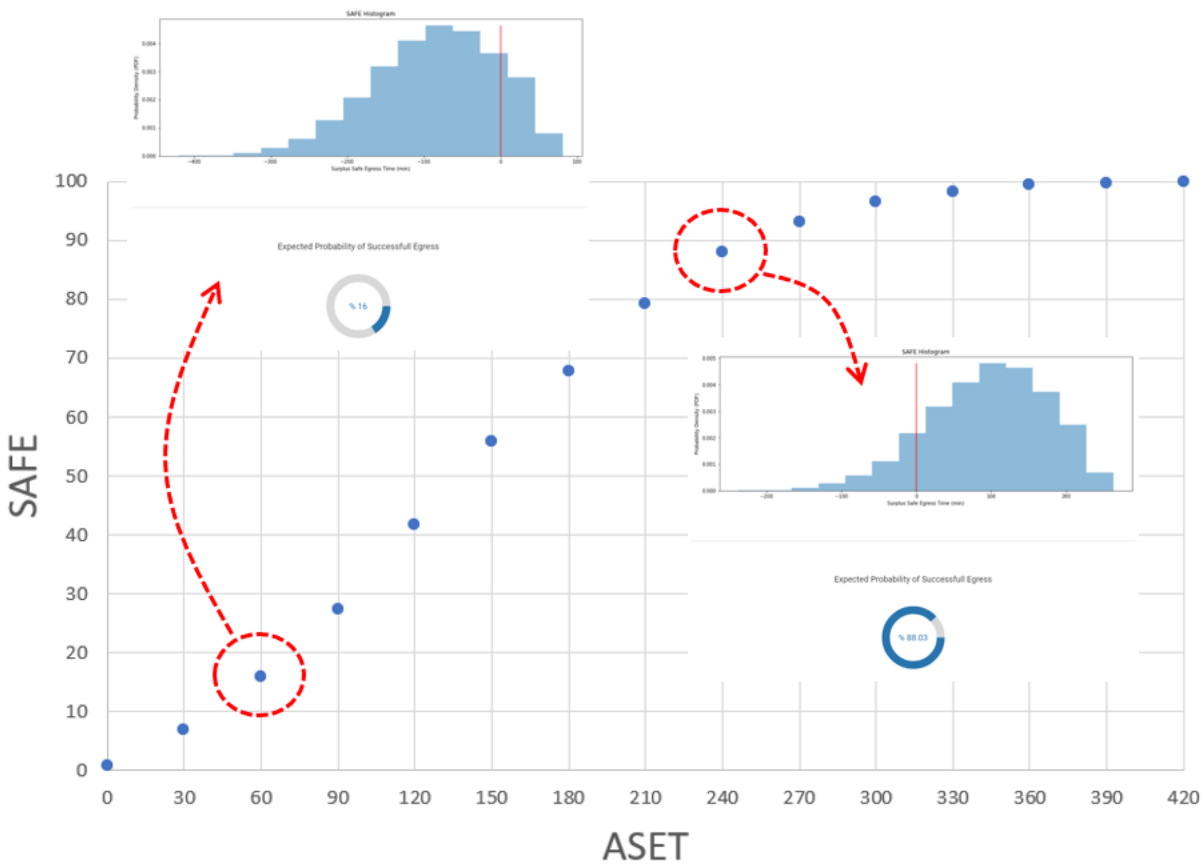

Figure 14: Sensitivity analysis of ASET

Table 2: Sensitivity analysis of demographic parameters and warning system

SAFE for Initial Conditions	Modified Parameter		SAFE	Change %
41.69	Penalties	Reduce time penalties for population without vehicle by a factor of 10	58.47	40%
		Reduce time penalties for population without vehicle by a factor of 20	69.54	67%
		Increase time penalties by a factor of 2	22.03	-47%
		Increase time penalties by a factor of 10	6.16	-85%
	Warning Failure Probability (Initial: 1)	0.8	44.2	6%
		0.5	49.64	19%

4. Opportunities for Using WISE for Decision-Making

A first validation of the WISE model through the Camp Fire test case successfully demonstrates that the WISE framework and the corresponding software platform provide a good foundation and unique opportunity for risk-informed, model and data-based evacuation planning.

The modular approach to WISE makes it a flexible platform for enhancing the underlying model, including:

Demographic data and human-behavior model:

- The model can be enhanced with more explicit consideration of the internal factors and their impact on the risk perception. This can be achieved through access to post-wildfire surveys, integration of elements analyzed for other emergency evacuations such as hurricanes, and subject matter expert judgment.
- The impact of other agents' actions (evacuating) on the ego agent can be added in future extensions. This impact is well recognized in the literature.
- The awareness time is modeled as a linear distribution. Other distributions can be explored considering the distances between houses (affecting awareness due to neighbors leaving or neighbors direct communication) and access to social media in different communities.
- The topography is not being modeled in the current human behavior modeling. However, it influences the external cues. For instance, if the community is located in the valley or on top of a hill, then the cues from the fire may be more or less visible.
- It is recognized in the literature that humans tend to make intermediate stops when evacuating, e.g., for picking up relatives. This can be added to the model, in addition to the time of the evacuation. For example if the evacuation takes place during the day, parents may stop at schools to pick up their children.

Transportation:

- Multi-modal transportation analysis could be added. For instance, the municipality may offer buses to expediate the evacuation of the people in some regions,
- Effect of topography can be added to the traffic modeling,
- Possible intermediate stops can be identified and added.

Comprehensive scenario definitions:

- WISE considers one shelter point. Yet, it can be extended for modeling multi-shelter scenarios.
- Evacuation in different times of the day/night.

Data sources and validation

- The model was validated using the Camp Fire. It should be tested against other past fires for further calibration.

Multi-purpose analysis

- The model and software platform were aimed at predicting, at this stage, the success of an evacuation. Granularity could be added to certain parts of the model so that it could be used for decision-making prior and during evacuations, such as:
    - Localization of the most vulnerable populations for reinforcement of evacuation efforts,
    - Decision on when to warn certain communities considering the time it takes for those communities to evacuate,
    - Identification of the best routes for evacuation with further consideration of the human behavior (e.g., intermediate stops),
    - Comparison between different evacuation strategies, e.g., phased evacuation and total evacuation.

5. References

[1] "Fire Information (Statistics: Wildfires and Acres)," National Interagency Fire Center, [Online]. Available: https://www.nifc.gov/fire-information/statistics/wildfires. [Accessed 11 02 2022].

[2] "Verisk Wildfire Risk Analysis," Verisk, [Online]. Available: https://www.verisk.com/insurance/campaigns/location-fireline-state-risk-report/. [Accessed 11 02 2022].

[3] "PG&E 2021 Wildfire Mitigation Plan Report," Pacific Gas and Electric Company, https://www.pge.com/pge_global/common/pdfs/safety/emergency-preparedness/natural-disaster/wildfires/wildfire-mitigation-plan/2021-Wildfire-Safety-Plan.pdf, 2021.

[4] A. Harris, P. Roebber and R. Morss, "An agent-based modeling framework for examining the dynamics of the hurricane-forecast-evacuation system," *International Journal of Disaster Risk Reduction,* vol. 67, 2022.

[5] B. Wolshon, Z. Zhang, S. Parr, B. Mitchell and J. Pardue, "Agent-based Modeling for Evacuation Traffic Analysis in Megaregion Road Networks," *Procedia Computer Science,* vol. 52, pp. 908-913, 2015.

[6] H. Suk Na and A. Banerjee, "Agent-based discrete-event simulation model for no-notice natural disaster evacuation planning," *Computers & Industrial Engineering,* vol. 129, pp. 44-55, 2019.

[7] X. Chen and F. Zhan, "Agent-based modelling and simulation of urban evacuation: relative effectiveness of simultaneous and staged evacuation strategies," *J. Oper. Res. Soc.,* vol. 59, pp. 25-33, 2008.

[8] M. Siam, H. Wang, M. K. Lindell, C. Chen, E. I. Vlahogianni and K. Axhausen, "An interdisciplinary agent-based multimodal wildfire evacuation model: Critical decisions and life safety," *Transportation Research Part D: Transport and Environment,* vol. 103, 2022.

[9] B. Melendez, S. Ghanipoor Machiani and A. Nara, "Modelling traffic during Lilac Wildfire evacuation using cellular data," *Transportation Research Interdisciplinary Perspectives,* vol. 9, 2021.

[10] S. Vaiciulyte, L. M. Hulse, A. Veeraswamy and E. R. Galea, "Cross-cultural comparison of behavioural itinerary actions and times in wildfire evacuations," *Safety Science,* vol. 135, 2021.

[11] E. Kuligowski, "Evacuation decision-making and behavior in wildfires: Past research, current challenges and a future research agenda," *Fire Safety Journal,* vol. 120, 2021.

[12] S. Grajdura, X. Qian and D. Niemeier, "Awareness, departure, and preparation time in no-notice wildfire evacuations," *Safety Science,* vol. 139, 2021.

[13] E. Ronchi and S. Gwynne, "Computational Evacuation Modeling in Wildfires," *Encyclopedia of Wildfires and Wildland-Urban Interface (WUI) Fires. Springer,* no. https://doi.org/10.1007/978-3-319-51727-8_121-1, 2019.

[14] E. Ronchi, S. M. Gwynne, G. Rein, P. Intini and R. Wadhwani, "An open multi-physics framework for modelling wildland-urban interface fire evacuations," *Safety Science,* vol. 118, pp. 868-880, 2019.

[15] A. Sorichetta, G. Hornby and F. Stevens, "High-resolution gridded population datasets for Latin America and the Caribbean in 2010, 2015, and 2020," *Sci Data,* vol. 2, p. 150045, 2015.

[16] M. Finney, "FlamMap," [Online]. Available: https://www.firelab.org/project/flammap.

[17] A. Maranghides, E. Link, W. ". Mell, S. Hawks, M. Wilson, W. Brewer, C. Brown, B. Vihnaneck and W. D. Walton, "A Case Study of the Camp Fire – Fire Progression Timeline (NIST Technical Note 2135)," U.S. Department of Commerce, National Institute of Standards and Technology, 2021.

6. Appendix: Platform Implementation

The WISE platform is implemented as a web application that provides the analysts with an intuitive and graphical environment to create wildfire egress scenarios and analyze the results. This section contains step-by-step workflow of the platform through snapshots of the Camp Fire egress simulation.

Figure 15 shows the first step in which the fire dynamics is imported into the platform. Here, the fire spread is modeled in FlamMap, and the results are stored in a GeoTIFF format. This format is a simple raster file, which includes some additional information such as map projection and coordinate system to make the raster data compatible with GIS-based applications. Note that, however, WISE is not bound to FlamMap. Any other wildfire modeling engine/software can be used. The only requirement is the final raster file containing fire arrival times for every pixel. After clicking the "*RUN*" button in this step, the wildfire raster file is uploaded into the PostGIS database, and a simple representation of the fire is shown on the map. The analyst can list some values between zero and one, and the fire representation will be made by limited pixels corresponding to those percentages of fire progress. In this figure, only pixels corresponding to 5%, 35%, and 100% fire progress are shown on the map.

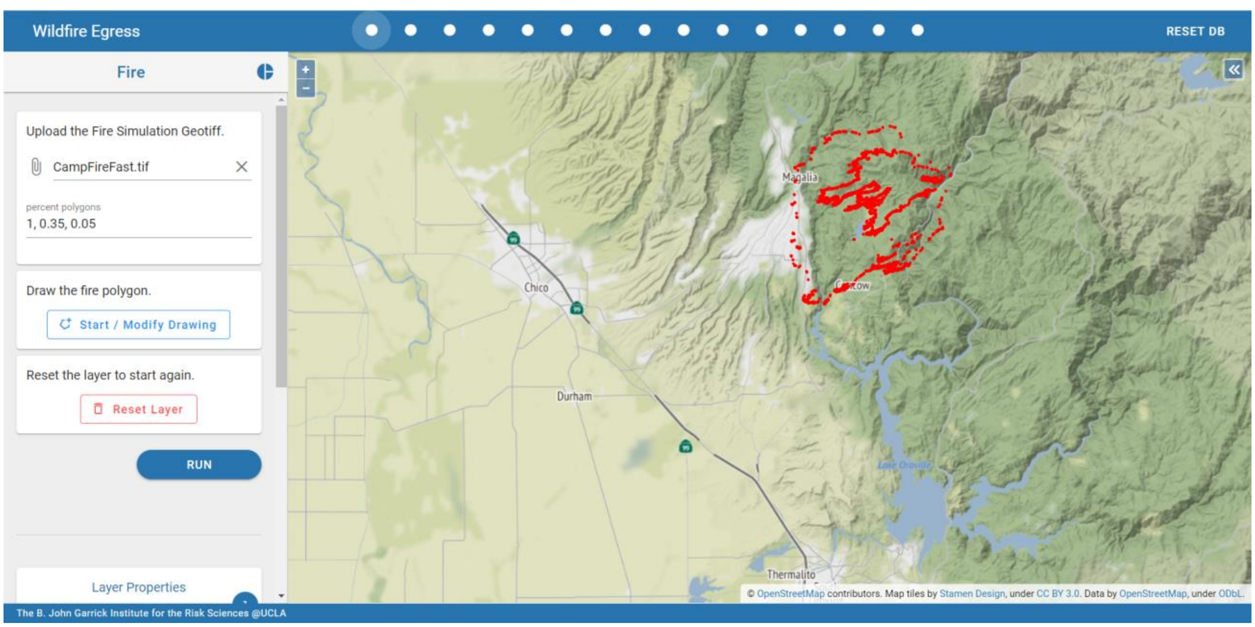

Figure 15: Importing the fire dynamics model into WISE

In the next step, the analyst determines the endangered community by simply drawing a polygon on the map (Figure 16). The fire model, several available base-map layers, and zooming capabilities, help the analyst to draw the polygon properly. It is possible to clear this layer by clicking the "*Reset Layer"* button or even to modify an existing polygon by clicking "Start / Modify Drawing" button. Some additional options are also available to configure the community's layer visual parameters such as color and opacity.

After clicking the *"RUN"* button, the community polygon is saved in the database and all the population grid cells, which their centroids are inside the polygon, are queried and shown on the map. These grid cells are defined by the WorldPop dataset, and each one contains the total number of people living in that roughly 1 km x 1 km area. The gridded version of the community will be used in the next steps to estimate the socio-demographic characteristics of the community.

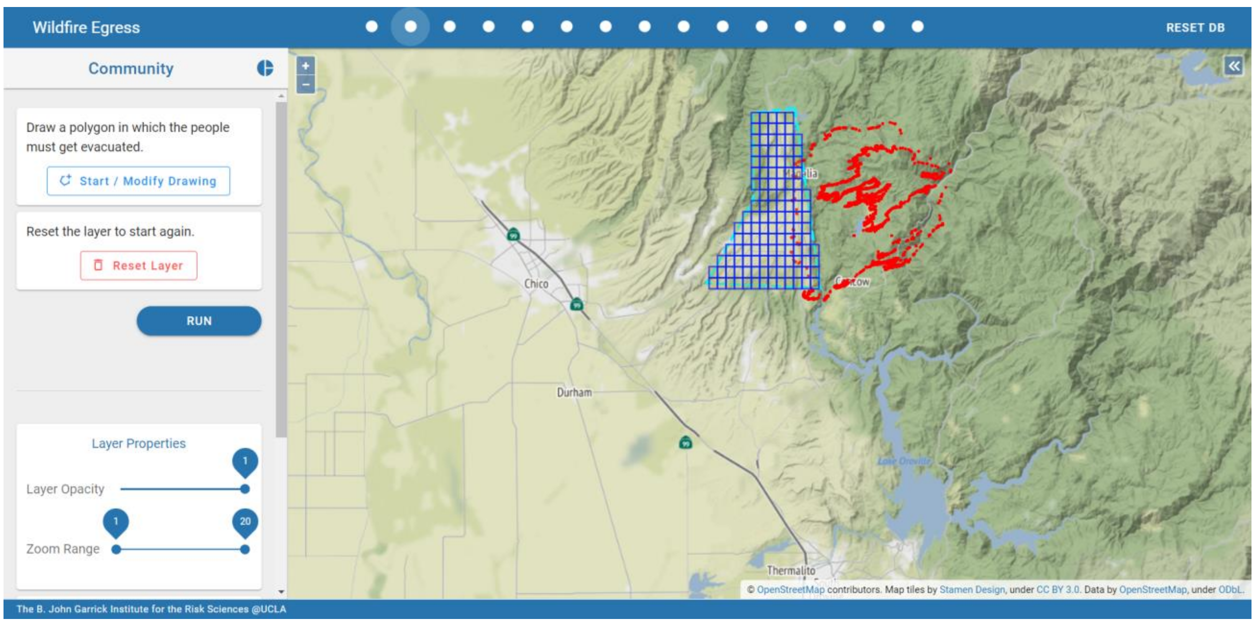

Figure 16: Drawing the community polygon, and gridding the polygon

Figure 17 shows the next step in which the total number of people in the community is estimated from the WorldPop dataset. In this step, the analyst can check the number of people living in each grid cell by moving the mouse cursor over that cell. It is also possible to filter out the cells with population less that certain amount.

The WISE platform also includes a complete CDC Social Vulnerability Index (SVI) dataset for California. Figure 18 shows how WISE queries the demographic tracts which have intersection with the community polygon. Moving the mouse cursor over any tract on the map, some selected features of that tract are shown on the left pane of the page. WISE assumes that the demographic characteristics of the community are homogeneous inside every tract. Therefore, the residents of different tracts would have distinct behaviors in the case of an approaching wildfire.

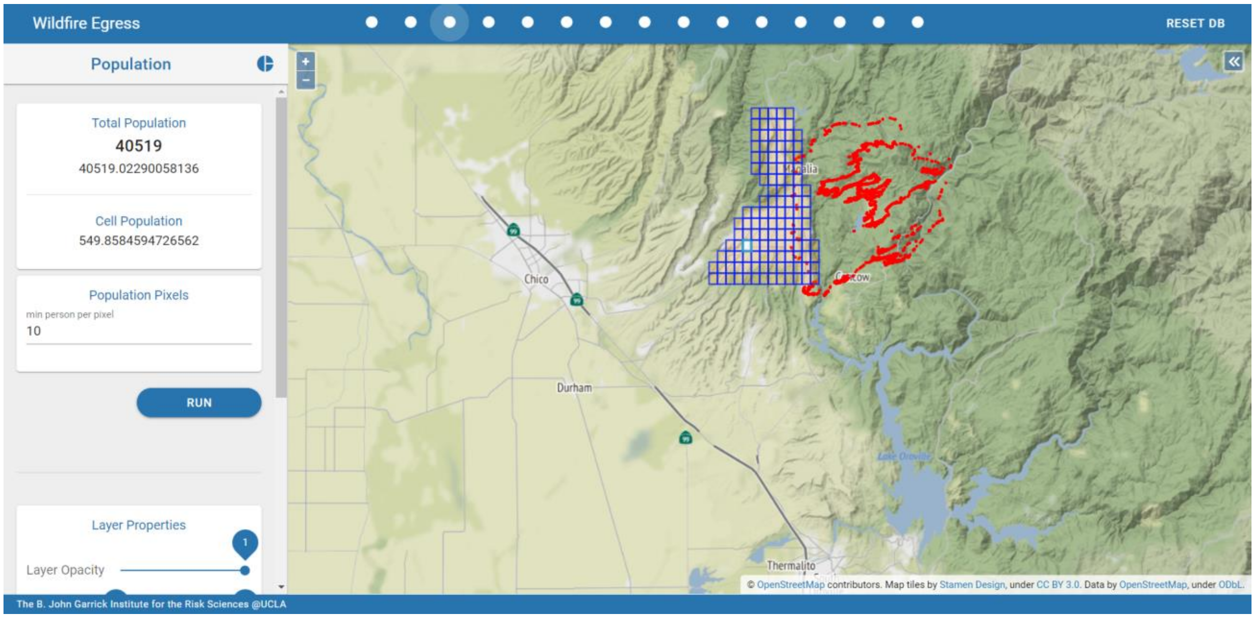

Figure 17: Querying the community population

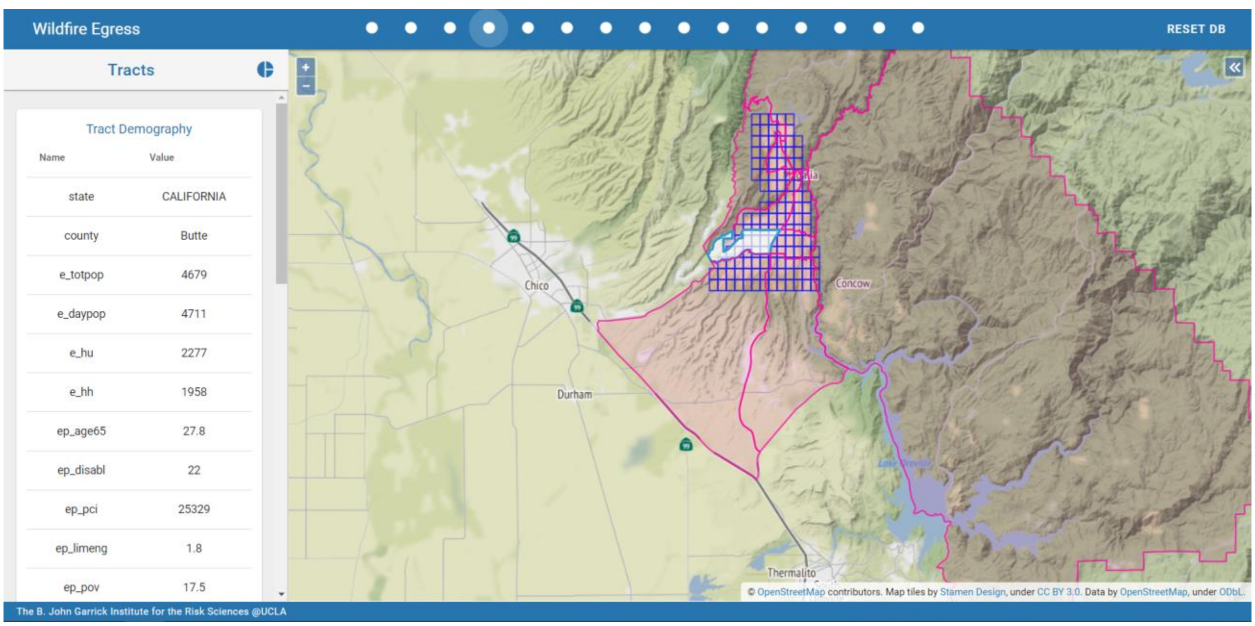

Figure 18: Querying demographic tracts which have intersection with the community

Figure 19 shows the next step in which the WorldPop and the SVI datasets are merged. In this step, for every grid cell, the corresponding demographic tract is found. This way, each cell would have both population and SVI features. The figure shows how analyst can review the characteristics of each cell by moving the mouse cursor on each cell.

Figure 20 shows the next step in which the awareness trigger time and the warning system failure probability are set. WISE finds the first time that the fire touches the borders of community in the GIS-based database. In this case, the wildfire reaches the community after 9.7 hours of ignition. This information helps the analyst to decide correctly about the trigger time by knowing rough estimations and limit for it.

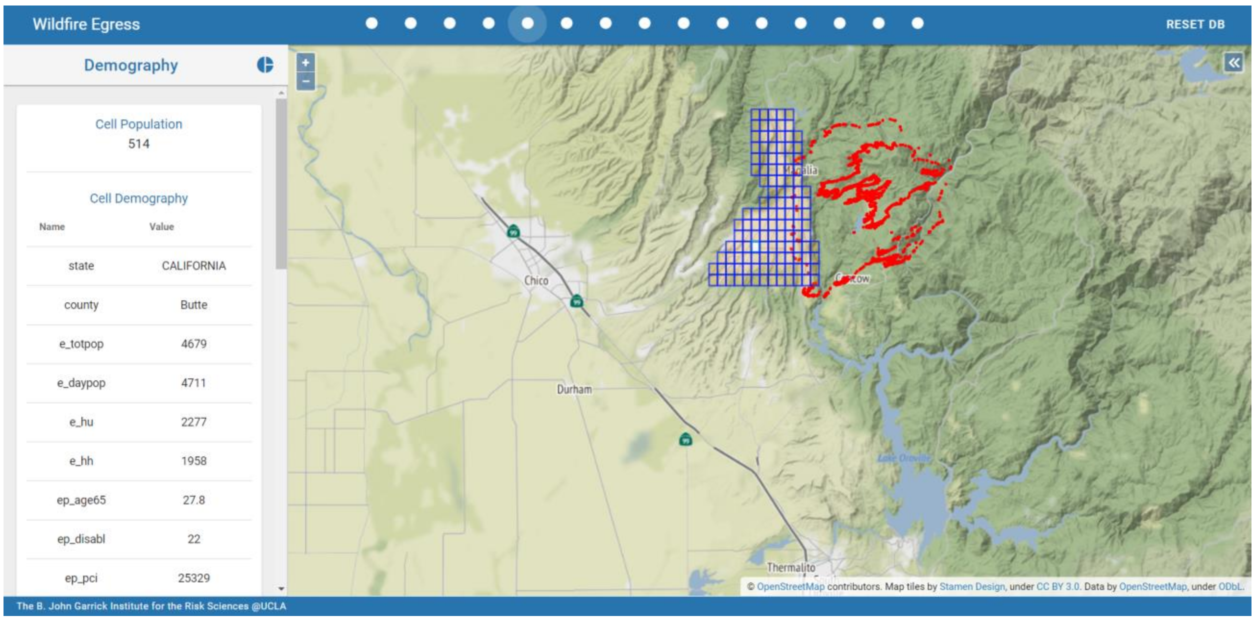

Figure 19: Merging the population distribution and demographic data on each cell of the grid

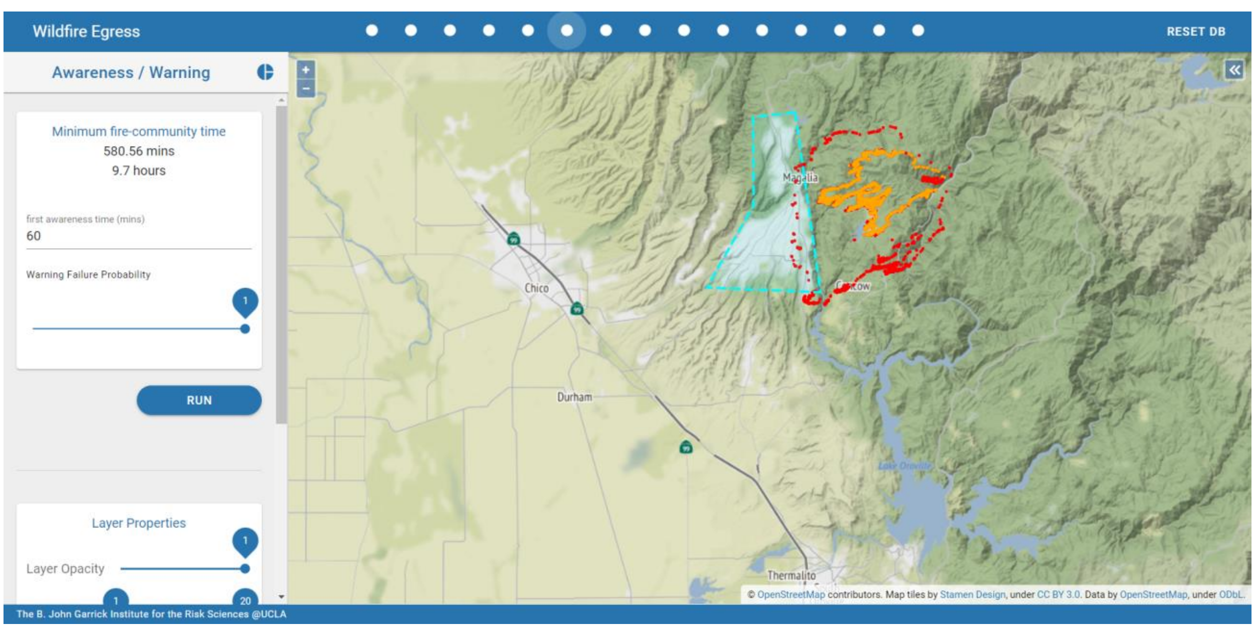

Figure 20: Determining the warning system parameters

Next, for each cell the pre-evacuation time is calculated (Figure 21). The calculation is done through implying penalties for different categories of vulnerable populations. In this page, the penalties can be determined/modified by the analyst. However, the default values are chosen based on the literature and calibrated with the Camp Fire egress case. Similar to previous steps, moving the mouse cursor over the cells helps the analyst to see the corresponding pre-evacuation times.

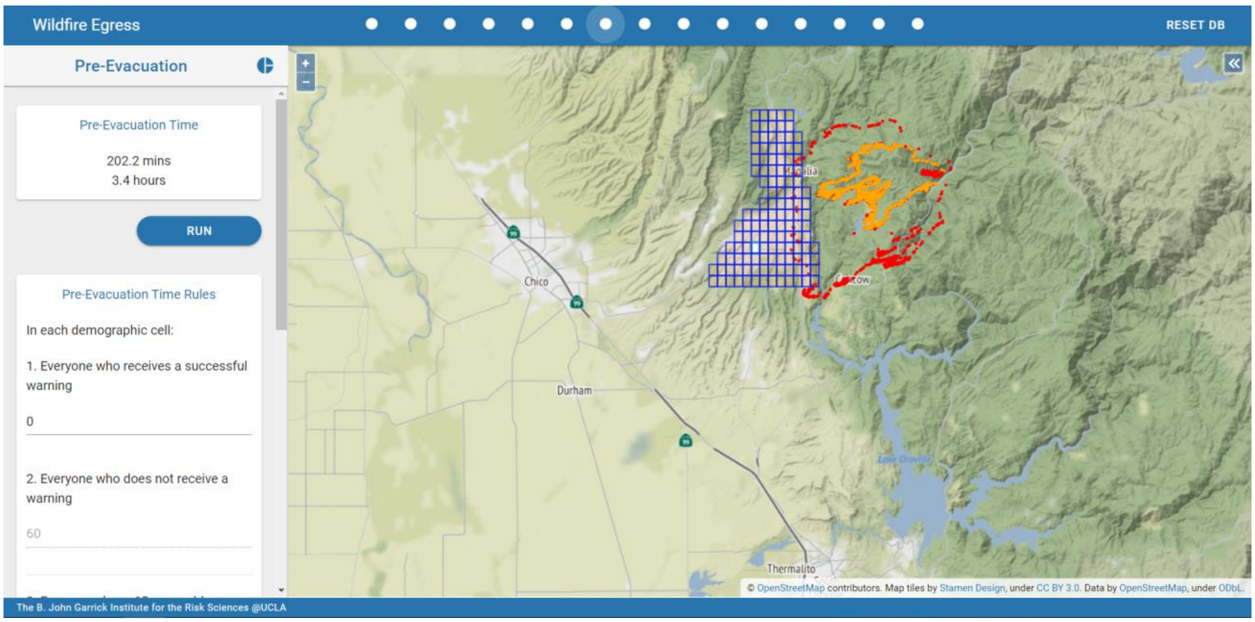

Figure 21: Calculating the pre-evacuation time for each grid cell

Figure 22 and Figure 23 demonstrate how the user adds the shelter point and the safe zone limit to the study. The shelter point is assumed to be a point somewhere far from the danger zone. The evacuees are ordered to evacuate toward the shelter point. However, after going far enough from the wildfire-threatened area, the agents are considered safe although they have not arrived at the shelter yet. This limit is determined by the analyst's judgement. Both shelter and the safe zone limit are drawn graphically on the map.

As discussed in the previous sections, the shelter point will be the destination of all routing processes for the agents. The routing process is done inside a table of the database which includes all road segments in California. This table has almost 2 million records, leading to a computationally intensive routing process. To make it faster we could limit the routing to some restricted area around the fire, the community, and the shelter. Figure 24 shows how the analyst isolates the evacuation area from the outside world by drawing a polygon on the map. By clicking the *"RUN"* button on this page, a new table containing only the road segments inside this polygon will be created in the database. This new table will be used in the upcoming steps in the platform.

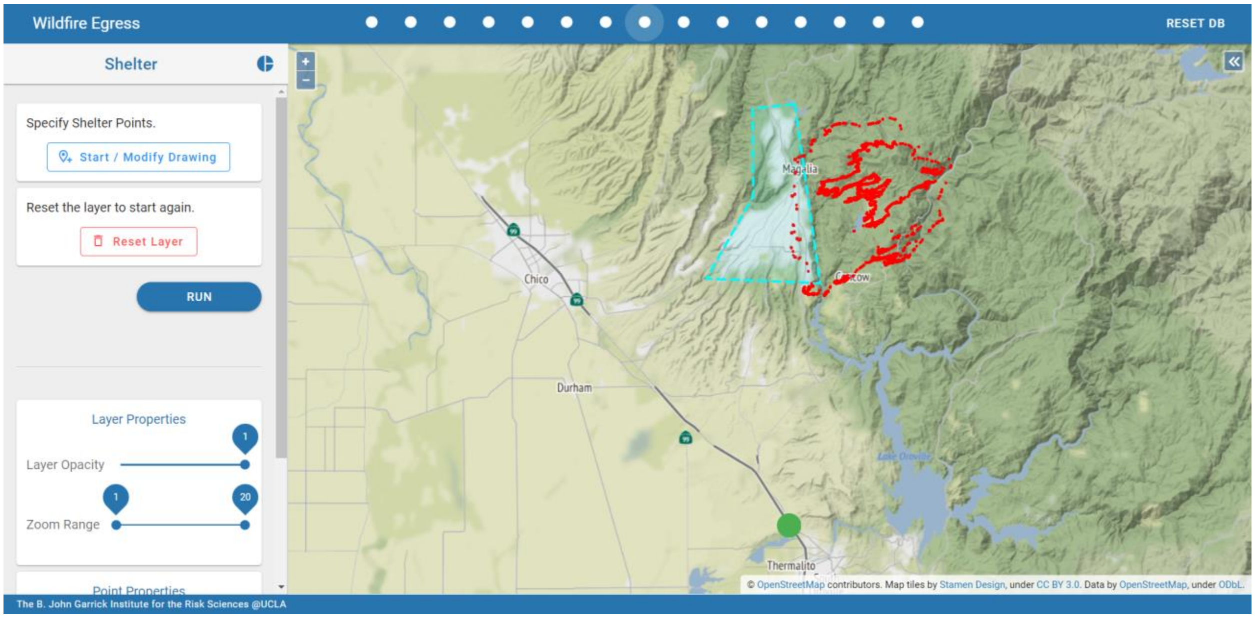

Figure 22: selecting a shelter point (the green dot)

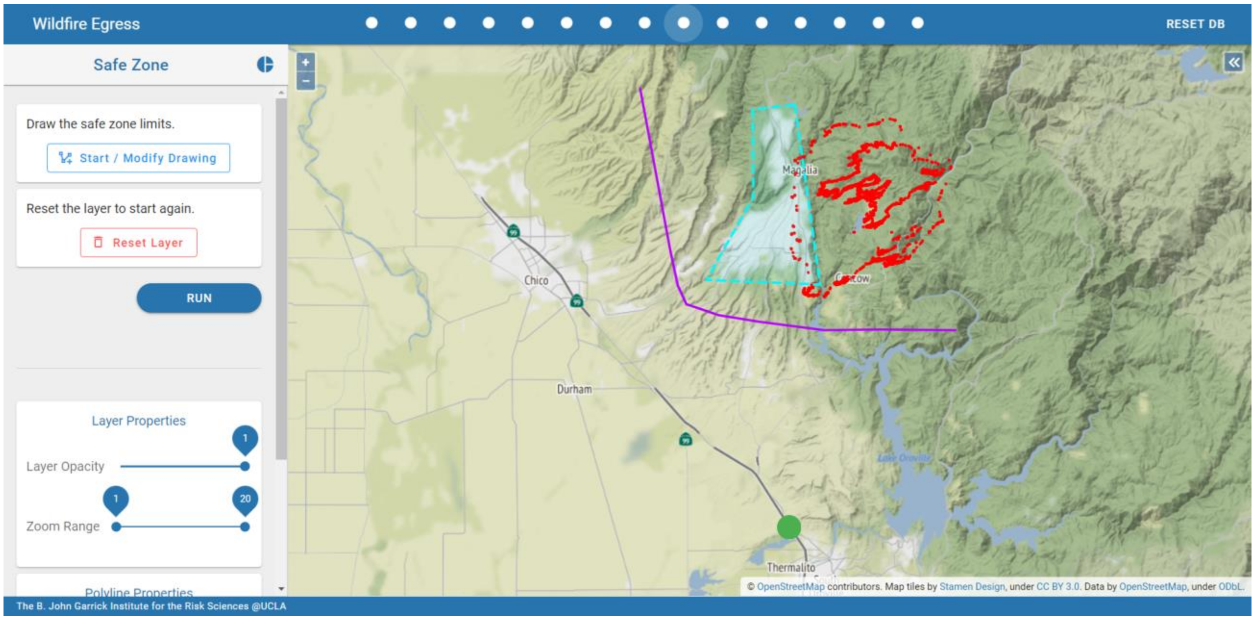

Figure 23: Drawing the safe zone limit

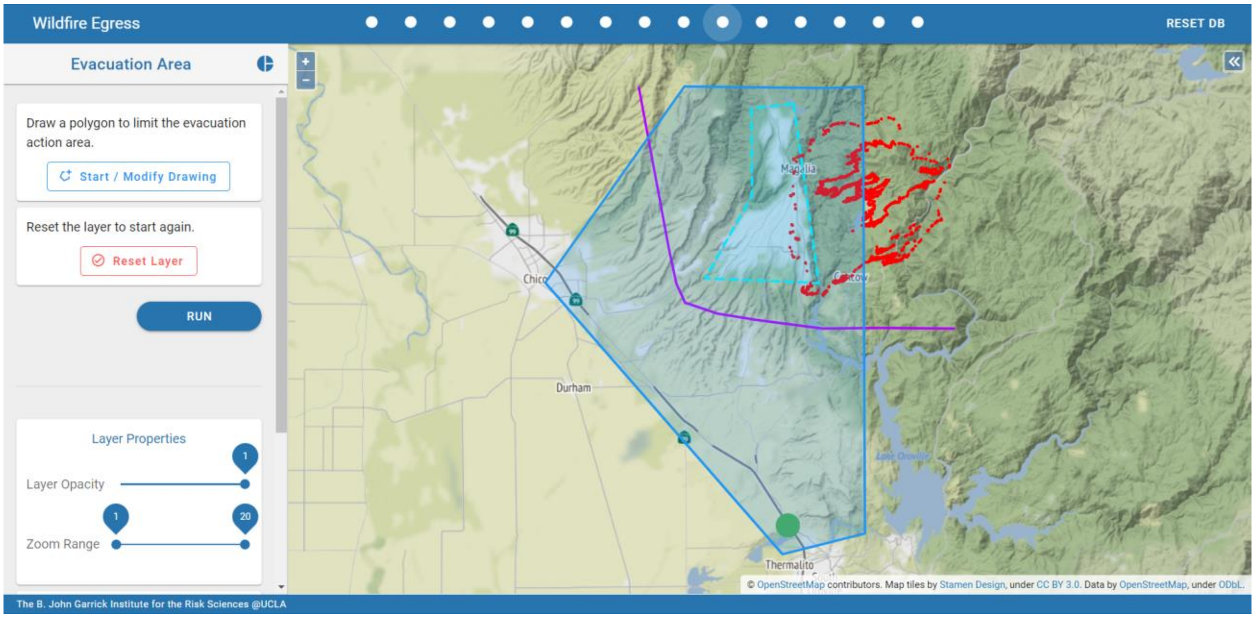

Figure 24: Isolating the evacuation operation area

Now, everything is ready for egress simulation. The first step in simulation is to generate enough agents based on the community population. WISE assumes that all the evacuees use private cars and every vehicle carries 3 persons on average. Therefore, for each grid cell in the community the number of agents is known. Moreover, each cell already has its own pre-evacuation time based on its demographic characteristics. Through a Poisson process simulation, WISE generates random departure times for each agent. Figure 25 shows this step in the platform. Clicking the *"RUN"* button opens a sliding pane showing our current location in the Bayesian belief network.

The next step performs an agent-based simulation for travel time calculations (Figure 26). Having an ordered list of agent departure times, WISE generates random origin points for each agent and then finds the optimum route to the shelter point. The platform keeps tracking every agent in during their travel. After increasing 1 minute in the departure time, WISE finds all agents locations on the map, updates the traffic model in the area, and modifies the traffic cost for each road segment. For the upcoming agents, the routing engine uses the modified/penalized traffic costs. This encourages the new agents to choose routes with less traffic. As shown in Figure 26, every route is divided into the route segment inside the danger zone, and the route segment in the safe zone. WISE only calculates the travel time for the first segment. In the database, every road segment has a comprehensive list of features, such as number of lanes, permitted velocity, road type, and geometric shape of the road segment. The segment velocity is also modified/penalized during the traffic model update. This way, traffic congestion will affect the travel times for the evacuees.

When the travel time is calculated for all agents, a sliding pane opens and in addition to the current node of the BBN, it demonstrates the histogram of the travel time for all agents (Figure 27).

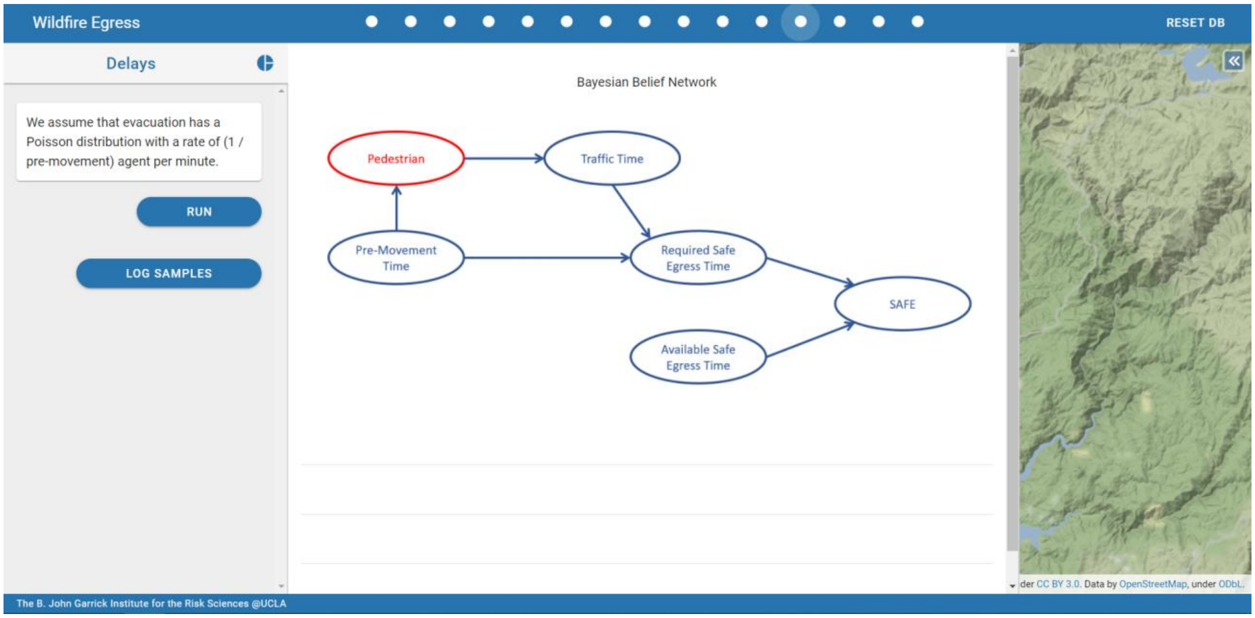

Figure 25: Generating the departure delays for every agent

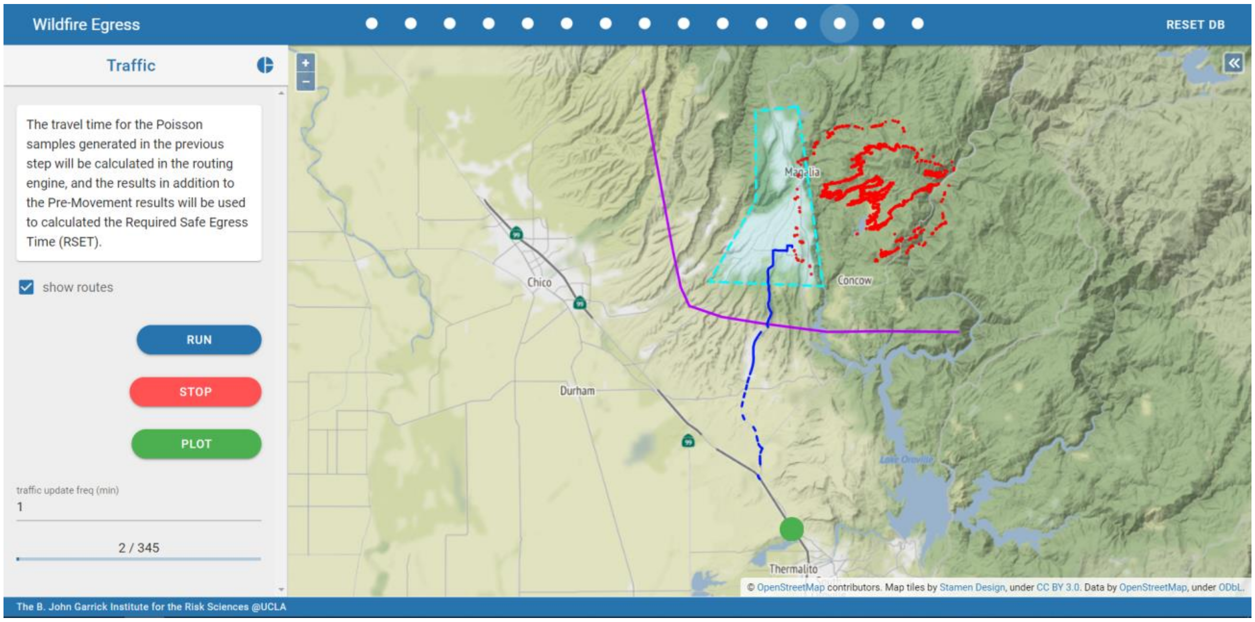

Figure 26: Finding the optimum route between the origin point and the shelter for every agent

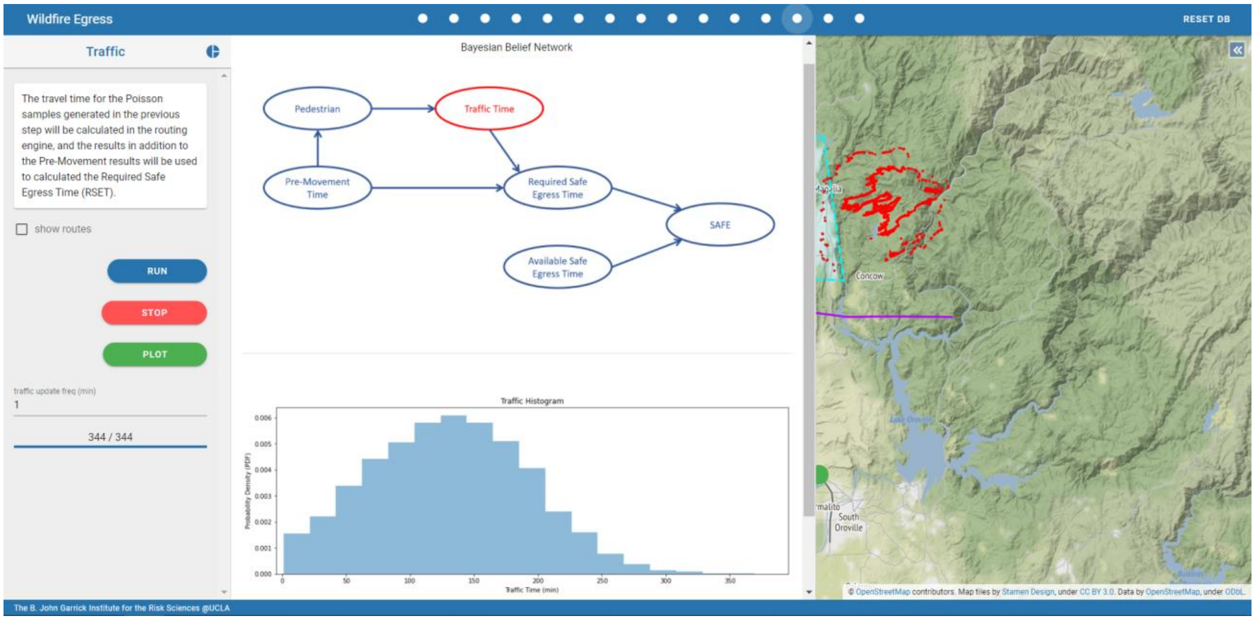

Figure 27: The traffic time histogram for the whole community

Figure 28 shows the next step in which two BBN nodes are evaluated together: RSET and ASET. The Required Safe Egress Time is the summation of the pre-evacuation time and travel time for every agent. RSET is shown as a histogram. On the other hand, Available Safe Egress Time is calculated based on the fire dynamics uploaded to the platform. Here, the ASET has a rectangular distribution and the parameters of the distribution are editable by the analyst. Therefore, the same egress scenario can be evaluated by different ASET histograms.

Finally, Figure 29 shows the last step of the simulation. In this step, RSET and ASET are compared and the probability of a successful evacuation is calculated. This step includes the histogram of surplus safe egress time for all agents. The red vertical line shows the agents for which the RSET and the ASET are exactly equal. These agents can evacuate safely in the last moment. The agents on the right side of this threshold are the ones who safely evacuated in the simulation, and the ones on the left side are the agents who needed more time for safe evacuation. This histogram provides the analyst with a deep insight into the egress mechanism.

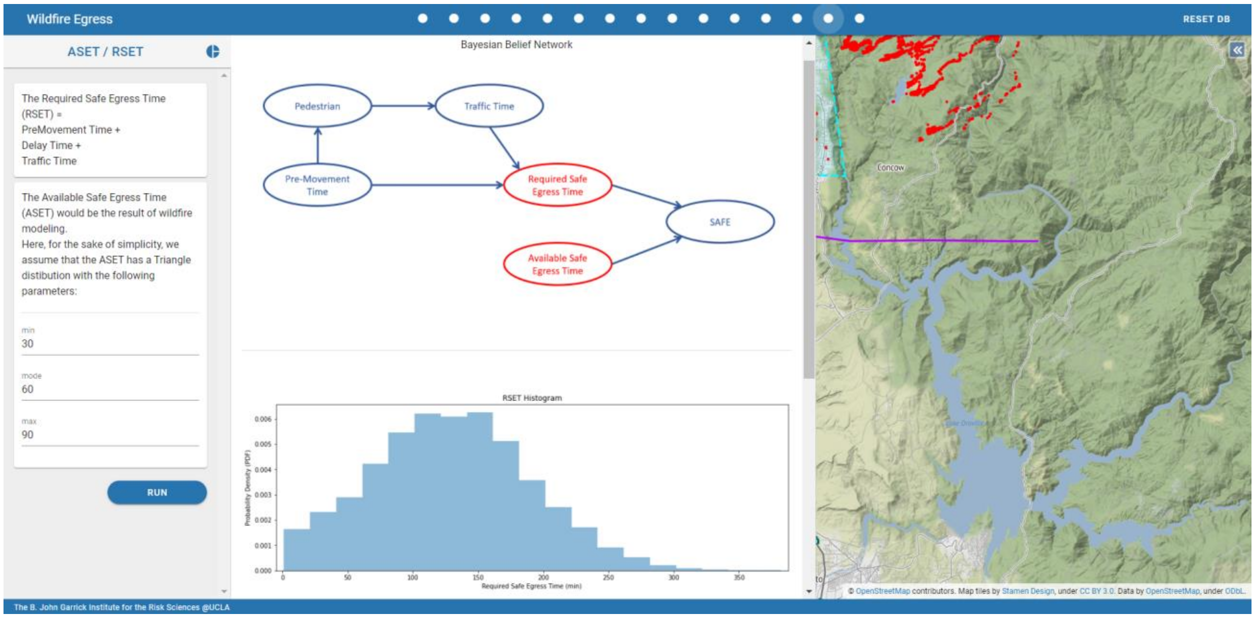

Figure 28: Calculating RSET based on the previous steps, and determining ASET for the scenario

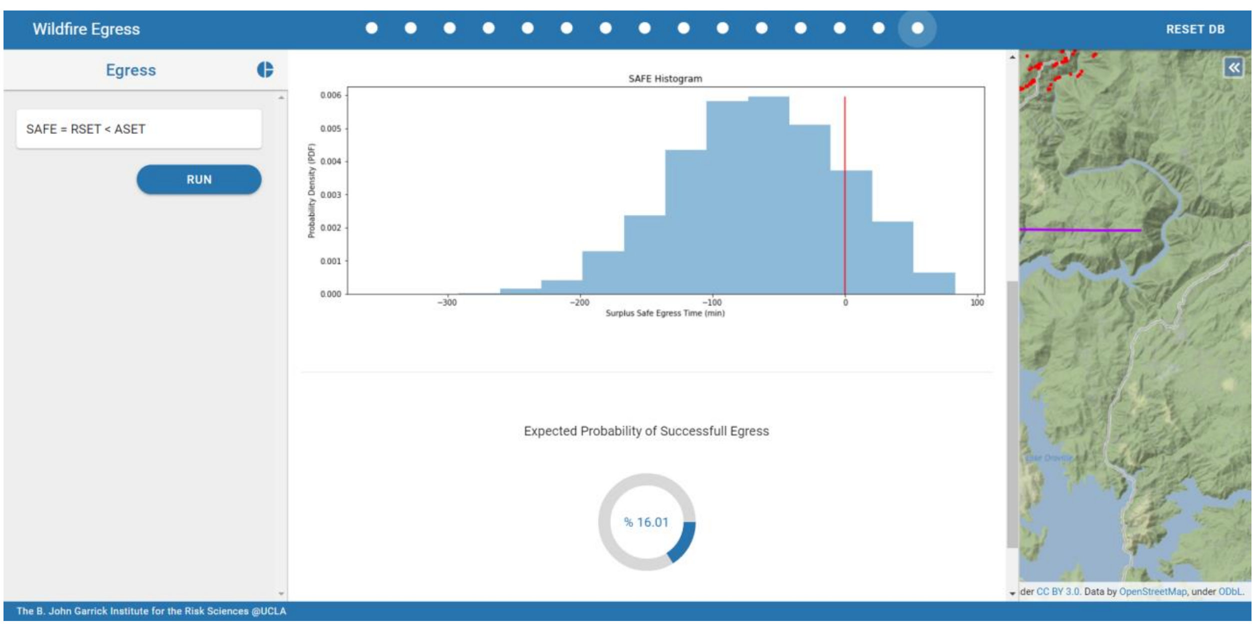

Figure 29: The surplus safe egress time and the probability of a successful evacuation

GIRS-2022-03
DOI:10.34948/G4159S

The B. John Garrick Institute for the Risk Sciences
UCLA