RESEARCH REPORT

Institute of Transportation Studies | UNIVERSITY OF CALIFORNIA

Testing Wildfire Evacuation Strategies and Coordination Plans for Wildland-Urban Interface (WUI) Communities in California

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16. Abstract

In the event of a wildfire, government agencies need to make quick, well-informed decisions to safely evacuate people. Small communities, such as in Marin County, with a mix of residences and flammable vegetation in Wildland-Urban Interface zones tend to lack resources to conduct evacuation studies. Consequently, this study uses a framework of wildfire and traffic simulations to test the performance of potential evacuation strategies, including reducing the volume of evacuating vehicles through car-pooling, phasing evacuations by staggering evacuation times by zone, and prohibiting street parking in four representative areas of Marin County. Results show that reducing vehicle numbers lowers the average travel time by 20%-70% and average exposure time to wildfire by 27%-60% from the baseline. Phased evacuations with suitable time intervals lower the average travel time by 13.5%-70%, but may expose more vehicles to fire in some situations. Prohibiting street parking yields varying results due to different numbers of exits and evacuees. In some cases, prohibiting street parking reduces the average travel time by over 50%, while in other cases it only reduces the average travel time by 9%, contributing little to evacuation efficiency. Altogether, Marin County may want to consider developing a communication and parking plan to reduce the number of evacuating vehicles in wildfire situations. Phased evacuation is also highly recommended, but the suitable phasing interval depends on the speed of fire spread and number of evacuees. Further, whether to establish street parking prohibition policies for a certain area depends on the number of exits and the number of vehicles on the streets.

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Disclaimer

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Executive Summary

Executive Summary

Due to the combination of warmer temperatures and drought brought on by climate change, wildfires have become an ongoing crisis particularly in transitional Wildland Urban Interface (WUI) areas where residential development has been expanding into forested regions of California. Where lives are at risk, mass evacuation is frequently the sole feasible way to ensure people's safety. Current evacuation strategies rely on standard, but static, approaches such designating evacuation zones to notify residents in the event of a fire. The most at-risk zones can be evacuated first which helps emergency personnel manage the traffic flow and more easily prevent the traffic jams that could occur when everyone tries to leave the area at the same time. However, these procedures may be difficult to implement in the case of rapidly moving fires and where the community lacks robust communication infrastructure, such as local radio and emergency alert systems.

Many small, resource-strapped communities in WUI zones do not have resources to conduct detailed evacuation studies and many such studies do not consider the impact of background traffic on evacuation processes. Therefore, this study explores the likely performance of a set of generalizable evacuation strategies incorporating background traffic for several areas in Marin County: the Ross Valley, Woodacre Bowl, Tamalpais Valley, and an area near Highway 101 and Ignacio Boulevard in Novato (hereafter referred to as 'Novato Neighborhood'). Using a wildfire-traffic simulation framework several strategies were tested including reducing the number of vehicles involved through carpooling, phased evacuations, and off-street parking prohibitions.

Wildfire-Traffic Simulation Framework

The proposed framework has three parts: (i) wildfire spread simulation, (ii) evacuation behavior, (iii) and traffic evacuation simulation. For the wildfire spread simulation, the model considers terrain topography, fuel, and meteorological conditions along with fire ignition location and time. The results show how the fire is likely to progress over time in one-hour time steps. These data subsequently become inputs for the traffic simulation which provides information to develop a plan of evacuation. For the evacuation behavior portion, three kinds of strategies were considered in this study: (a) vehicle reduction, (b) phased evacuation, and (c) prohibiting vehicles from remaining on the streets (and moving vehicles off the street). These strategies can affect the number of vehicles participating in the evacuation, their respective departure times, and the available road capacity needed for them to reach safety.

For evaluating the *vehicle reduction* strategy, five different options were tested, including one person/vehicle, two persons/vehicle, three persons/vehicle, four persons/vehicle, and five persons/vehicle. For *phased evacuation*, four options were tested, including simultaneous departure, 15-minute departure intervals in the daytime scenario or 20-minute departure interval in the nighttime scenario, 30-minute departure intervals in the daytime scenario or 40-minute departure intervals in the nighttime scenario, 45-minute departure intervals in the daytime scenario or 60-minute departure intervals in the nighttime scenario. For *parking prohibition*

strategies, we assume that if street parking is allowed, road capacity would be reduced by 15 percent compared with prohibiting street parking. The information from these scenarios is used to inform the traffic simulation model. The traffic simulation model is a mesoscopic traffic model, which examines small groups of vehicles and can track the trajectory of each vehicle during the evacuation. For the traffic simulation, the model produces various metrics of evacuation efficiency, such as the time needed for vehicles to reach two miles away from the fire area, the number of vehicles exposed to fire risk at different times, average evacuation travel time, and average exposure time to the fire hazard, to evaluate the performance of the different evacuation strategies.

Case Studies

The four study sites represent diverse fire and traffic characteristics in high-risk communities. For each site, two different evacuation scenarios were designed: one at 1 a.m., when all the residents are at home, another at 9 a.m., when background traffic is heavy.

The estimated number of residents who need to evacuate is different between the morning and nighttime scenarios because many residents are at work during the day, while most are at home at night. The background Origin-Destination (OD) data from the Metropolitan Transportation Commission identifies the location where each person begins their travel day, and this place is regarded as their residence. Using this information, it is possible to determine how many residents are at home when the fire ignites, and need to evacuate. For Ross Valley, the number of evacuees is 1,965 in the daytime scenario and 4,893 in the nighttime scenario. For Woodacre Bowl, the number of evacuees is 1,356 in the daytime scenario and 2,196 in the nighttime scenario. For Tamalpais Valley, the number of evacuees in the daytime scenario is 2,010 and 5,492 in the nighttime scenario and for Novato Neighborhood, there are 7,662 evacuees in the daytime scenario and 17,519 in the nighttime scenario.

The analysis showed that different strategies perform better or worse in different areas and times due to differences in road networks, fire ignition points and progression, number of evacuees, and the normal traffic around the areas.

Generally, sharing a vehicle among multiple persons is a good strategy in each case, as this can greatly reduce traffic congestion and speed up the evacuation process. However, it is difficult and time-consuming to coordinate having persons from different households share one vehicle in emergency situations. On the contrary, it is quite easy to encourage persons to share one or two vehicles among their own family members. We recommend a policy that at least two persons should be in each car during the evacuation.

Phasing the evacuation process improves evacuation efficiency, however, a longer departure interval does not necessarily result in a more efficient evacuation. This is because over time fires may spread quickly and approach zones that were initially far from the initial ignition points. Therefore, it is not advisable to make the persons in these zones wait too long before issuing an evacuation order if the fire is predicted to move quickly.

The effect of street parking on evacuation varies with the situation. In some cases, such as the nighttime scenario for Ross Valley and the daytime scenario for Woodacre Bowl, where we found little impact on evacuation. While in the other cases, prohibiting street parking can result in a significant increase in evacuation efficiency. The difference results from having different numbers of evacuees and numbers of exit routes. When the number of evacuees is relatively small compared with the number of background vehicles and the number of exits is high, the effect of street parking is small. Yet, if there are more evacuees and fewer exits, the impact of street parking is high. Overall, prohibiting street parking on fire danger days can effectively reduce evacuees' travel time. If possible, this strategy should be implemented in all cases. However, where that is not feasible, we recommend at a minimum prohibiting on-street parking during the daytime for Ross Valley, at night for Woodacre Bowl, during both the daytime and nighttime for Tamalpais Valley, and at night for the Novato Neighborhood. Prohibiting street parking on days when fire danger is high could significantly improve evacuation performance.

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Introduction

Wildfire evacuations have posed persistent challenges in California in recent years particularly in Wildland Urban Interface (WUI) communities where there is a significant mix of residences and flammable vegetation. Current strategies rely on standard, but static approaches such as issuing evacuation orders by designated zones. However, these approaches are likely to be problematic in actual incidents, given the difficulties implementing them under rapidly moving fire conditions and fragile communications infrastructures.

Most small, resource-strapped WUI communities in Marin County do not have the resources to conduct dedicated evacuation studies. This research evaluates a set of generalizable evacuation strategies for four areas in Marin County: Ross Valley, Woodacre Bowl, Tamalpais Valley, and an area near Highway 101 and Ignacio Boulevard in Novato (hereafter referred to as “Novato Neighborhood”). The strategies include *vehicle reduction* from carpooling, *off-street parking prohibitions*, and *phased evacuations*, which were tested using a wildfire-traffic simulation framework. The strategies were evaluated based on their outcomes in several evacuation scenarios for each of the study communities, as well as their ease of incorporation into standard procedures. Additionally, the impact of background traffic, which refers to the normal traffic passing through the case study areas when evacuations occur, was taken into account during the evaluation. This is important because the presence of background traffic can cause significant delays in evacuation, and previous research has not adequately considered its impact (Soga et al., 2021). Therefore, this research includes background traffic in the traffic simulation to more accurately evaluate the potential strategies. Based on our results, we provide recommendations for the different responses and strategies.

Evaluating Wildfire Evacuation Strategies

Wildfire evacuation strategies have been largely informed by the experiences learnt from other types of disasters (e.g., hurricanes, tsunamis), but also have specific considerations given the dynamic characteristics of wildfire and the spatial areas they impact. Most strategies focus on how to improve evacuation efficiency to reduce evacuation time given the speed and short notice of wildfires, through measures such as temporarily widening lanes (e.g., by using shoulders and medians for vehicle travel). Other evacuation strategies are designed to (i) improve road network capacity through measures such as contraflow (reversing the direction of traffic on individual lanes) (Araujo et al, 2014, Chen et al., 2020) or prohibiting street parking, or (ii) optimize road use by evacuees through strategies such as carpooling, which reduces the number of departing vehicles, and phased evacuations that lower peak traffic volumes on roadways by spreading out evacuees.(Zhao and Wong 2021). On-street parking restrictions can increase the capacity of low-capacity roads (Cova 2005). Phased evacuations can be staggered to permit those closer to fire danger to leave first and prevent bottlenecks (So and Daganzo 2010). Chen and Zhan (2008) tested all phased sequences in a road network with four evacuation zones and found that if the affected area has a high population density and the road network follows a grid structure, implementing a phased evacuation strategy that involves alternating non-adjacent zones can effectively reduce the overall evacuation time. Encouraging carpooling can also reduce the number of vehicles involved in an evacuation and effectively mitigate resulting traffic congestion (Zhao and Wong 2021).

Although there are many evacuation strategies proposed in existing research, there is no comprehensive study that compares the applicability and relative gains from each type of wildfire evacuation strategies under different network topology, evacuation demand, and fire spread dynamic situations. For many communities affected by wildfires, a preliminary understanding of the potential applicability of previously proposed strategies can still be greatly helpful for developing preliminary plans before carrying out further detailed investigations. One area that has often not received sufficient attention has been the effect of background traffic, which refers to the traffic that was unable to be redirected and passes through the evacuation area, despite its potentially huge impact on evacuation efficiency. For many fire-prone communities along major highways, discussions regarding background traffic are crucial, as during peak hours highways may lack capacity to accommodate the additional evacuation traffic.

Traffic simulations can be useful in testing the performance of various evacuation strategies, as shown in Table 1. Microscopic simulation software, such as Paramics (Cova and Johnson, 2002), can provide fast setup for the simulation model. A dedicated agent-based simulation model can provide greater flexibility and higher simulation efficiency (Soga et al., 2021; Zhao and Wong 2021). Quick, simplified manual calculations (Cova and Johnson, 2002) and adjusted four-step models (de Araujo et al., 2014), can be useful for developing a conceptual understanding of the evacuation situation and potential bottlenecks. The data required for running simulation models are often readily available from sources such as OpenStreetMap and digitized aerial imagery for network inputs, and regional parcel maps can be used for identifying residential locations for estimating the number of persons needing to be evacuated. Models can generate aggregated metrics such as travel time, fire exposure time, and link-level congestion status. Altogether, traffic simulation is frequently applied across hazards, with a focus on investigating changes in evacuation performance metrics through parametric studies that analyze detailed evacuation choices, such as departure time, route, and destination (Zhao and Wong, 2021).

Other keys to developing wildfire evacuation strategies concern gathering information on evacuation behavior, which can be obtained through observations and surveys (Gwynne et al., 2023), mathematical models (Lovreglio et al., 2019; McCaffrey et al., 2018), and recently the application of emerging technology such as GPS (Zhao et al., 2022). One important consideration is when evacuees need to be notified of the evacuation warning or order which can be aided by information on how fires spread, and the operation of communication systems, which can be integrated into the evacuation simulations for a more comprehensive depiction of possible scenarios (Soga et al., 2021).

Table 1. Selected Studies That Employ Simulations or Traffic Models for Studying Wildfire Evacuation (adapted from Zhao and Wong, 2021)

Reference	Model Characteristics				Metrics	Strategies or Scenarios
	Traffic generation	Departure time	Destination and route choices	Simulation type		
Cova and Johnson (2002)	250 households; vehicles per household follows Poisson distribution (mean: 0.5-3 vehicles/household)	Departure time follows Poisson distribution (mean: 5-25 min after fire occurs)	The neighborhood exits or shelters; dynamically updated lowest-cost route	Microscopic (Paramics)	Clearance time, mean vehicle/ household travel time	Setting different number of evacuee vehicles and departure time
Cova and Johnson (2003	30-150 vehicles per zone	Uniformly generated within 15 min	Various static routing (minimizing total travel distance, minimize merging or balanced)	Microscopic (Paramics) and manual capacity analysis	Clearance time, total travel distance, number of merges	Reducing intersection merge delays with turn restrictions
Sbayti and Mahmassani (2006)	1,794-5,692 vehicles	Simultaneous or optimal departure time solved by an optimization model	System-optimal traffic assignment	Microscopic (DYNASMART -P)	Clearance time, mean travel time	Phased evacuation

Reference	Model Characteristics				Metrics	Strategies or Scenarios
Li et al. (2022)	47,410 vehicles	Simultaneous or optimal departure time solved by an optimization model	System-optimal traffic assignment	Non-simulation, solved by an optimization model	Mean travel time, average fire exposure time	Phased evacuation
Zhao and Wong (2021)	7,438 households; 44%/43%/13% households leave with 1/2/3 vehicles	Departure time follows normal distribution (40 min±20 min)	Outside the fire threat area, updated lowest-cost route	Spatial-queue-based dynamic simulation model	Mean evacuation time, total exposure time	Slowing fire speed, number of evacuating vehicles, phased evacuation

Developing Evacuation Scenarios

The framework of the wildfire and traffic simulation used in this study is shown in Figure 1. The proposed framework covers three parts: (i) wildfire spread simulation, (ii) evacuation behavior, (iii) and traffic evacuation simulation. For the wildfire spread simulation, inputs include terrain topography, fuel (amount and condition of burnable material), and meteorological conditions along with fire ignition location and time. The outputs from this step analyze different aspects of the fire simulation, specifically, fire propagation divided into one-hour time intervals. These data provide fire information for evacuation planning. For the evacuation behavior step, three types of strategies were considered in this study: (a) vehicle reduction, (b) phased evacuation, and (c) prohibition of parking vehicles on the streets (and providing alternative parking to help move vehicles off the street). These strategies can reduce the number of vehicles needed for evacuation, quicken departure times, and increase road capacity, respectively. Such information also become inputs to the traffic simulation step. For the traffic simulation, the model produces various evacuation efficiency evaluation metrics, such as the number of exposed vehicles at different times, average evacuation travel time, and average exposure time to the fire hazard. These metrics are used to evaluate the performance of the different evacuation strategies.

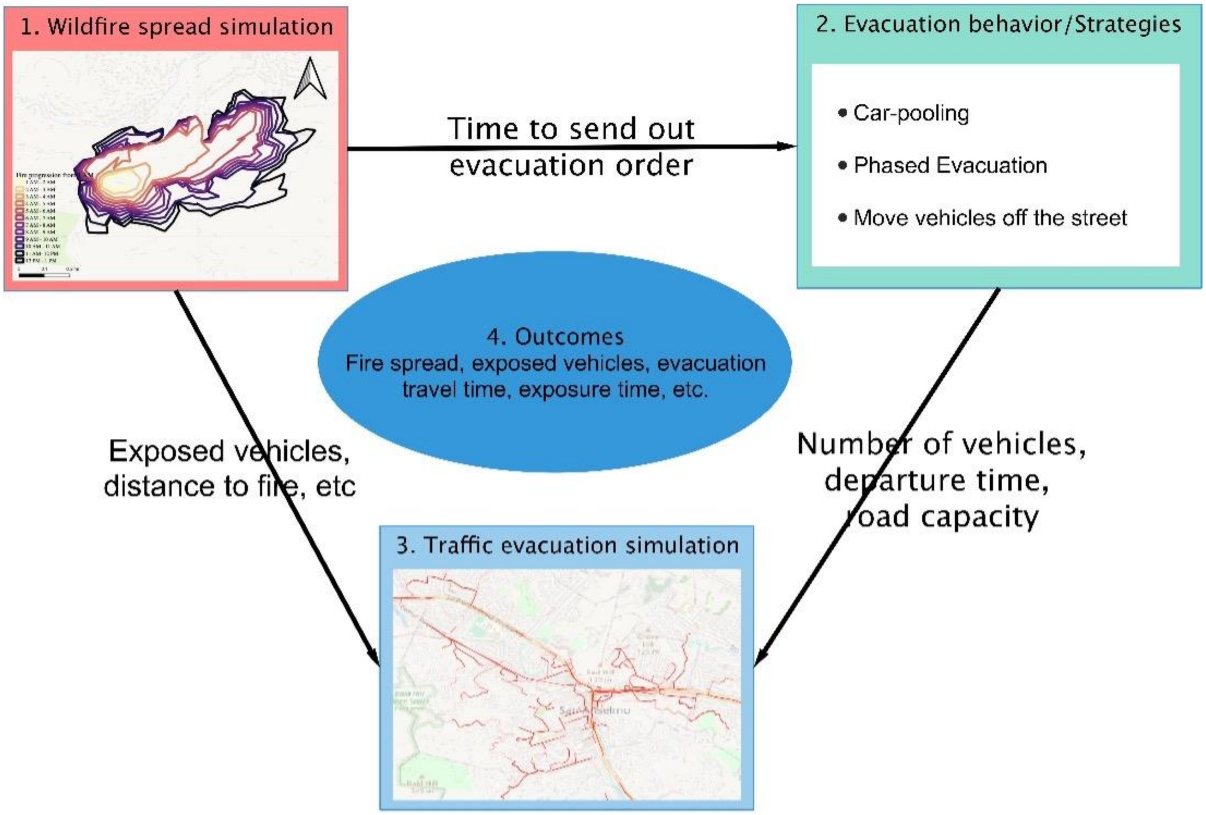


Figure 1. Study Flowchart

Wildfire Spread Simulation

The fire simulation provides information on how quickly the fire may propagate through an area under different meteorological, topographical, and fuel conditions (Finney and Andrews, 1999). For this study, fire simulations were conducted using FARSITE software designed by M.A. Finney for spatial and temporal simulation of fire behavior under various conditions (Finney, 1998). The software requires a variety of input data regarding terrain topography, fuel, and meteorological conditions that are fundamental factors affecting fire behavior. The framework of the fire simulation is shown in Figure 2.

The first step was to define ignition points for each fire both by geography, identifying the areas involved in the fires, and timing, determined by analyzing data for specific days taken from the nearest weather stations. Following that, data including terrain topography, fuel, and meteorology are collected to run the simulations. Topographic data refers to the structure and shape of the terrain (such as elevation, slope, and aspect). Tree cover data includes canopy cover, stand height, canopy base height, and canopy bulk density. Fuel data was determined by using the 40 Scott and Burgan Fire Behavior Fuel Model (FBFM40), which divides the area into 40 different fuel types. For meteorological metrics, data on wind speed, wind direction, air temperature, humidity, and solar radiation data were collected and entered into FARSITE. Simulation-related parameters, such as simulation duration, are also set at this step. These steps lead to the fire simulation output, which is the fire propagation status (e.g., areas with active fires, flame length) at each timestamp.

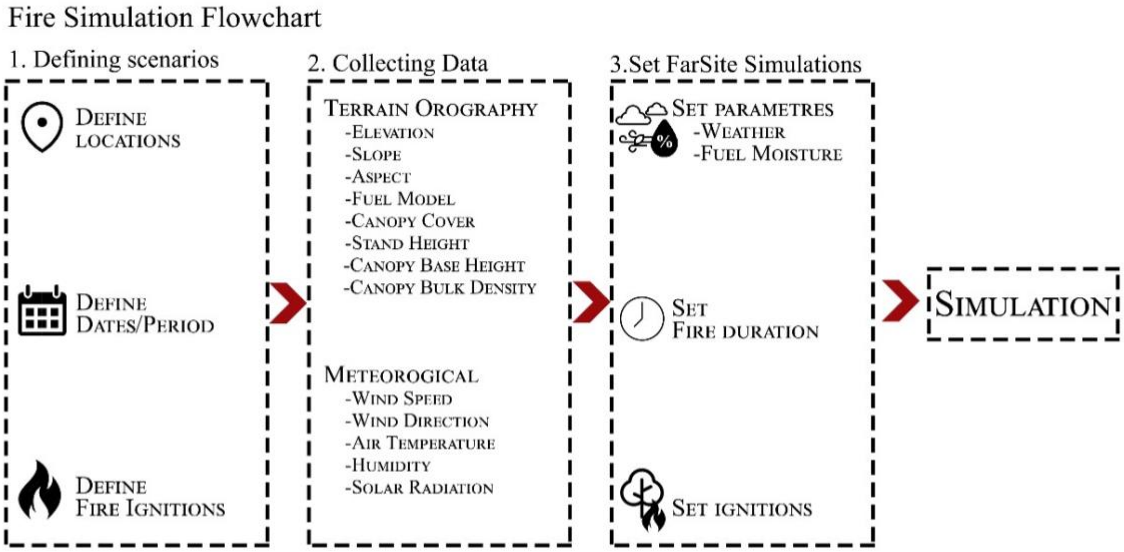


Figure 2. Framework of Fire Simulation

Spatial-Queue Based Traffic Simulation

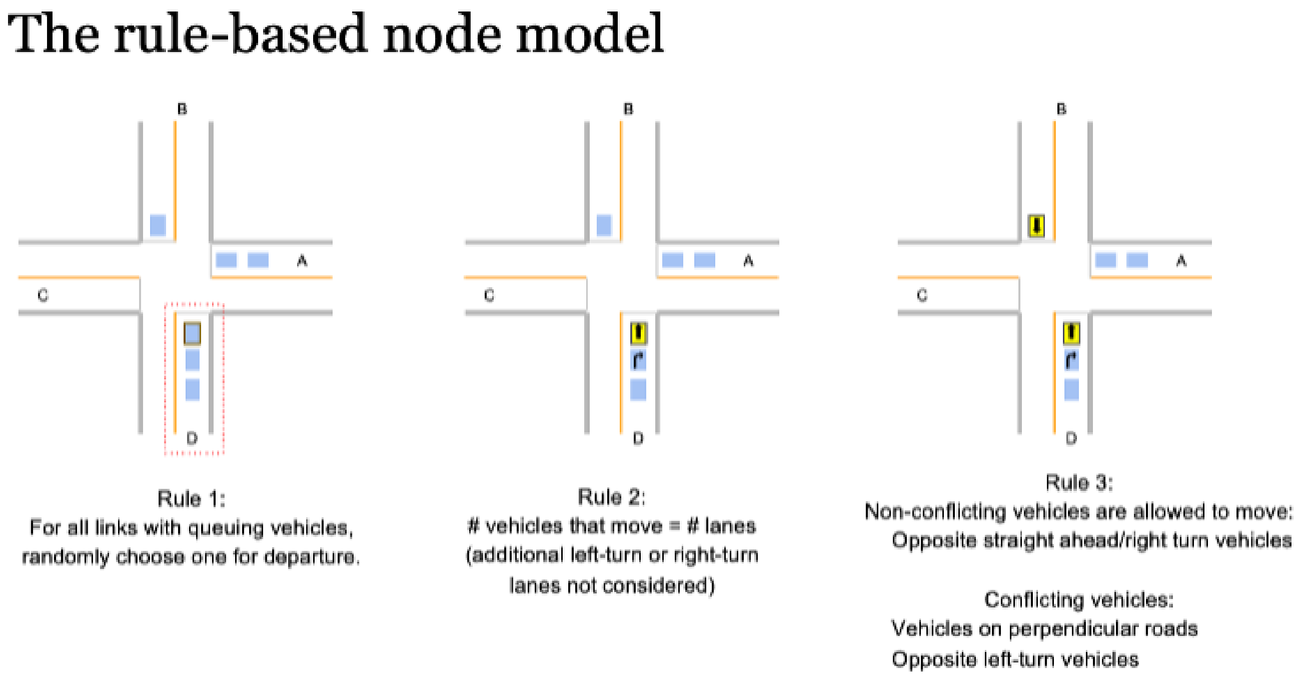
A spatial queue based traffic model, developed by the research team (https://github.com/cb-cities/spatial_queue), was used to simulate the evacuation process. We used this model rather than popular microscopic simulators based on car-following and lane-changing behavior since it is less data intensive and easier to program. The simulation model consists of three basic elements: (i) vehicles, (ii) intersections (nodes), and (iii) road links. Figures 3-4 illustrate features of the node model and the link model.

Each vehicle is treated as an independent actor. Each vehicle is assigned an initial evacuation route, and the routes are updated every 10 seconds based on the evolving traffic status (e.g., level of congestion), in a manner that imitates how route recommendations are updated in real time in navigation apps like Google Maps, Apple Maps, and Waze.

Each link in the road network corresponds to a stretch of road between two intersections. The model simulates the time that it takes for a vehicle to move from the upstream node to the downstream node, creating queues and spillbacks, according to the actions of all other vehicles. Vehicles spend at least as long as the free flow travel time on a link before leaving the link or joining a queue at the downstream end. When the end of the queue formed by vehicles reaches back to the upstream end of the link, spillback occurs, and no more vehicles can enter this link.

The link flow capacity is assumed to be 1,900 vehicles/(hour·lane), and link capacities are imposed in a flip-coin probability manner at each one-second time step, with a probability of a queuing vehicle at the front leaving the current link or entering the next link at 0.53 vehicles/(second·lane). The model moves vehicles at the front of each link to the next link at each one-second time step, if there is room in that link, and they do not conflict with other vehicles moving through the intersection at that time step, such as those turning left or entering from perpendicular directions.

Vehicles entering an intersection are assumed to have equal priority, except for vehicles already in roundabouts, which have higher priority than vehicles feeding into the roundabouts. All intersections were modeled as non-signalized in anticipation of power failures.



The rule-based node model

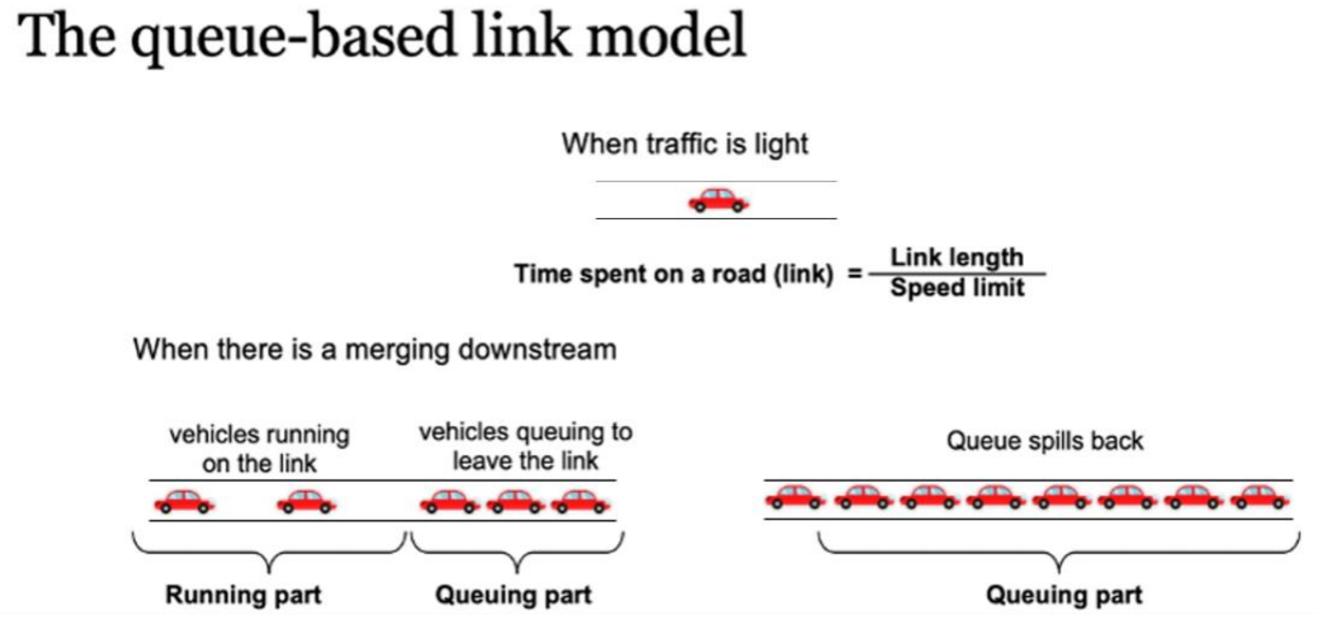
Rule 1:
For all links with queuing vehicles,
randomly choose one for departure.

Rule 2:
vehicles that move = # lanes
(additional left-turn or right-turn
lanes not considered)

Rule 3:
Non-conflicting vehicles are allowed to move:
Opposite straight ahead/right turn vehicles

Conflicting vehicles:
Vehicles on perpendicular roads
Opposite left-turn vehicles

Figure 3. An Illustrative Node Model



The queue-based link model

When traffic is light

$$\text{Time spent on a road (link)} = \frac{\text{Link length}}{\text{Speed limit}}$$

When there is a merging downstream

Figure 4. An Illustrative Link Model

Evacuation Strategies and Scenario Development

This study compared the effectiveness of various evacuation strategies/policy options by testing different scenarios under specified conditions. The scenarios consisted of three types:

- **Vehicle reduction.** As a small increase in the number of vehicles on the roads during the evacuation can significantly increase congestion, this scenario tests whether and how much carpooling can make a difference on evacuation efficiency (Wong and Shaheen, 2019).
- **Phased evacuation.** Many studies have demonstrated the effectiveness of phased evacuation, as it can reduce the traffic congestion during the evacuation (So and Daganzo, 2010, Chen and Zhan, 2008). While some evacuees further from the fire danger are delayed, allowing those closer to the fire to leave first reduces exposure time and limits the amount of downstream congestion so those leaving later can evacuate more quickly. In this study, we quantify the effects of the phased evacuation strategy on evacuation.
- **Prohibiting on-street parking on "Red Flag" days.** On-street parking reduces the number of accessible lanes, which in turn reduces road capacity and storage, causing delays in the evacuation progress (Cao et al., 2017, Wijayaratna and Wijayaratna, 2016). Therefore, this scenario analyzes the quantitative impact of prohibiting on-street parking when fire danger is high (i.e., Red Flag Days).

For each set of strategy variables, base case values were chosen for comparison. Details of each strategy are given in Table 2.

Table 2. Description of Scenarios

Strategy	Options (baseline value underlined)	Description
Vehicle reduction	1 person/vehicle 2 persons/vehicle 3 persons/vehicle 4 persons/vehicle 5 persons/vehicle	1. Reduce the number of vehicles used for evacuation, mainly through carpooling by each household or several nearby households. 2. The baseline case assumes that there is no car-pooling, everyone drives a vehicle. 3. The alternative cases assume increasing levels of carpooling.
Phased evacuation	0 min 15 mins (day) or 20 mins (night) 30 mins (day) or 40 mins (night) 45 mins (day) or 60 mins (night)	1. Evacuation zone is divided into three zones based on distance to the fire origin. 2. During the day, it is assumed that people can receive the warnings quickly and prepare for the evacuation swiftly, while during the night, evacuee's response time of becomes longer as they need more time to prepare. 3. The baseline case assumes "no phased evacuation:" all vehicles in the three zones have the same departure time. 4. The alternative cases assume that the evacuation orders are staggered for the three zones at certain time intervals with those zones closest to the fire going first.
Prohibiting on-street parking	No street parking With street parking	1. On-street parking can affect the number of lanes of roads and further limit road capacity (vehicles/hour) and road storage (vehicles/km). 2. The baseline case assumes there is no on-street parking. 3. The alternative case assumes that all residential roads have on-street parking. According to some studies, street parking can reduce the road capacity by 16-35% (Biswas et al., 2017, Wijayaratna, 2015). As there is no research on street parking in Marin County, we used the average of the reduction values from the existing studies, which is 25%.

Evaluation of Evacuation Strategies

In this study, two commonly used evaluation performance indicators were employed to evaluate the outcomes under different evacuation strategies: average travel time and average exposure time to the fire hazard. The first metric represents the average time spent in the evacuation process, from leaving the origin to reaching a point at least two miles away from the dynamic fire area. We assumed that reaching two miles away guarantees the evacuees' safety. The second metric is the average fire exposure time, which is represented by the average duration of time that evacuees are within a half-mile radius of the active fire front. Since this area is considered especially dangerous, it is crucial to know how long an evacuee stays in such a hazardous zone, which reflects the average level of threat that they face. Figure 5 illustrates an example of how to calculate the travel time and exposure time.

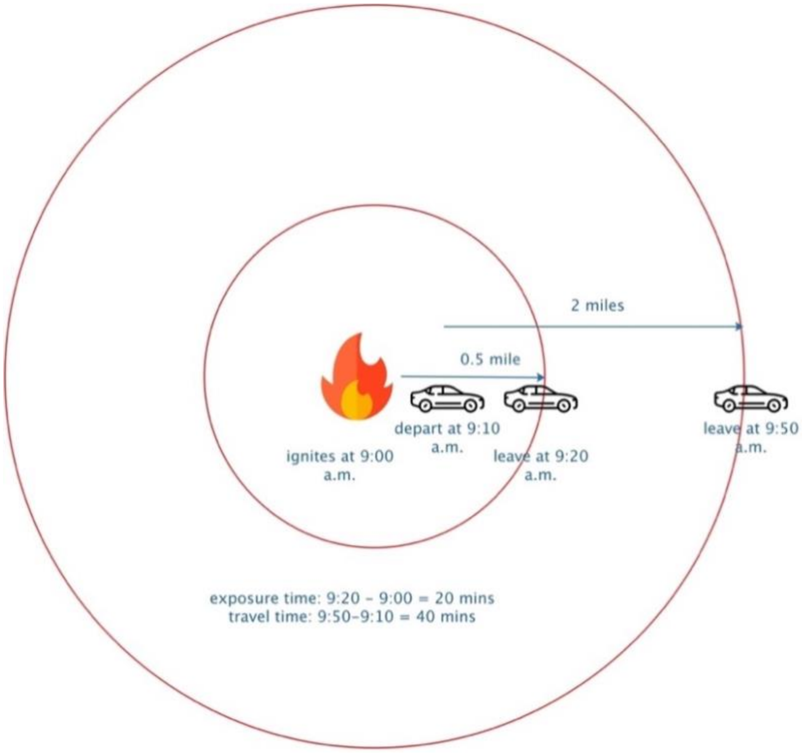


Figure 5**. Illustration of Evacuation Time and Exposure Time Calculations**

Case Studies

Given the multiplicity of small communities in WUI areas in California and their susceptibility to wildfire threats and losses each year, it is imperative to work with local communities and their planning and fire prevention agencies to find practical and generalizable solutions to address wildfire threats. This study compared the effectiveness of different evacuation response/policy options through scenario testing with control variables.

In previous research, we recognized that the randomness and unpredictability of wildfires, insufficient communications options, as well as the disproportional high evacuation demand in WUI areas are the main factors causing bottlenecks in the evacuation process (Zhao and Wong, 2021). Recognizing the need for designing and upgrading wildfire evacuation strategies for small WUI communities, we partnered with the Marin Wildfire Prevention Authority (MWPA), the single agency in Marin County responsible for preventing wildfire threats, to test the applicability of some commonly adopted evacuation measures over a wide set of case study characteristics and scenarios. MWPA identified four neighborhoods in Marin County as representative case study areas (Figure 6). These four sites represent diverse fire, and traffic characteristics in high-risk communities.

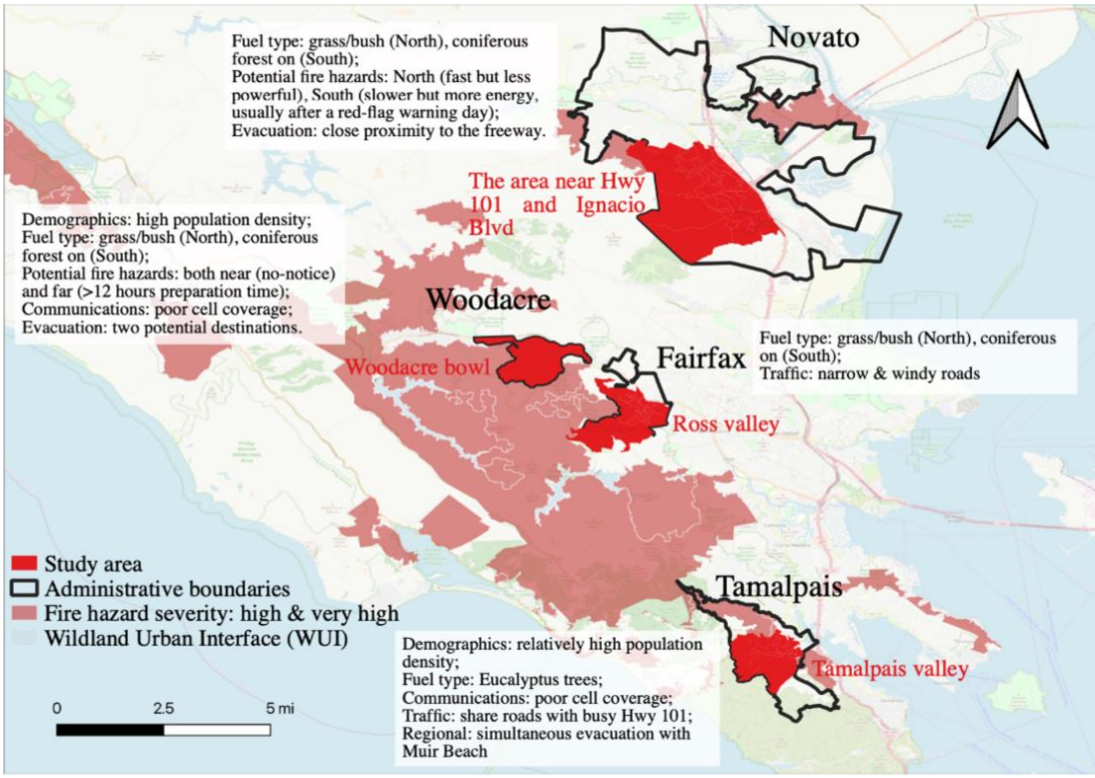


Figure 6. Four Study Areas in Marin County and Fire Hazard Areas

Scenario Development

This section explains the development of the various scenarios. We first constructed a model of the existing road network. We then chose a fire ignition location for each study area and developed a model to simulate the fire's propagation and obtained data on the background traffic travelling though Marin County. Finally, we calculated the number of persons and vehicles that would be evacuating each study area during the daytime and nighttime scenarios.

Road Network

The simulated evacuations occur in Marin County, CA. Since background traffic may significantly affect evacuation efficiency the road network used in the simulation models includes not only the four study areas, but all roads in Marin County. The road network for the study area was obtained from OSMnx, a python package (https://osmnx.readthedocs.io/), and then a directed node-and-link-based road network for Marin County was obtained (see Figure 7). Nodes and links are commonly used structures to represent a network, where a node represents one road intersection, and a link represents the stretch of road between two intersections. The final Marin County Road network consists of 40,209 links and 17,857 nodes.

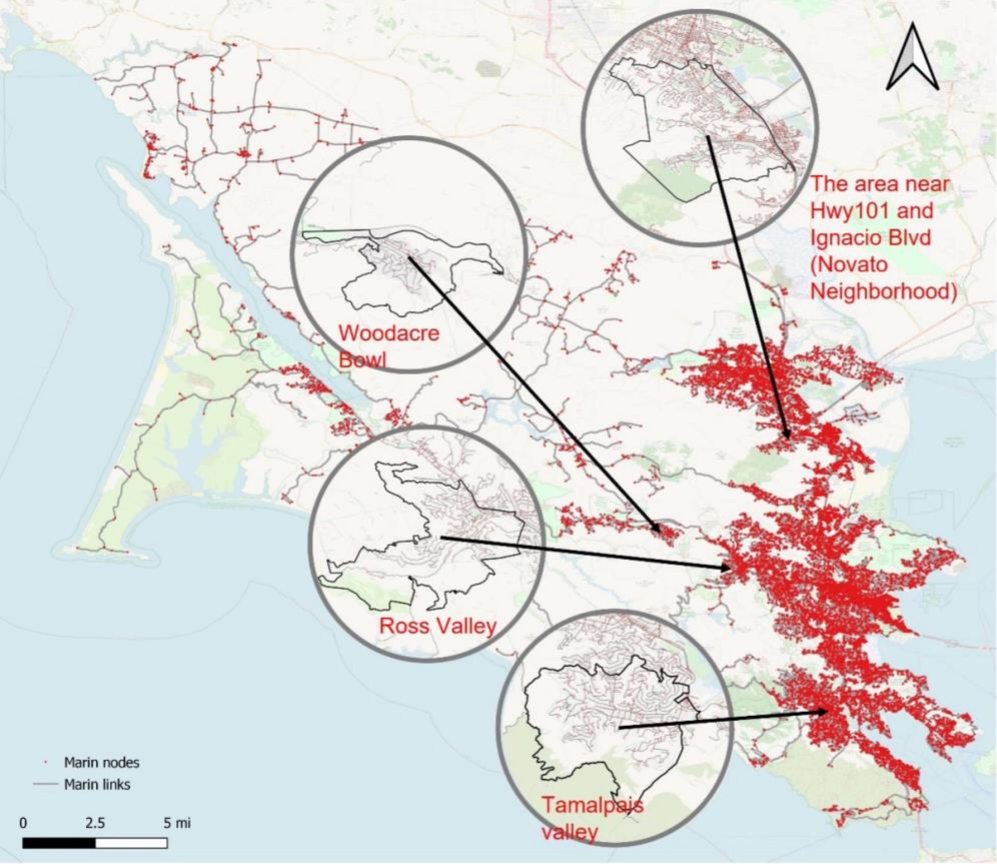


Figure 7. The Road Network of Marin County

Fire Propagation

As introduced in the section entitled Wildfire Spread Simulation, several inputs are required to run the fire propagation simulations for the Marin County cases, including ignition locations, day and time of the fire (to retrieve meteorological information), data on terrain topography, and vegetation/fuel status. The ignition points (shown in Figure 8) were chosen to be within a two-mile radius from selected city boundaries and contain fuels such as grass or shrubs. Terrain topography and fuel data were collected from the LandFire database (http://landfire.gov/). The meteorological data were obtained from the FAMWeb Data Warehouse database (http://www.wildfire.gov/application/famweb-data-warehouse) for three stations: Station 042312 - Middle Peak; Station 042309 - Woodacre; Station 042310 - Big Rock. These stations were considered the most suitable for the proposed scenarios due to their proximity and data availability. The locations of these weather stations are also shown in Figure 8.

The typical wildfire season runs from May to November in California, though recently year-long fire threats are becoming more common. For this study, the hypothetical fire event was set to occur on August 8, 2020, the day when the Lightning Complex Fires occurred. The meteorological data for the study areas were extracted from the above identified weather stations for this day.

For the four study areas in Marin County most residents typically work outside the area during the day and return in the evening. Given this, we chose two ignition times: 1 am, when most people are at home and the evacuation travel demand is the highest, and 9 am, when most people have left for work or other places and fewer evacuation vehicles are needed. This produced a total of eight simulations for the four case study areas, with two scenarios per area (daytime and nighttime).

The meteorological conditions for the fire simulations were slightly adjusted for some scenarios to produce ‘dangerous’ or ‘worst case’ scenarios, which would trigger evacuations. In some cases, the fire simulations using the actual recorded data would generate fire propagation scenarios that reach the city's boundaries; in others, this was not possible within the simulation time window of 12 hours. In the case of Ross Valley, fire simulations using the actual recorded meteorological data were a half mile away from the WUI boundary of the town, which likely would not trigger an evacuation. For this reason, the wind direction was slightly adjusted to create fire spread that reaches the Ross Valley boundary. The actual recorded meteorological parameters for Ross Valley on

August 8, 2020, and the modified inputs for the fire simulation are given in Table 3. Figures 9-12 illustrate the fire progression for Ross Valley, Woodacre Bowl, Tamalpais Valley, and the Novato Neighborhood, respectively.

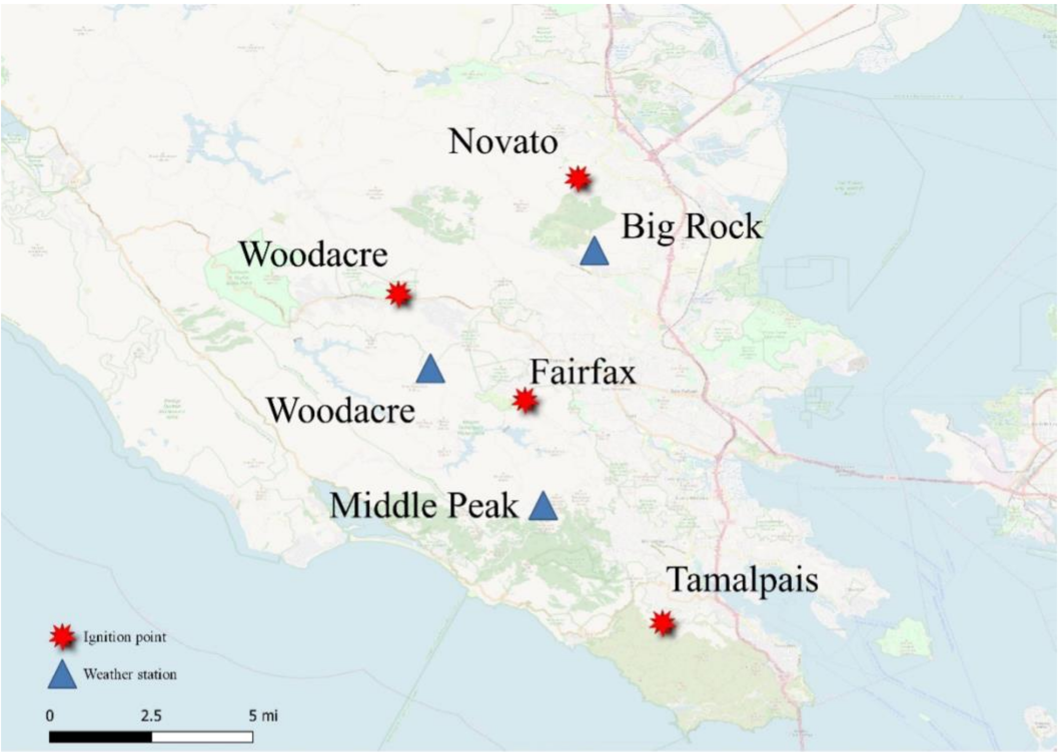
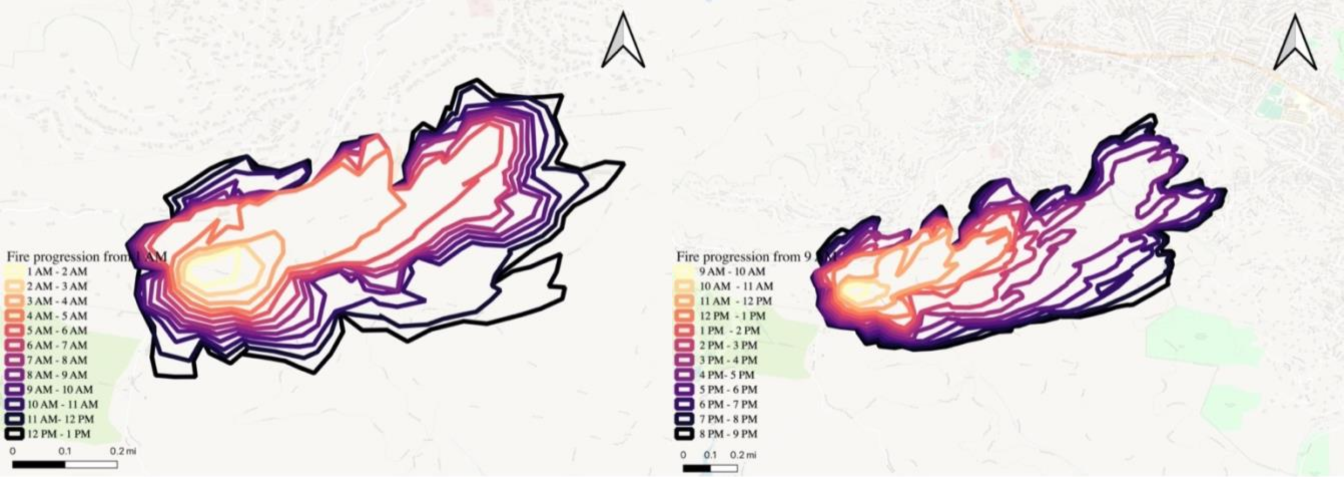


Figure 8. Ignition Points for the Four Cases and the Locations of Weather Stations

Table 3. Modified Meteorological Parameters for the Ross Valley Scenario

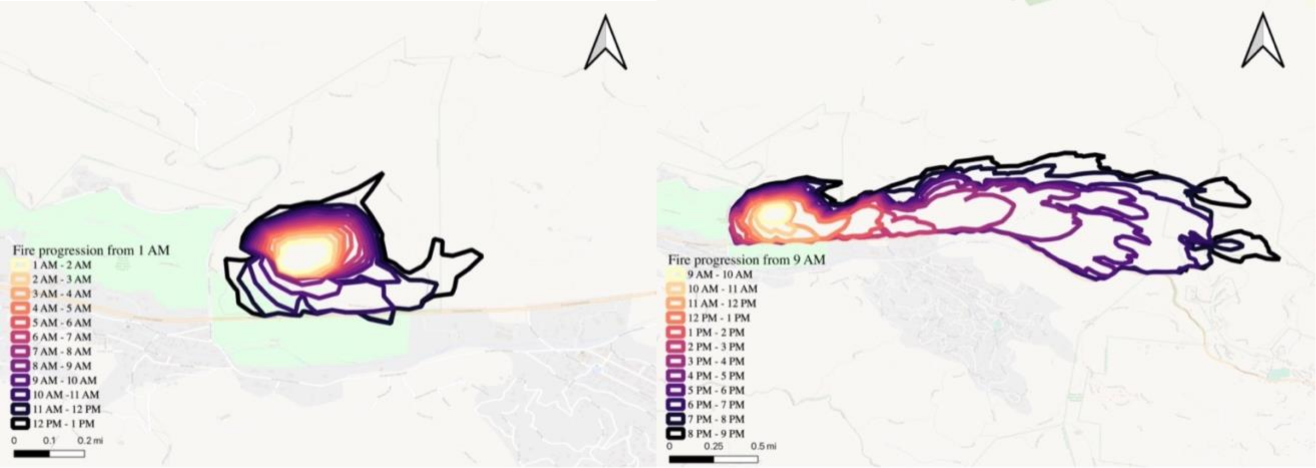
Date	Time	Temperature (ºF)	RH (%)	Wind Speed (GUTS) mph	Real Wind Direction (º)	Used Wind Direction (º)
2020/8/18	01:00 a.m.	82	36	18	304	218
2020/8/18	02:00 a.m.	82	36	18	297	215
2020/8/18	03:00 a.m.	81	39	16	311	221
2020/8/18	04:00 a.m.	80	41	18	297	215
2020/8/18	05:00 a.m.	80	39	18	324	234
2020/8/18	06:00 a.m.	80	37	19	324	234
2020/8/18	07:00 a.m.	80	41	19	305	215

Date	Time	Temperature (ºF)	RH (%)	Wind Speed (GUTS) mph	Real Wind Direction (º)	Used Wind Direction (º)
2020/8/18	08:00 a.m.	82	42	17	335	245
2020/8/18	09:00 a.m.	86	31	16	322	232
2020/8/18	10:00 a.m.	88	22	18	313	223
2020/8/18	11:00 a.m.	93	26	17	324	234
2020/8/18	12:00 p.m.	91	25	14	330	240
2020/8/18	01:00 p.m.	93	23	19	332	242
2020/8/18	02:00 p.m.	94	20	21	314	224
2020/8/18	03:00 p.m.	92	20	22	298	215
2020/8/18	04:00 p.m.	88	22	28	309	219
2020/8/18	05:00 p.m.	87	17	36	303	215
2020/8/18	06:00 p.m.	84	16	39	311	221
2020/8/18	07:00 p.m.	82	15	36	327	237
2020/8/18	08:00 p.m.	80	17	39	283	230



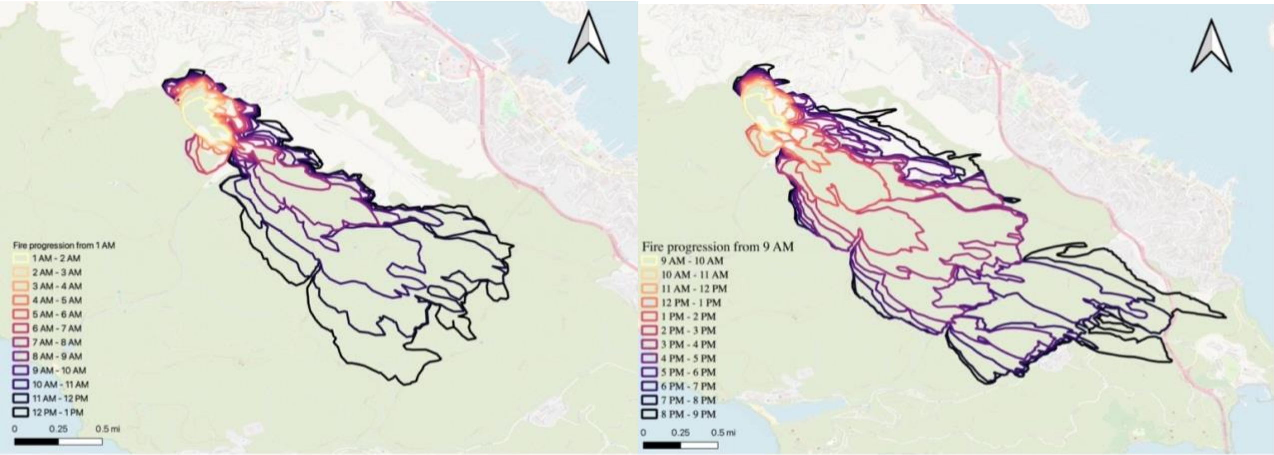
(a) Fire Progression from 1 a.m. (b) Fire Progression from 9 a.m.

Figure 9. Fire Propagation for Ross Valley Scenarios



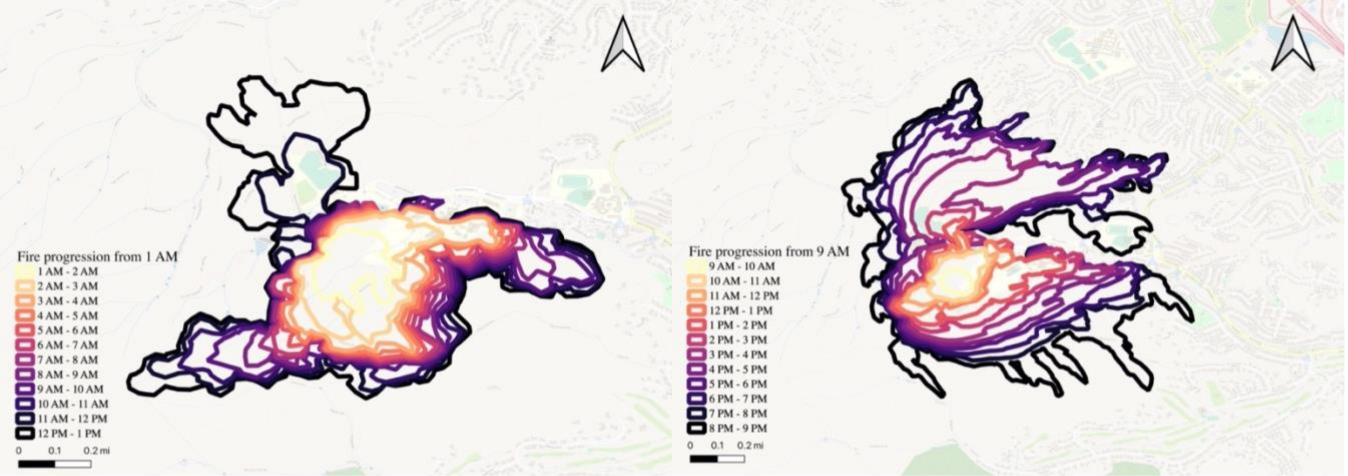
(a) Fire Propagation from 1 a.m. (b) Fire Propagation from 9 a.m.

Figure 10. Fire Propagation for Woodacre Bowl Scenarios



(a) Fire Propagation from 1 a.m. (b) Fire Propagation from 9 a.m.

Figure 11. Fire Propagation for Tamalpais Valley Scenarios



(a) Fire Propagation from 1 a.m. (b) Fire Propagation from 9 a.m.

Figure 12. Fire Propagation for Novato Neighborhood Scenarios

Background Traffic

The background traffic origin/destination (OD) demand data was obtained from the Metropolitan Transportation Commission (MTC) at https://mtcdrive.app.box.com/v/pba50-2015-TM152-IPA-17. An activity-based travel model was used to simulate the travel-related choices of Bay Area residents. The model used data from the MTC 2015 Bay Area Travel Behavior survey, which included two-day travel diaries from over 15,000 households. The model's unit of analysis was a "tour" which represents a closed or half-closed chain of trips starting and ending at home or the workplace; it includes at least one destination and at least two successive trips. The model generated tour and trip lists for each resident. The individual and joint trips were later aggregated into origin-destination metrics.

The MTC traffic OD data covers trips in the whole Bay Area. However, in this study, our focus was limited to Marin County. Therefore, trips which do not pass through Marin County were filtered out. The remaining trips that did pass through Marin County were truncated to keep only the trip segments within Marin County to reduce the subsequent computing time. This process is illustrated in Figure 13. After the pre-processing, the number of background OD trips during one modeled day was 823,916. The spatial and temporal distributions of the background traffic OD is shown in Figures 14-15. The ODs are concentrated in the eastern part of the Marin County. The largest number of trips were those originating from/destined to the Golden Gate Bridge and Richmond-San Rafael Bridge. During the peak hours from 7 a.m.-10 a.m. and 3 p.m.-6 p.m., the number of vehicles accounted for around 50 percent of the total background vehicles in a day. If a wildfire occurs during peak hours, then the presence of background vehicle traffic could have a major impact on the evacuating vehicles.

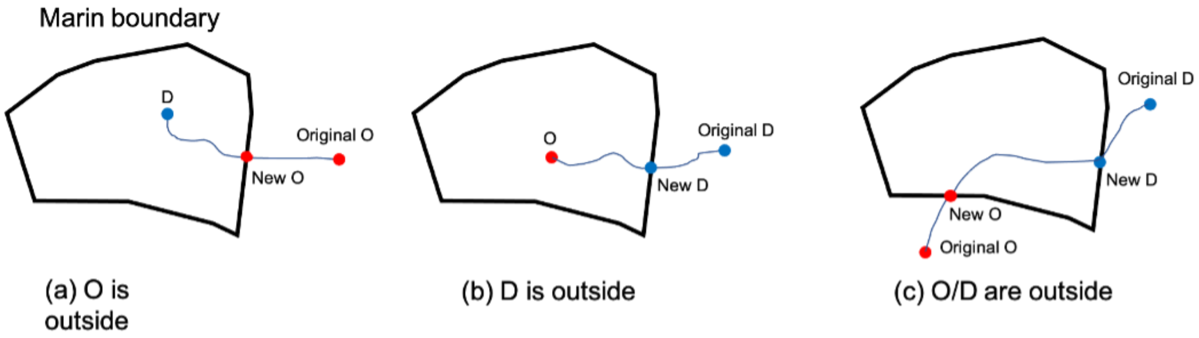


Figure 13. Change of O/D which are outside Marin County to the border of Marin

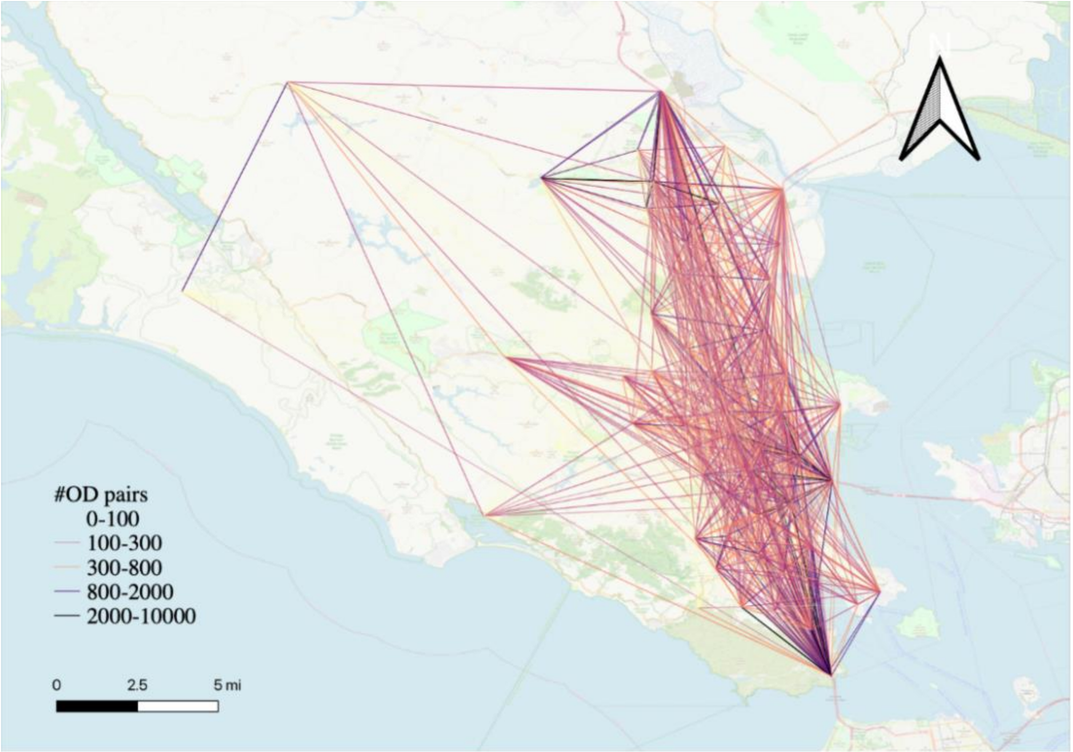


Figure 14. The Spatial Distribution of Background OD pairs within Marin County

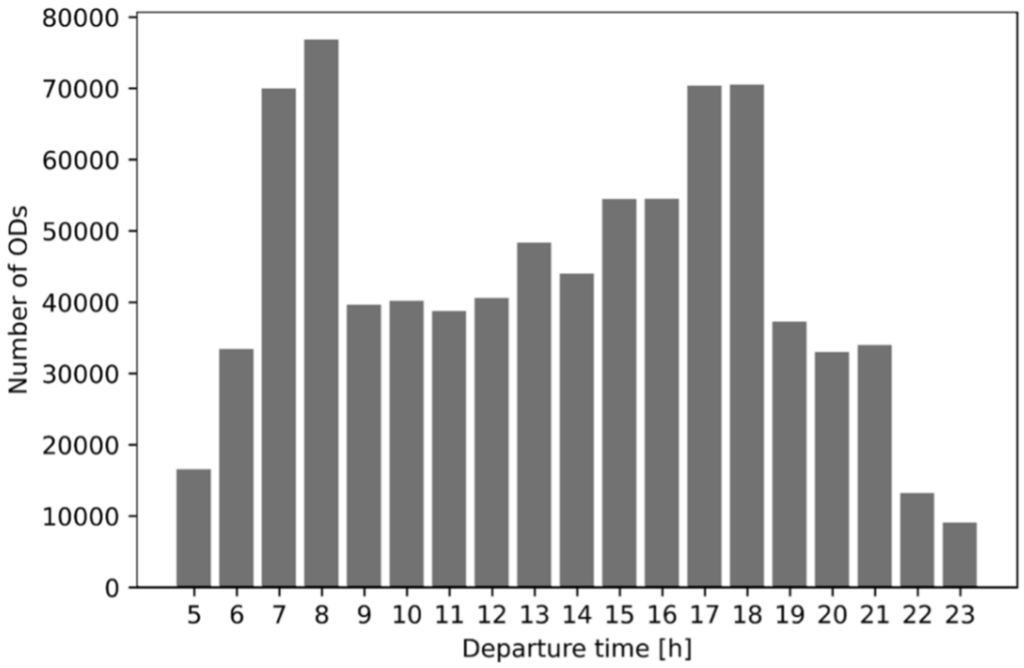


Figure 15. Temporal Distribution of Background OD Pairs within Marin County

Evacuee OD Demand

The number of residents who need to be evacuated is different between the daytime scenario and the nighttime scenario because many residents would be at work during the day, while most would be at home at night. From the background OD data, the location where each person begins their day is known and this place is regarded as their residence. Using the background OD data, it was possible to determine how many residents were at home when the fire ignited, and these residents were classified as evacuees.

Table **4** provides a summary of the number of evacuees for each scenario.

The simulated evacuation destinations were set on the border of Marin County and other counties, as depicted in Figure 16. Four evacuation destinations were available for evacuees to choose from, and the assumption was that individuals would select the closest option to them. Generally, the evacuees from Tamalpais Valley would choose the southern two destinations (Golden Gate Bridge and Richmond-San-Rafael Bridge) as their destinations; evacuees from Ross Valley and Woodacre Bowl would choose the middle destination; and evacuees from the Novato Neighborhood would choose the northern two destinations (Redwood Highway and Sears Point Bridge) and the middle destination (Richmond-San-Rafael Bridge). The treatment of destination choices is simplistic and does not consider factors such as shelter availability, proximity to resources, and destination safety, which all may affect an evacuee's decision. To minimize these outside influences, this study focused mainly on the most dangerous part of the trip, the time taken to reach a point two miles away from the final fire extent. (The time taken to reach the destination is not reported here, as it provides minimal information on the evacuees' risks due to the proximity to the fires.)

The evacuees’ departure times were based on a truncated normal distribution (i.e., truncated around the mean ± one standard deviation). The means and the standard deviations of the departure times are different for the nighttime evacuation and daytime evacuation scenarios. We assumed that during the day people are more likely to receive fire alert messages from various media promptly and take action more quickly. Conversely, in the late evening people are likely asleep and less likely to be aware of such messages. Therefore, for the daytime evacuation, the mean departure time was set to 9:10 a.m. ± 10 minutes, while for the nighttime evacuation, the mean departure time was set to 1:20 a.m. ± 20 minutes.

Table 4. Summary of Number of Evacuees for Different Scenarios

Study area	Fire ignition time	# residents	# residents who have departed to other places before the fire occurs	# evacuees
Ross Valley	9 a.m.	4,893	2,928	1,965
	1 a.m.	4,893	0	4,893
Woodacre Bowl	9 a.m.	2,196	840	1,356
	1 a.m.	2,196	0	2,196
Tamalpais Valley	9 a.m.	5,492	3,482	2,010
	1 a.m.	5,492	0	5,492
Novato Neighborhood	9 a.m.	17,519	9,857	7,662
	1 a.m.	17,519	0	17,519

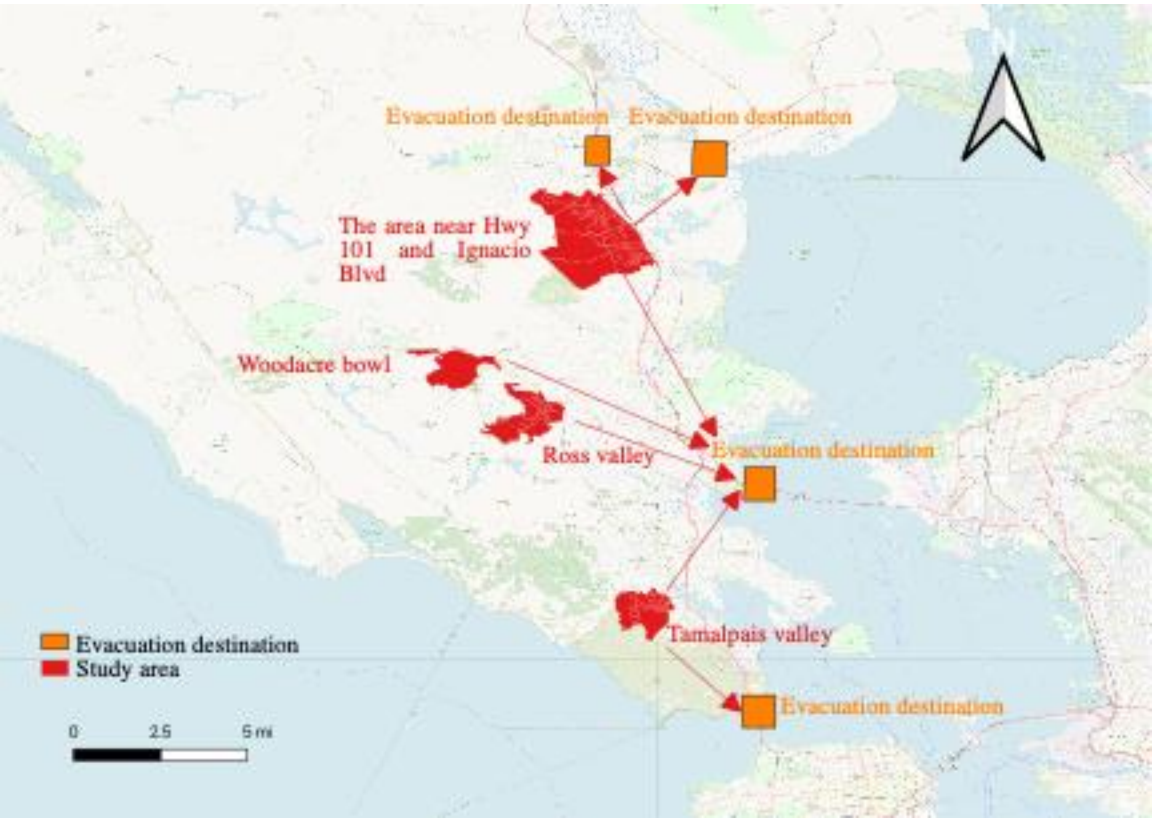


Figure 16. Evacuation Destinations

Validation of the Simulation

Before evaluating the evacuation strategies, we conducted a validation analysis on the "no evacuation" scenario, where only background traffic OD data was used to run the traffic simulations, and the simulated traffic volumes at key locations on several main roads at different times were compared with real observations (traffic count data) collected by Fehr&Peers (https://www.fehrandpeers.com/). The comparison results are presented in Table 6 and 6. These two tables show the differences between the traffic volume generated by simulation and count data during morning peak hours and afternoon peak hours. As shown, the percentage difference in volume on most roads is less than 20 percent. According to the 2017 California Regional Transportation Plan Guidelines, a commonly used criterion for volume-count validation is a percentage root mean square error less than 40 percent (Commission, 2017). The value of the percentage root mean square error of our simulation is 18.9 percent, much less than the threshold. Therefore, our simulation performs well.

Table 5. Comparison of Model Traffic and Counts from Roadside Detectors during Morning Peak

#	Type	Direction	Location	# vehicles during morning peak period (6 a.m.-10 a.m.)		Percentage difference
				Model	Count	
1	Mainline	North bound	US 101 at San Francisco /Marin County Line	12,784	10,000	27.84%
2	Mainline	South bound		21,094	17,984	17.29%
3	Mainline	North bound	US 101 at Corte Madera Creek	16,591	13,000	27.60%
4	Mainline	South bound		25,718	20,000	28.59%
5	Mainline	North bound	US 101 at San Rafael Creek	16,042	19,000	-15.57%
6	Mainline	South bound		23,148	28,000	-17.33%
7	Mainline	East bound	I-580 at Contra Costa/Marin County Line	8,601	7,900	8.87%
8	Mainline	West bound		13,947	12,800	8.96%
9	Mainline	North bound	US 101 at Sonoma /Marin County Line	6,607	8,100	-18.43%
10	Mainline	South bound		11,031	11,000	0.28%

Table 6. Comparison of Model Traffic and Counts from Roadside Detectors during Afternoon Peak

#	Type	Direction	Location	# vehicles during afternoon peak period (3 p.m.-7 p.m.)		Percentage of the difference
				Model	Count	
1	Mainline	North bound	US 101 at San Francisco /Marin County Line	17,201	19,000	-9.47%
2	Mainline	South bound		13,364	13,000	2.80%
3	Mainline	North bound	US 101 at Corte Madera Creek	20,304	21,000	-3.31%
4	Mainline	South bound		21,212	20,000	6.06%
5	Mainline	North bound	US 101 at San Rafael Creek	20,522	22,000	-6.72%
6	Mainline	South bound		17,477	20,000	-12.62%
7	Mainline	East bound	I-580 at Contra Costa/Marin County Line	12,802	12,700	0.80%
8	Mainline	West bound		9,537	8,600	10.90%
9	Mainline	North bound	US 101 at Sonoma /Marin County Line	8,576	11,900	-27.93%
10	Mainline	South bound		5,756	8,000	-28.05%

Impact of Background Traffic

This section analyzes the impact of background traffic on evacuation efficiency. We conducted comparative experiments to show the difference in evacuation time between the scenarios with background traffic and without background traffic at each of the four study sites. The results are shown in Figures 17-20. These figures show the number of evacuees that reach their destinations over time with/without background traffic and during the daytime and nighttime scenarios for the four study sites. Table 7 shows the average travel times for each scenario.

These figures show that background traffic has almost no impact on nighttime evacuations (the nighttime. curve is entirely covered up by daytime curve) but has a significant impact on daytime evacuations. The results make sense as there is little background traffic at 1 a.m. and consequently, there would be little effect on evacuation times. In daytime, there are many more commuting vehicles than evacuating vehicles; therefore, the background traffic would have a large influence. Table 7 shows that, when the evacuation/fire ignition starts at 9 a.m., the average evacuation times with background traffic are one and a half hours more for Ross Valley, one- and three-quarter hours more for Woodacre Bowl, one third of an hour more for Tamalpais Valley, and a half hour more for the Novato Neighborhood than without background traffic. These differences highlight the importance of taking background traffic into account when developing evacuation strategies, as it can significantly affect evacuation efficiency.

The impact of background traffic on the evacuation of Ross Valley and Woodacre Bowl is much larger than that of Tamalpais Valley and the Novato Neighborhood. Figure 21 shows that the exits for Ross Valley and Woodacre are concentrated on Sir Francis Drake Blvd, which is a very busy main road. When an evacuation is ordered, it will cause a heavy traffic jam on this road. Compared with these two places, Tamalpais Valley and Novato Neighborhood have many widely dispersed exits. Even if the background traffic volume is high, the evacuees can find many exit routes, hence, the impact of background traffic on the evacuation is comparatively small in these areas.

Overall, background traffic needs to be taken into account when planning for daytime evacuations, but its impact differs with the topology of the road networks.

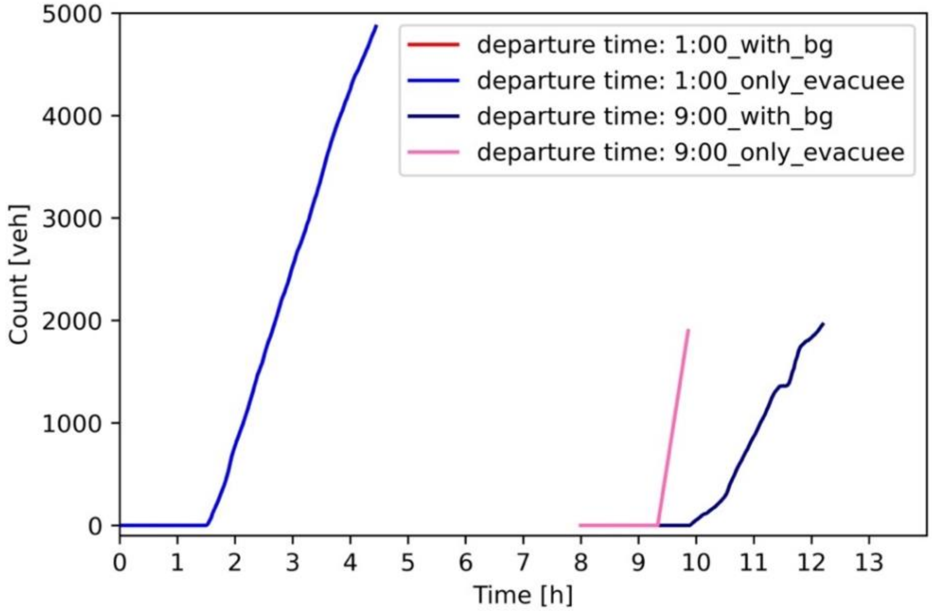


Figure 17. Arrival Times for Ross Valley

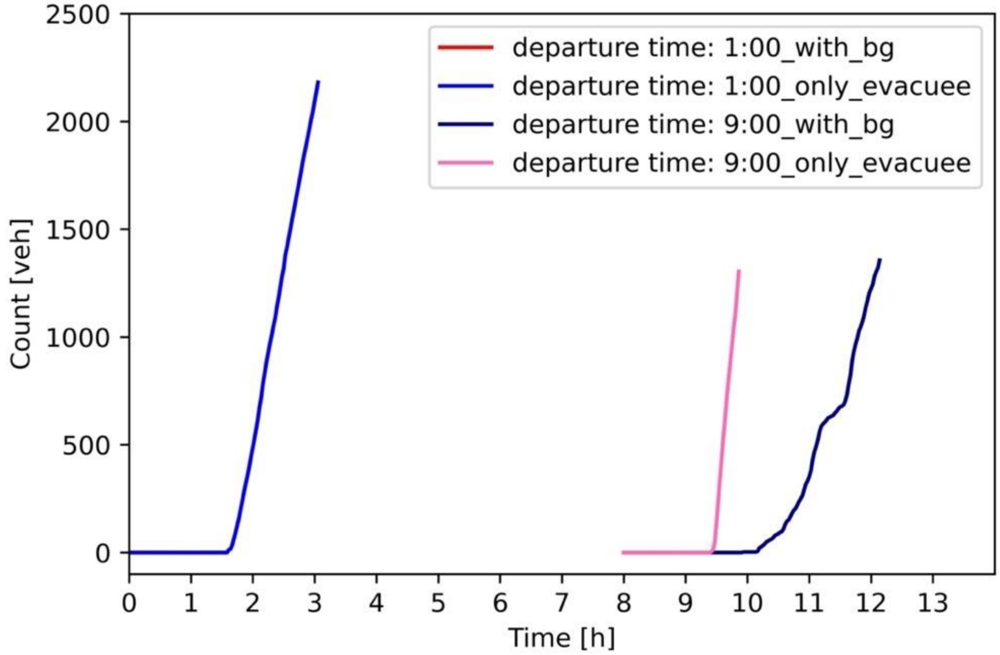


Figure 18. The Arrival Times for Woodacre Bowl

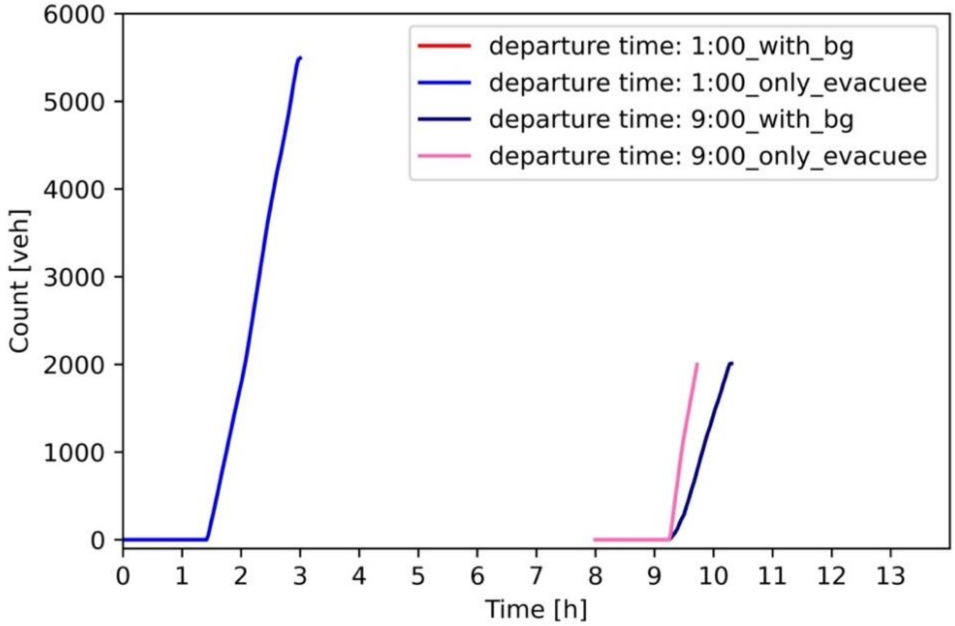


Figure 19. The Arrival Times for Tamalpais Valley

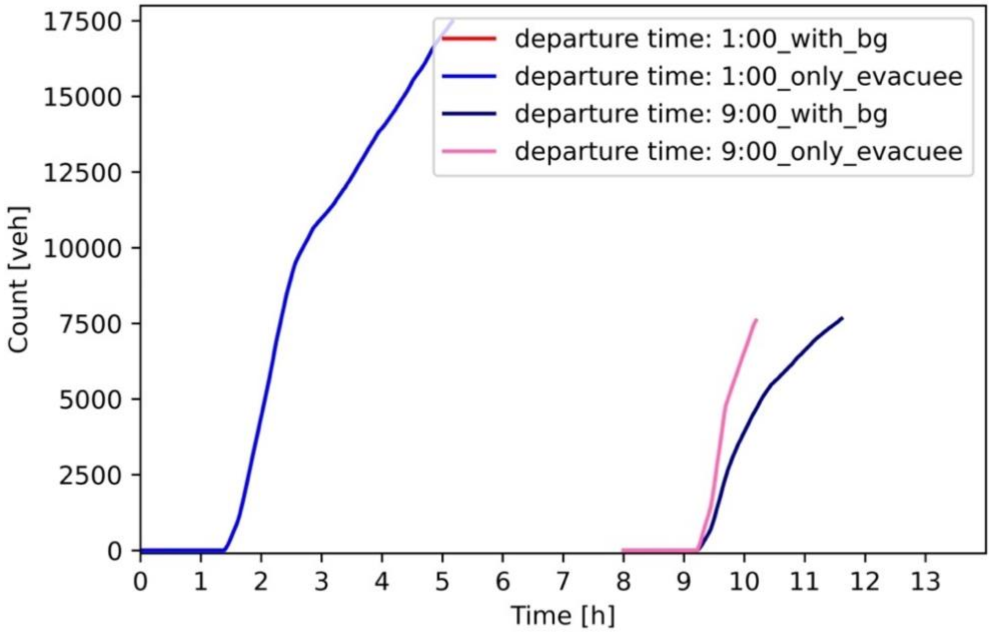


Figure 20. Arrival Times for Novato Neighborhood

Table 7. Comparison of Average Evacuation Time With and Without Background Traffic

Study site	Fire ignition time	Average evacuation time [h]		Difference	
		With background	Without background	Absolute	Percent
Ross Valley	1 a.m.	1.30	1.30	0	0%
	9 a.m.	1.79	0.28	1.51	532%
Woodacre Bowl	1 a.m.	0.71	0.71	0	0%
	9 a.m.	2.04	0.33	1.71	518%
Tamalpais Valley	1 a.m.	0.58	0.58	0	0%
	9 a.m.	0.49	0.16	0.33	206%
Novato Neighborhood	1 a.m.	1.21	1.21	0	0%
	9 a.m.	0.82	0.34	0.48	141%

(a) topology and exits for Ross Valley. (b) topology and exits for Woodacre Bowl

(c) topology and exits for Tamalpais Valley (d) topology and exits for Novato Nhbd

Figure 21. Network Topologies and Exits for the Four Case Study Areas

Strategy Analysis

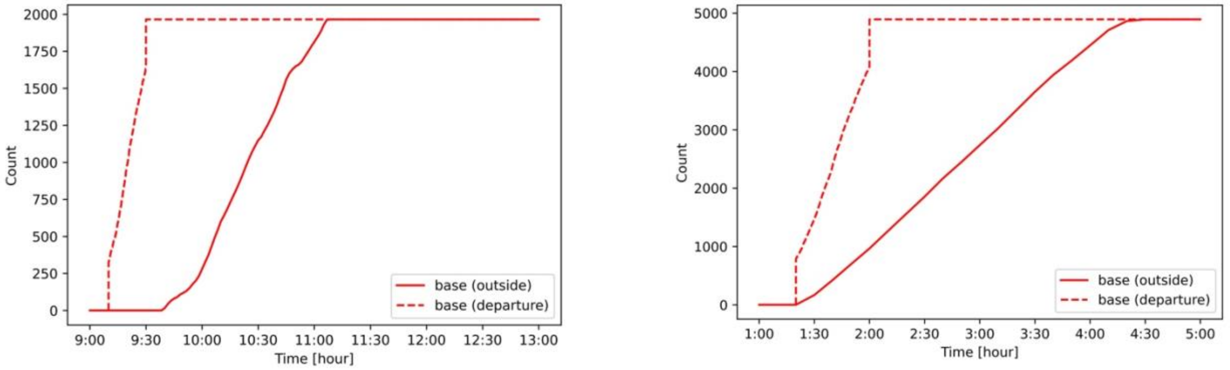
The purpose of this study was to understand the applicability of commonly used evacuation strategies under different settings. These strategies, including vehicle reduction, phased evacuation, and banning on-street parking were shown in Table 2 above. Each alternative strategy option was simulated, and the results compared against the base scenario (the underlined values in Table 2). The following sections present evacuation performance metrics and other results for the baseline scenario and the various alternative scenarios. Recommendations are given at the end.

Baseline

The base cases for the wildfire simulation for the four case studies are: no car-pooling, no phased evacuation, and no on-street parking. Figures 22-26 show the number of evacuees that reach a point at least two miles outside the fire area over time, number of evacuees still within a half mile of the fire area over time, and the cumulative person-hours of exposure to the fire over time for the four case studies.

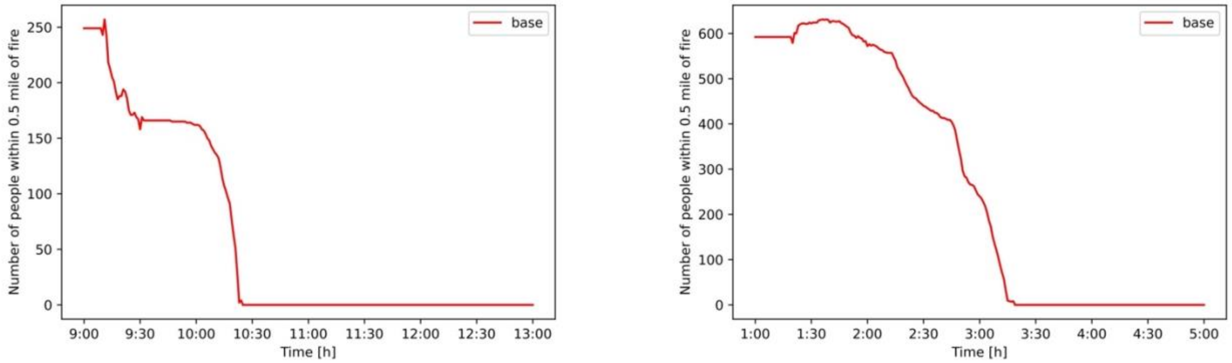
For the daytime evacuation, the distribution of departure times follows a normal distribution with a mean value of 9 hours 20 minutes and a standard deviation of 10 minutes. For the nighttime evacuation, the distribution follows a normal distribution with a mean of 1 hour 40 minutes and a standard deviation of 20 minutes. This is consistent with the research of Zhao et al. (2021) which assumed that departure time would follow a normal distribution since once residents receive an evacuation notification, most will need time to prepare to leave and this will delay the peak departure time.

Figures 22(a)-(f) illustrate how the evacuation process for the Ross Valley proceeds. For the daytime evacuation scenario (fire ignites at 9 a.m.), all vehicles would reach two miles away from the fire area before 11:11 a.m. (solid blue line in Figures 22(a)-(b), and the average evacuation time would be one and a quarter hour. For the nighttime evacuation scenario (fire ignites at 1 a.m.), all vehicles would reach two miles away from the fire area before 4:15 a.m. (solid blue line in Figure 22(b)), and the average evacuation time would also be about one and a quarter hour. The average evacuation time for the nighttime scenario is similar to that during the day despite the much-reduced background traffic, mainly because of the higher number of evacuees in the nighttime scenario. The impact of the background traffic is nevertheless observed in another of the daytime scenarios. Figure 22(c) shows that, during the period of 9:30 a.m.-10 a.m., very few additional vehicles leaving the fire danger area make it beyond one half mile of the fire because background vehicles block the evacuation routes during these morning peak hours. However, this does not occur in the nighttime case (Figure 22(d)) when background traffic is far less. Figures 22(e)-(f) present the cumulative exposure time of all the evacuees for the daytime and nighttime cases. The cumulative exposure time when all the evacuees reach the destination is about 230 hours for the daytime scenario and 1050 hours in nighttime scenario. On average, though, evacuees in the nighttime scenario are less exposed to the fire, about seven minutes per person compared to 13 minutes for those in the daytime scenario.



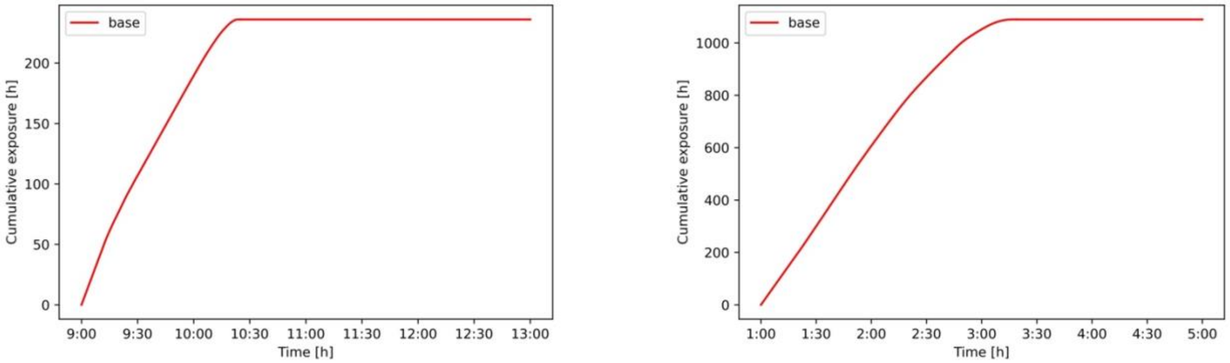
(a) #vehicles that reach 2 miles away from the fire area (daytime scenario)

(b) #vehicles that reach 2 miles away from the fire area (nighttime scenario)



(c) #persons within 0.5 mile of fire (daytime scenario)

(d) #persons within 0.5 mile of fire (nighttime scenario)

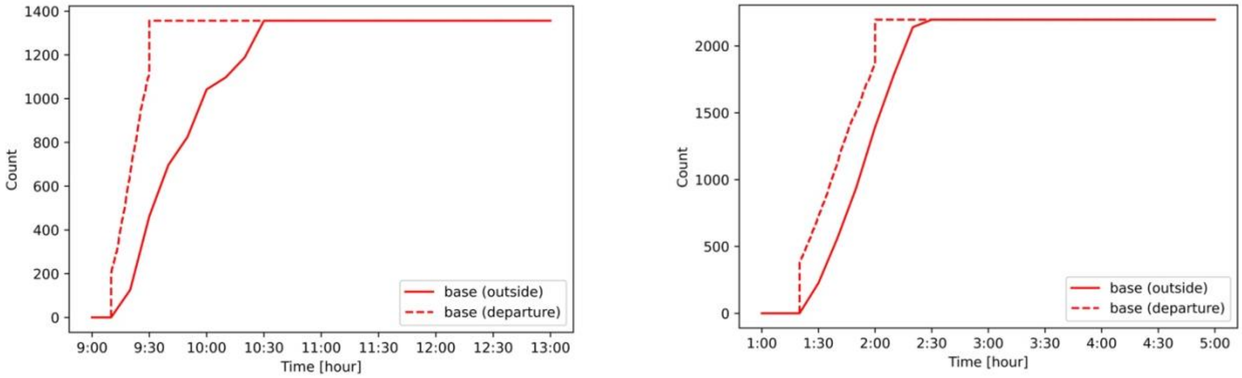


(e) Cumulative fire exposure (hours) (daytime scenario)

(f) Cumulative fire exposure (hours) (nighttime scenario)

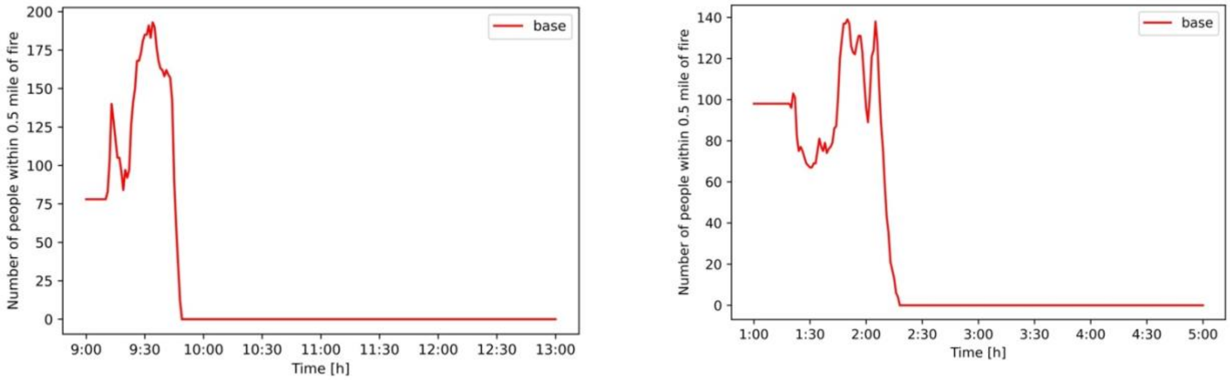
Figure 22. Baseline Case for Ross Valley

For the Woodacre Bowl case, if the fire ignites at 9 a.m., all vehicles reach two miles away from the fire area before 10:30 a.m., while if the fire ignites at 1 a.m., all vehicles reach two miles away before 2:30 a.m. Figures 23(c)-(d) show that the number of evacuees within a half mile of the fire first increases and then plummets. The reason for the initial increase is that the fire ignites one mile away from the residential area but covers the sole evacuation road. Therefore, evacuees need, first, to enter the fire area and then evacuate to the safe locations. Figures (e)-(f) present the cumulative exposure time of all the evacuees for the daytime and nighttime scenarios. Cumulative exposure when all the evacuees reach the safe destination is about 100 hours in the daytime scenario and 120 hours in the nighttime scenario. On average, each evacuee is exposed to the fire for around four and a half minutes in the daytime scenario and just over three minutes in the nighttime scenario.



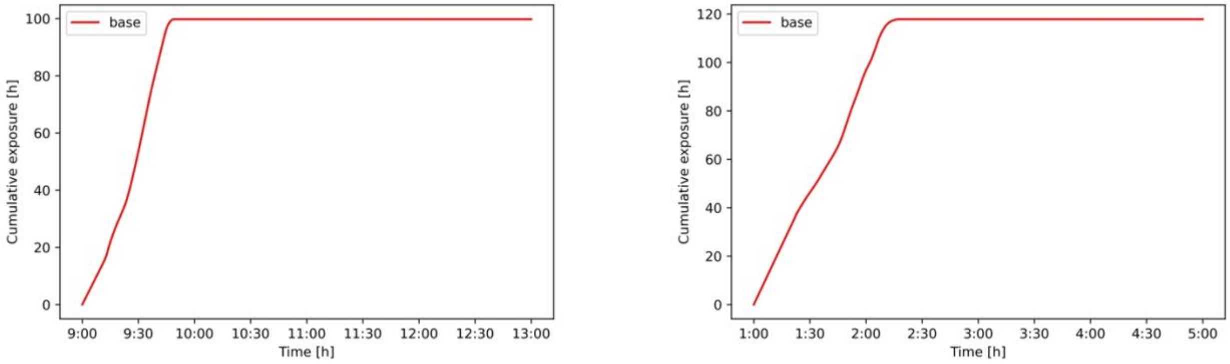
(a) #vehicles that reach 2 miles away from the fire area (daytime scenario)

(b) #vehicles that reach 2 miles away from the fire area (nighttime scenario)



(c) #persons within 0.5 mile of fire (daytime scenario)

(d) #persons within 0.5 mile of fire (nighttime scenario)

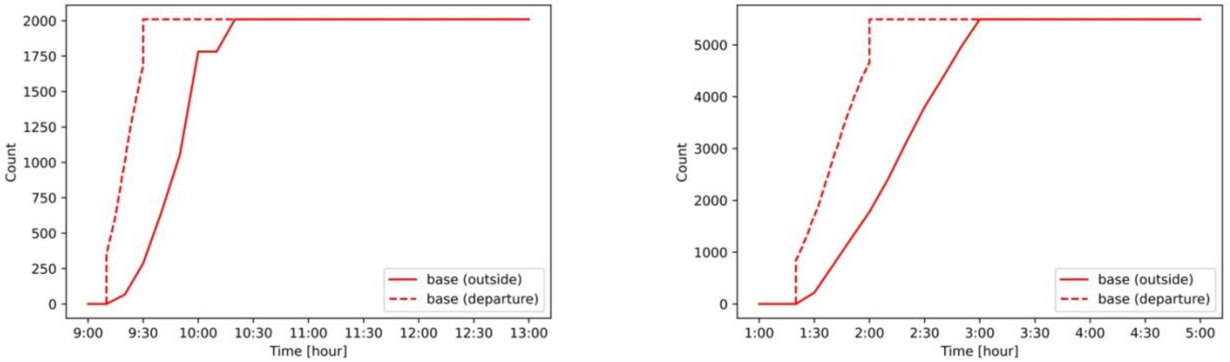


(e) Cumulative fire exposure (hours) (daytime scenario)

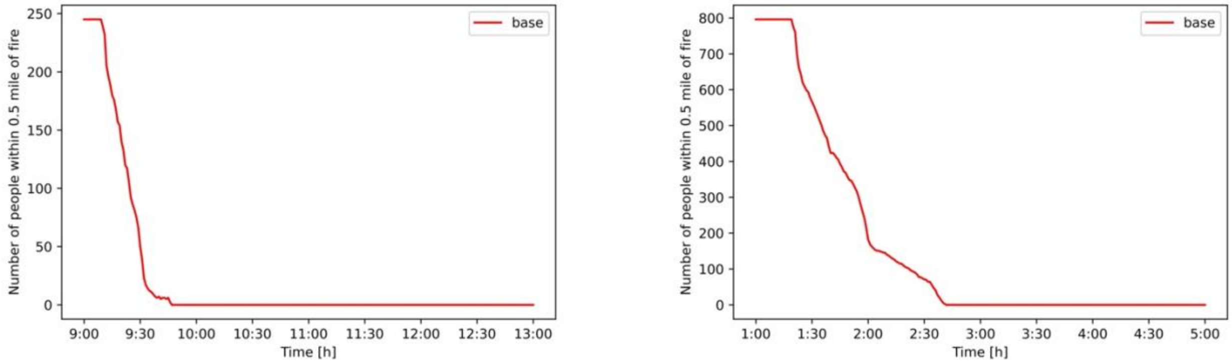
(f) Cumulative fire exposure (hours) (nighttime scenario)

Figure 23. Baseline Case for Woodacre Bowl

For the Tamalpais Valley case, if the fire ignites at 9 a.m., all vehicles will reach two miles from the fire before 10:20 a.m., while if the fire ignites at 1 a.m., all vehicles reach two miles away before 3 a.m. The evacuation time in the nighttime scenario is longer than in the daytime scenario because the number of evacuees is larger in the nighttime scenario. Even though there is little background traffic in the nighttime, the combined effect of having so many evacuees severely affect evacuation efficiency. Figures 24(c)-(d) illustrate that the evacuees move out of the danger area quickly within 45 minutes in the daytime, but it takes 100 minutes after the fire ignites in the nighttime. Figures 24(e)-(f) present the cumulative exposure time of all evacuees for the daytime and nighttime cases. The cumulative exposure when all evacuees reach the safe destination is about 90 hours in the daytime scenario and 650 hours in the nighttime scenario. On average, the evacuees in the nighttime scenario are exposed to the fire longer, for around three minutes, compared to seven minutes for those in the daytime scenario.

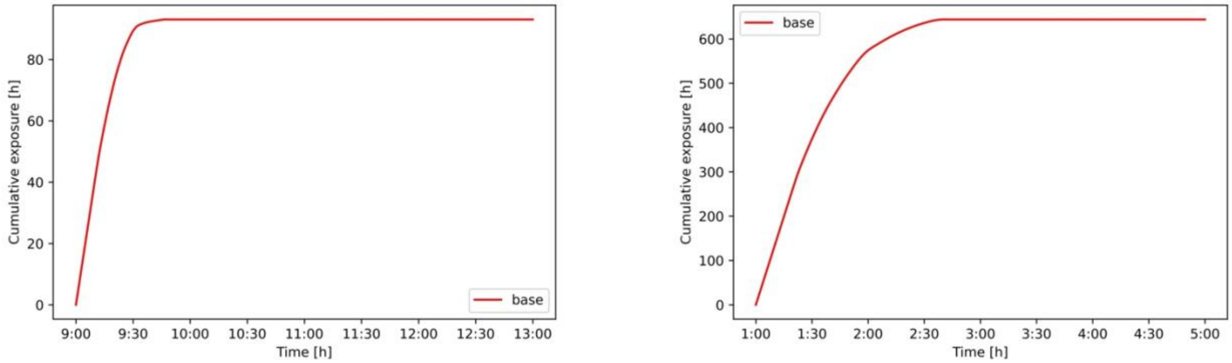


(a) #vehicles that reach 2 miles away from the fire area (daytime scenario) (b) #vehicles that reach 2 miles away from the fire area (nighttime scenario)



(c) #persons within 0.5 mile of fire (daytime scenario)

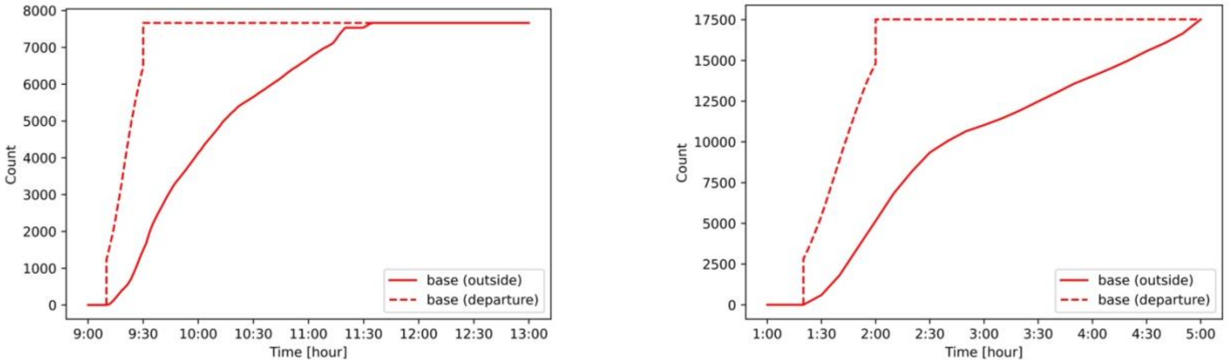
(d) #persons within 0.5 mile of fire (nighttime scenario)



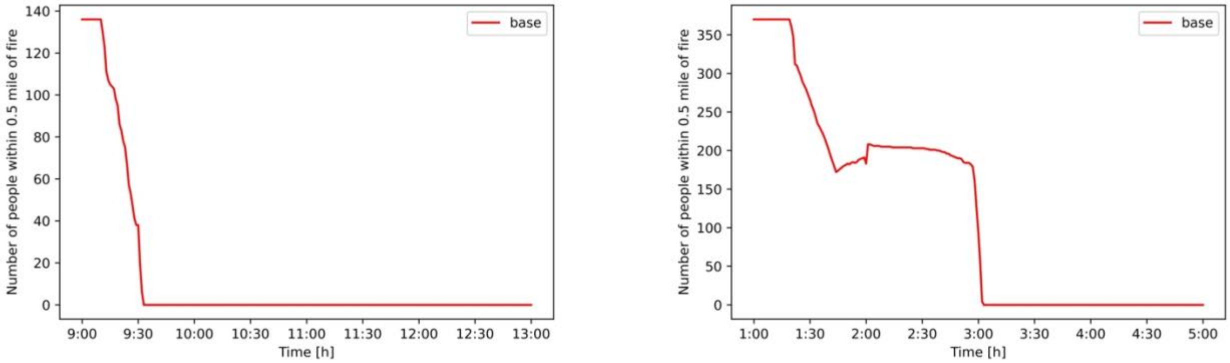
(e) Cumulative exposure (hours) (daytime scenario) (f) Cumulative exposure (hours) (nighttime scenario)

Figure 24. Baseline Case for Tamalpais Valley

For the Novato Neighborhood case, if the fire ignites at 9 a.m., all vehicles reach two miles away before 11:40 a.m., while if the fire ignites at 1 a.m., all vehicles reach two miles away before 5:00 a.m. Figures 25(c)-(d) show that some evacuees become blocked from 2:00-3:00 a.m. Since there is little background traffic at this time, the backup is presumably due to downstream evacuating vehicles blocking the way of the upstream vehicles. Figures 25(e)-(f) present the cumulative exposure time for all evacuees to reach the designated safe destination in the daytime is about 50 hours and 500 hours in the nighttime. On average, each evacuee is exposed to the fire for around one minute in the daytime and two minutes in the nighttime.

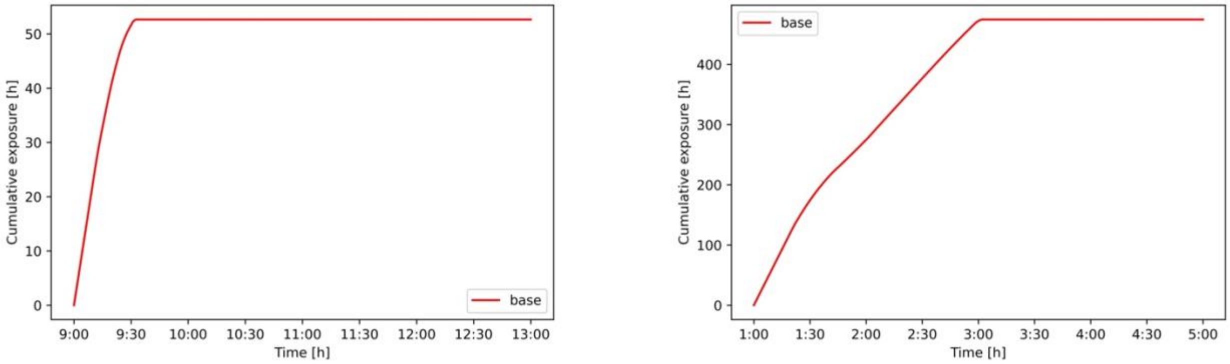


(a) #vehicles that reach 2 miles away from the fire area (daytime scenario) (b) #vehicles that reach 2 miles away from the fire area (nighttime scenario)



(c) #persons within 0.5 mile of fire (daytime scenario)

(d) #persons within 0.5 mile of fire (nighttime scenario)



(e) Cumulative exposure (hours) (daytime scenario)

(f) Cumulative exposure (hours) (nighttime scenario)

Figure 25. Baseline Case for Novato Neighborhood

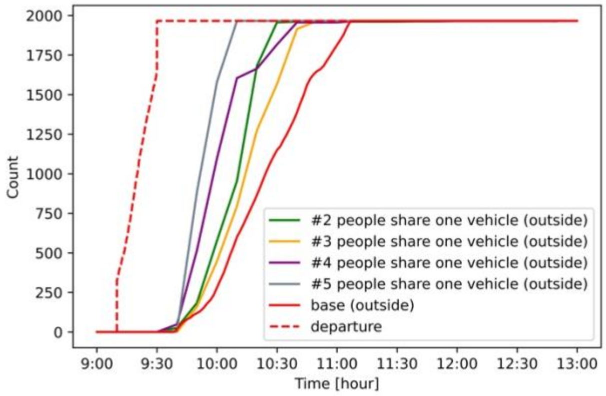
Vehicle Reduction

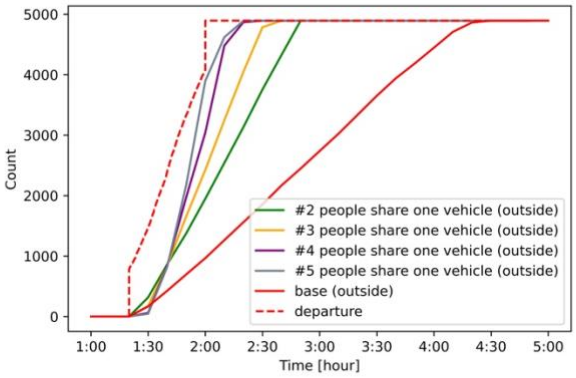
In this section we analyze the impact of reducing the number of vehicles involved in an evacuation through carpooling based on our model. Figures 26-29 show the number of evacuees that would reach two miles away from the fire area over time from the fire's ignition, number of evacuees still within a half mile of the fire area over time, and cumulative exposure time to the fire over time depending on whether one, two, three, four or five persons share a single vehicle for each of the four case studies. Table 8 and Figures 30-31 present the average travel time and average exposure time for each of the five different carpooling assumptions.

For the Ross Valley case, Figure 26 shows that if each vehicle has an average of one, two, or five persons, all evacuees will reach two miles away from the fire area before 11:10 a.m., 10:40 a.m., and 10:10 a.m., respectively in the daytime scenario and all evacuees will reach two miles away from the fire area before 4:20 a.m., 2:50 a.m., and 2:20 a.m., respectively in the nighttime scenario. The number of persons who remain within a half mile of the fire area is lowest with four or five persons sharing one vehicle and nearly all leave the danger area much more quickly, while having only one person in each vehicle strands most evacuees in the congested danger area for around one and a half hours in the daytime scenario and two and a half hours in the nighttime scenario.

Table 8 shows that the average evacuation time decreases with more carpoolers. For each additional person sharing a vehicle, the average travel time will be reduced by about 10 percent. Further, average fire exposure time is reduced from about seven minutes without carpooling to about four minutes with two persons sharing one vehicle. When three or more persons share one vehicle, the average exposure time drops to about three minutes. With three or more persons per vehicle the fire exposure threat for all evacuees is a bit less than three minutes.

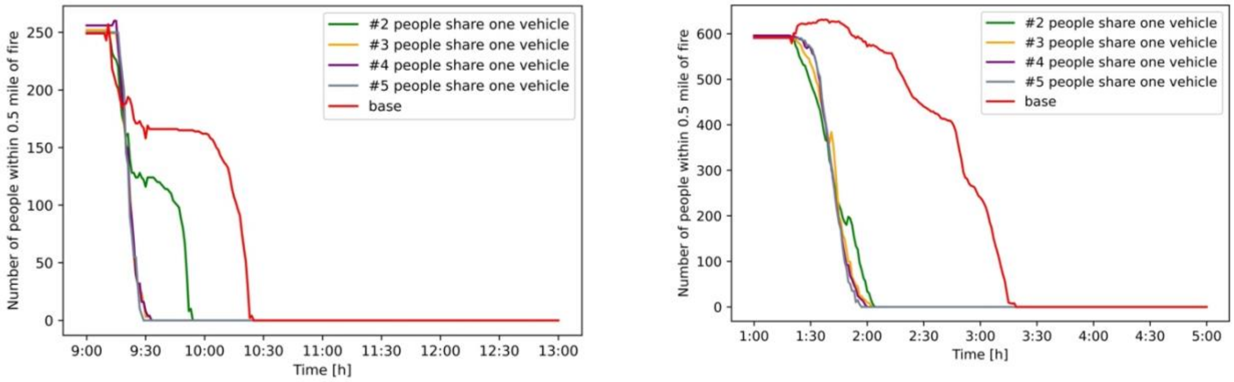
For the nighttime scenario, the average travel time significantly decreases to about 32 minutes if an average of two persons shares one vehicle, compared with around 74 minutes when there is no carpooling. Further, the average exposure time is reduced to about 5 minutes. When every vehicle is shared by three or more persons, the average travel time is reduced to a little over 15 minutes and the average exposure time stays the same at about 5 minutes.





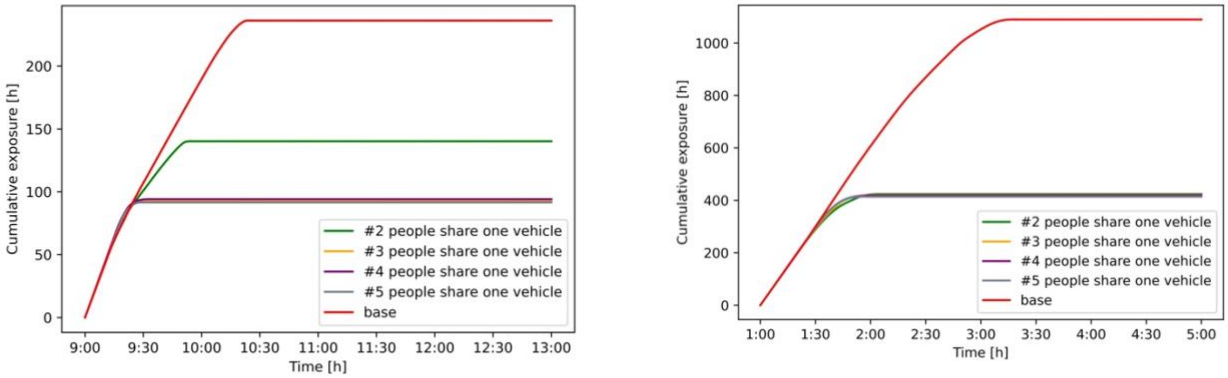
(a) #vehicles that reach 2 miles away from the fire area (daytime scenario)

(b) #vehicles that reach 2 miles away from the fire area (nighttime scenario)



(c) #persons within 0.5 mile of fire (daytime scenario)

(d) #persons within 0.5 mile of fire (nighttime scenario)



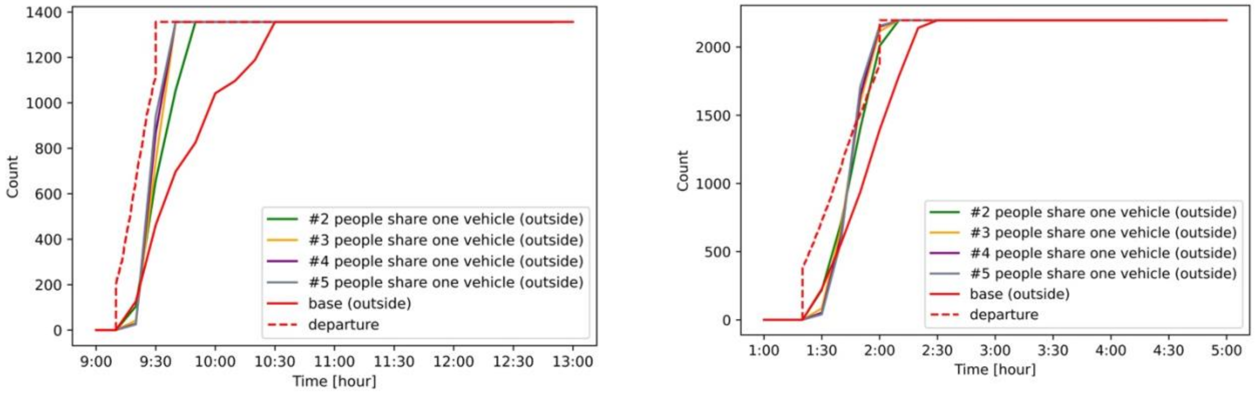
(e) Cumulative exposure (hours) (daytime scenario)

(f) Cumulative exposure (hours) (nighttime scenario)

Figure 26. Vehicle Reduction Strategy Performance Measures for Ross Valley

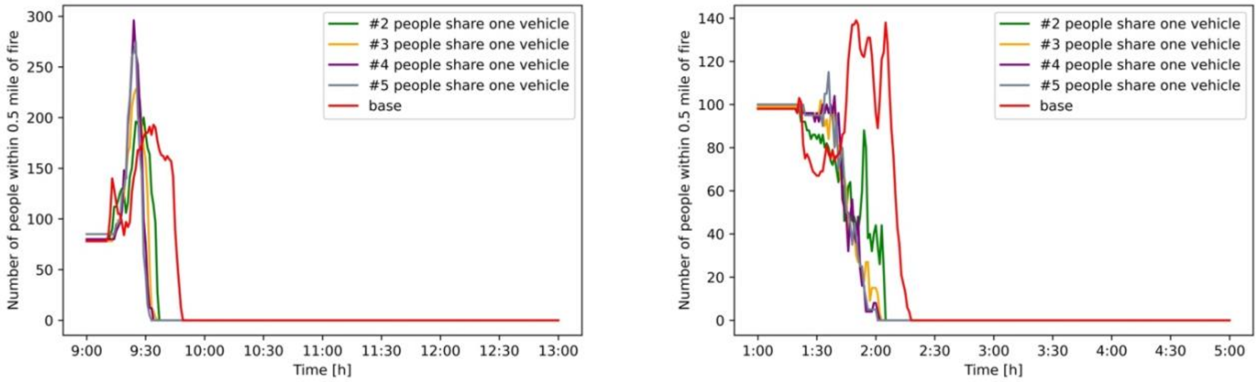
For the Woodacre Bowl case, Figure 27 shows that if each vehicle carries an average of one, two, three, four or five persons, all evacuees reach two miles away from the fire area before 10:30 a.m., 9:50 a.m., 9:40 a.m., 9:40 a.m., and 9:40 a.m., respectively in the daytime scenario and two miles away from the fire area before 2:30 a.m., 2:25 a.m., 2:25 a.m., 2:25 a.m. and 2:25 a.m., respectively in the nighttime scenario. The number of persons who remain within a half mile of the fire area is lower if there are at least two persons per vehicle and nearly all evacuees leave the fire danger area much more quickly, while the having only one person in each vehicle strands most evacuees in the congested danger area for around 0.75 hour and 1.5 hours, respectively in the daytime and nighttime scenarios.

Table 8 shows that in the daytime scenario, the average evacuation time is reduced nearly half when there are at least two persons per vehicle. When there are three persons per vehicle the time for everyone to reach a safe location is reduced by over half, though there is not much additional improvement in evacuation efficiency when there are four or more persons per vehicle. The same is true for average exposure time which remains about three minutes when there are more than three persons per vehicle. In the nighttime scenario, attaining at least two persons per vehicle can already significantly reduce traffic jams and speed up the evacuation progress; reducing the average evacuation time by about 47 percent and limiting the average exposure time by around 30 percent. Again, any additional increase in carpooling provides only marginal improvement.



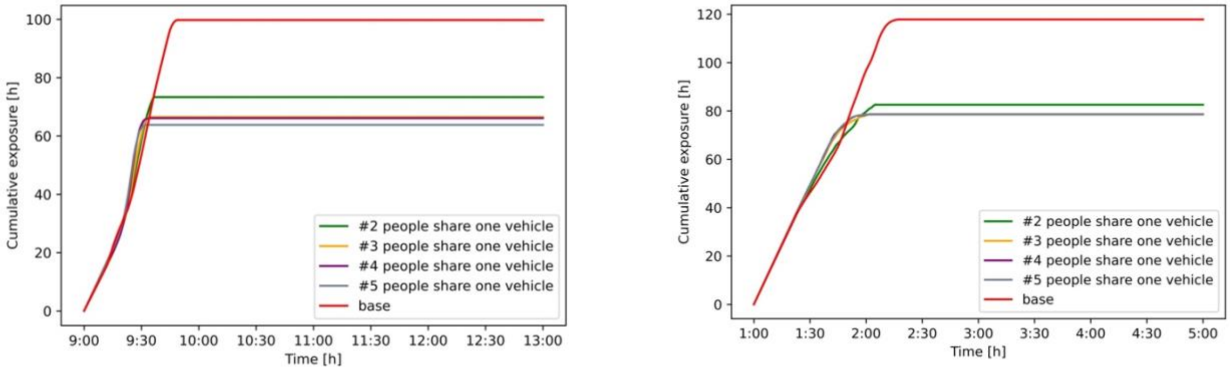
(a) #vehicles that reach 2 miles away from the fire area (daytime scenario)

(b) #vehicles that reach 2 miles away from the fire area (nighttime scenario)



€ #persons within 0.5 mile of fire (daytime scenario)

(d) #persons within 0.5 mile of fire (nighttime scenario)



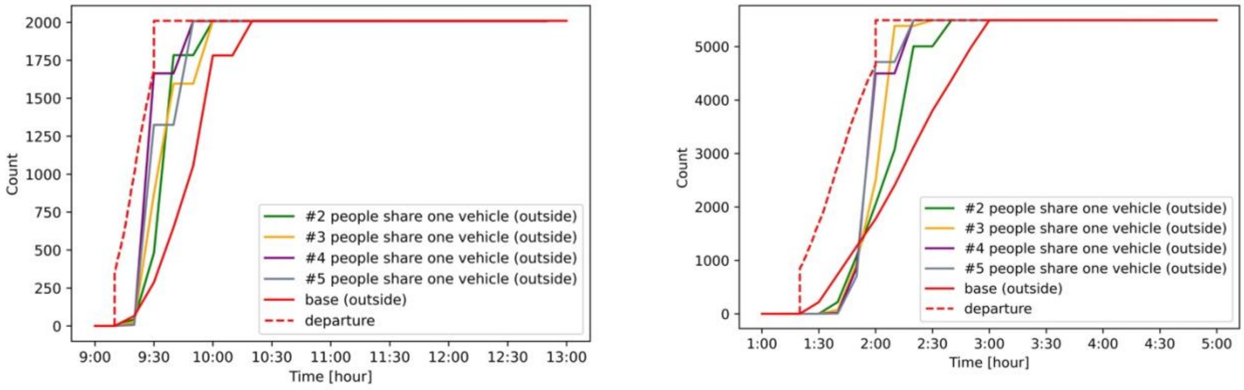
(e) Cumulative exposure (hours) (daytime scenario)

(f) Cumulative exposure (hours) (nighttime scenario)

Figure 27. Vehicle Reduction Strategy Performance Measures for Woodacre Bowl

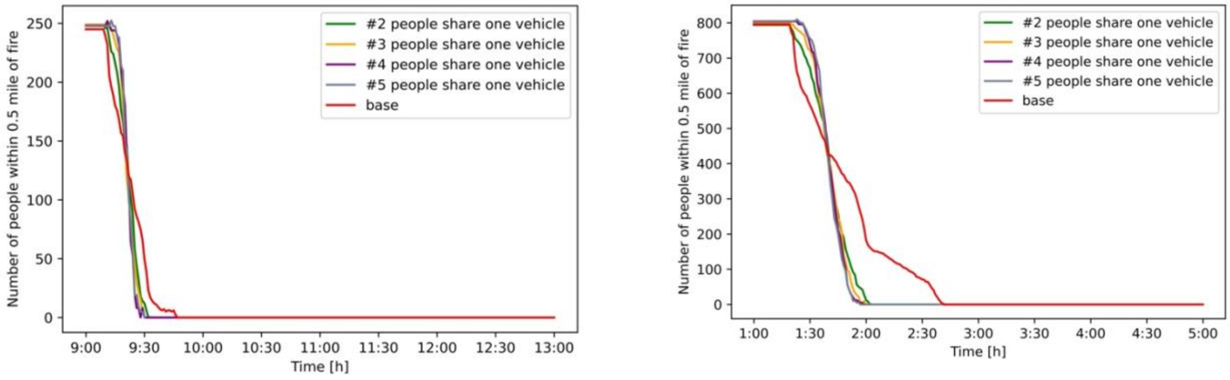
For the Tamalpais Valley case, Figure 28 shows that if evacuating vehicles carry an average of one, two, three, four or five persons, all evacuees will reach two miles away from the fire area before 10:20 a.m., 10:00 a.m., 10:00 a.m., 9:50 a.m., and 9:50 a.m., respectively in the daytime scenario and will reach two miles away from the fire area before 3:00 a.m., 2:40 a.m., 2:30 a.m., 2:20 a.m. and 2:20 a.m., respectively in the nighttime scenario. With at least two persons per vehicle nearly all evacuees leave the fire danger area much more quickly, while having only one person in each vehicle strands most evacuees in the fire danger area for around three quarters of an hour in the daytime scenario and one and three quarters hours in the nighttime scenario.

Table 8 shows that, in the daytime scenario, carpooling improves evacuation efficiency. With an average of two persons sharing one vehicle the average evacuation time is 21 minutes, about 16 minutes less then without carpooling. Little improvement results from having three persons per vehicle but having five riders per vehicle can shave an additional seven minutes off the evacuation time. Average exposure time is less than three minutes for all alternatives. Simulation results indicate that even without carpooling there is almost no heavy congestion within a half mile of the fire center. In the nighttime scenario, having an average of two persons sharing one vehicle reduces the average evacuation time by half from 44 minutes to 22 minutes and average exposure time from seven minutes to six minutes. With more persons per vehicle, the average evacuation time continues to decrease to about 13 minutes when all vehicles carry five persons. However, the average exposure time remains about six minutes which suggests that evacuation efficiency is maximized with an average of just two persons per vehicle.



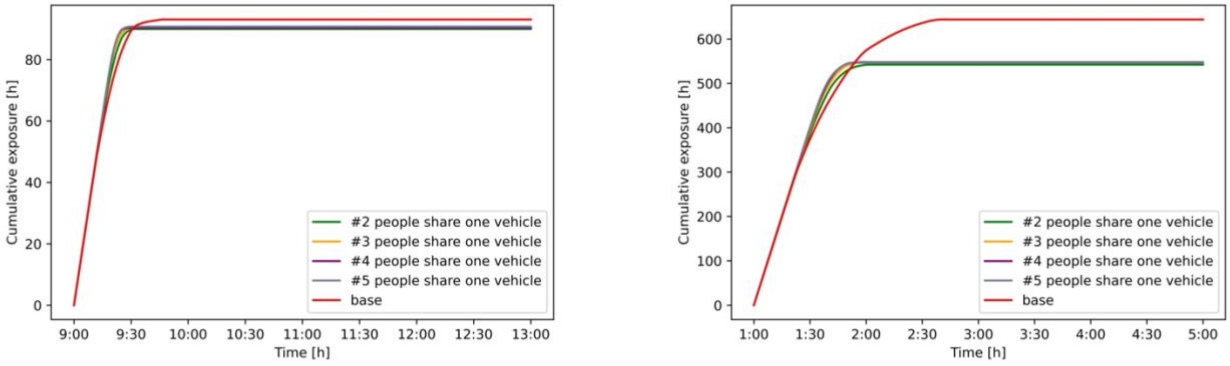
(a) #vehicles that reach 2 miles away from the fire area (daytime scenario)

(b) #vehicles that reach 2 miles away from the fire area (nighttime scenario)



(c) #persons within 0.5 mile of fire (daytime scenario)

(d) #persons within 0.5 mile of fire (nighttime scenario)



(e) Cumulative exposure (hours) (daytime scenario)

(f) Cumulative exposure (hours) (nighttime scenario)

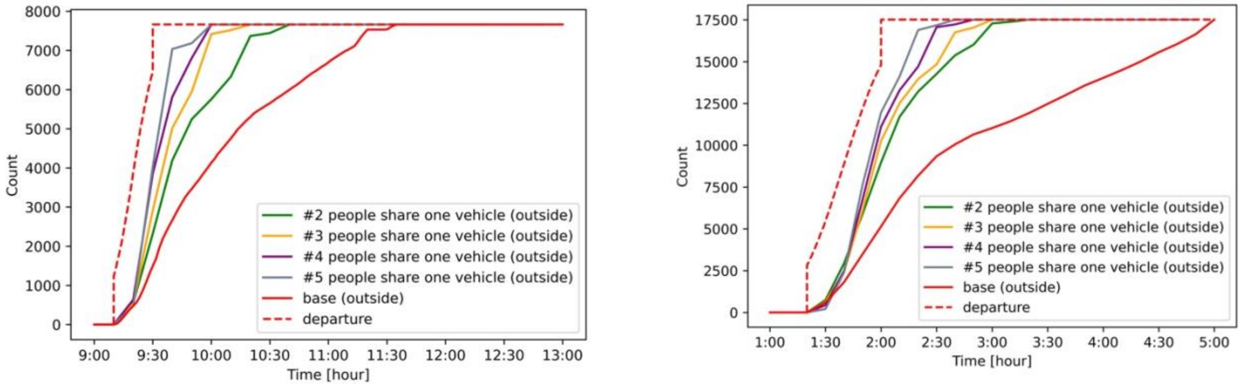
Figure 28. Vehicle Reduction Strategy Performance Measures for Tamalpais Valley

For the Novato Neighborhood case, Figure 29 shows that if the evacuating vehicles carry an average of one, two, three, four or five persons, all evacuees will reach two miles away from the fire area before 11:40 a.m., 10:40 a.m., 10:20 a.m., 10:00 a.m., and 10:00 a.m., respectively in the daytime scenario and will reach two miles away from the fire area before 5:00 a.m., 3:20 a.m., 3:00 a.m., 2:50 a.m. and 2:40 a.m., respectively in the nighttime scenario. For the daytime strategy, carpooling has little effect on the number of evacuees reaching a half mile from the fire area over time or the cumulative exposure time. However, for the nighttime scenario, having only one person per vehicle traps over 150 persons within the fire danger area for almost 1.5 hours.

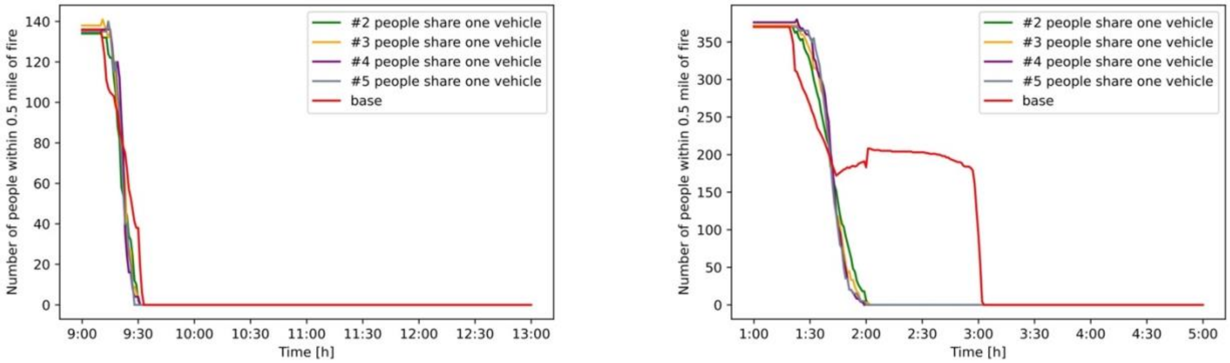
Table 8 show that for both the daytime and nighttime scenarios average evacuation times decrease with more than two persons per vehicle, but average fire exposure times do not. Having an average of at least three persons per vehicle in the daytime scenario and a least two persons per vehicle in the nighttime scenario can reduce the average evacuation time by over 50 percent.

Overall, the modeling shows that when the number of evacuating vehicles is reduced by 1/2, 1/3, 1/4, and 1/5, evacuation times can be reduced by 50, 66.7, 75, and 80 percent, respectively. The only exception is the scenario for the Ross Valley case study. Beyond a certain level, average evacuation times will not continue to decrease in some circumstances (e.g., from two persons/vehicle to five persons/vehicle in Woodacre Bowl nighttime scenario) because, other factors, such as the amount of background traffic, may be difficult to overcome, For example, there are only three exits in Woodacre Bowl (see Figure 21), and most of the evacuees will use the middle exit, which leads to congestion.

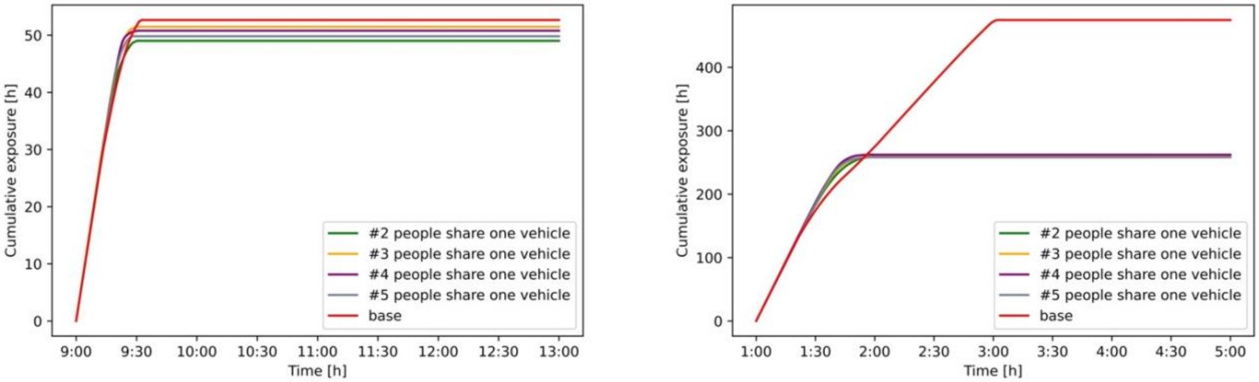
In summary, the value of reducing the number of evacuating vehicles depends on various factors. For instance, if there is a high level of background traffic (e.g., Ross Valley daytime scenario) or if there are only a few escape routes (e.g., Woodacre Bowl) reducing the number of evacuating vehicles may have little effect.



(a) #vehicles that reach 2 miles away from the fire area (daytime scenario) (b) #vehicles that reach 2 miles away from the fire area (nighttime scenario)



(c) #persons within 0.5 mile of fire (daytime scenario) (d) #persons within 0.5 mile of fire (nighttime scenario)



(e) Cumulative exposure (hours) (daytime scenario) (f) Cumulative exposure (hours) (nighttime scenario)

Figure 29. Vehicle Reduction Strategy Performance Measures for Novato Neighborhood

Table 8. Average Evacuation Time and Exposure Time for Vehicle Reduction Strategy, All Case Studies

Indicators	Average travel time [h]	%change from baseline	Average exposure time [h]	%change from baseline	Average travel time [h]	%change from baseline	Average exposure time [h]	%change from baseline
Ross Valley	Daytime case				Nighttime case			
Baseline	1.250	-	0.120	-	1.230	0	0.223	-
2 persons/veh	1.005	19.6%	0.071	40.8%	0.532	56.7%	0.087	61.0%
3 persons/veh	0.906	27.5%	0.047	60.8%	0.391	68.2%	0.086	61.4%
4 persons/veh	0.790	36.8%	0.048	60.0%	0.301	75.5%	0.085	61.9%
5 persons/veh	0.651	47.9%	0.047	60.8%	0.254	79.3%	0.085	61.9%
Woodacre Bowl	Daytime case				Nighttime case			
Baseline	0.577	-	0.074	-	0.389	-	0.054	-
2 persons/veh	0.300	48.0%	0.054	27.0%	0.206	47.0%	0.038	29.6%
3 persons/veh	0.260	54.9%	0.049	33.8%	0.196	49.6%	0.036	33.3%
4 persons/veh	0.246	57.4%	0.049	33.8%	0.197	49.4%	0.036	33.3%
5 persons/veh	0.238	58.8%	0.047	36.5%	0.195	49.9%	0.036	33.3%
Tamalpais Valley	Daytime case				Nighttime case			
Baseline	0.618	-	0.045	-	0.731	-	0.117	-
2 persons/veh	0.356	42.4%	0.045	0.0%	0.365	50.1%	0.099	15.4%
3 persons/veh	0.356	42.4%	0.045	0.0%	0.263	64.0%	0.100	14.5%
4 persons/veh	0.308	50.2%	0.045	0.0%	0.230	68.5%	0.100	14.5%
5 persons/veh	0.252	59.2%	0.045	0.0%	0.222	69.6%	0.100	14.5%
Novato Neighborhood	Daytime case				Nighttime case			
Baseline	0.830	-	0.007	-	1.061	-	0.027	-
2 persons/veh	0.480	42.2%	0.006	14.3%	0.519	51.1%	0.015	44.4%
3 persons/veh	0.359	56.7%	0.007	0.0%	0.464	56.3%	0.015	44.4%
4 persons/veh	0.282	66.0%	0.007	0.0%	0.407	61.6%	0.015	44.4%
5 persons/veh	0.271	67.3%	0.007	0.0%	0.361	66.0%	0.015	44.4%

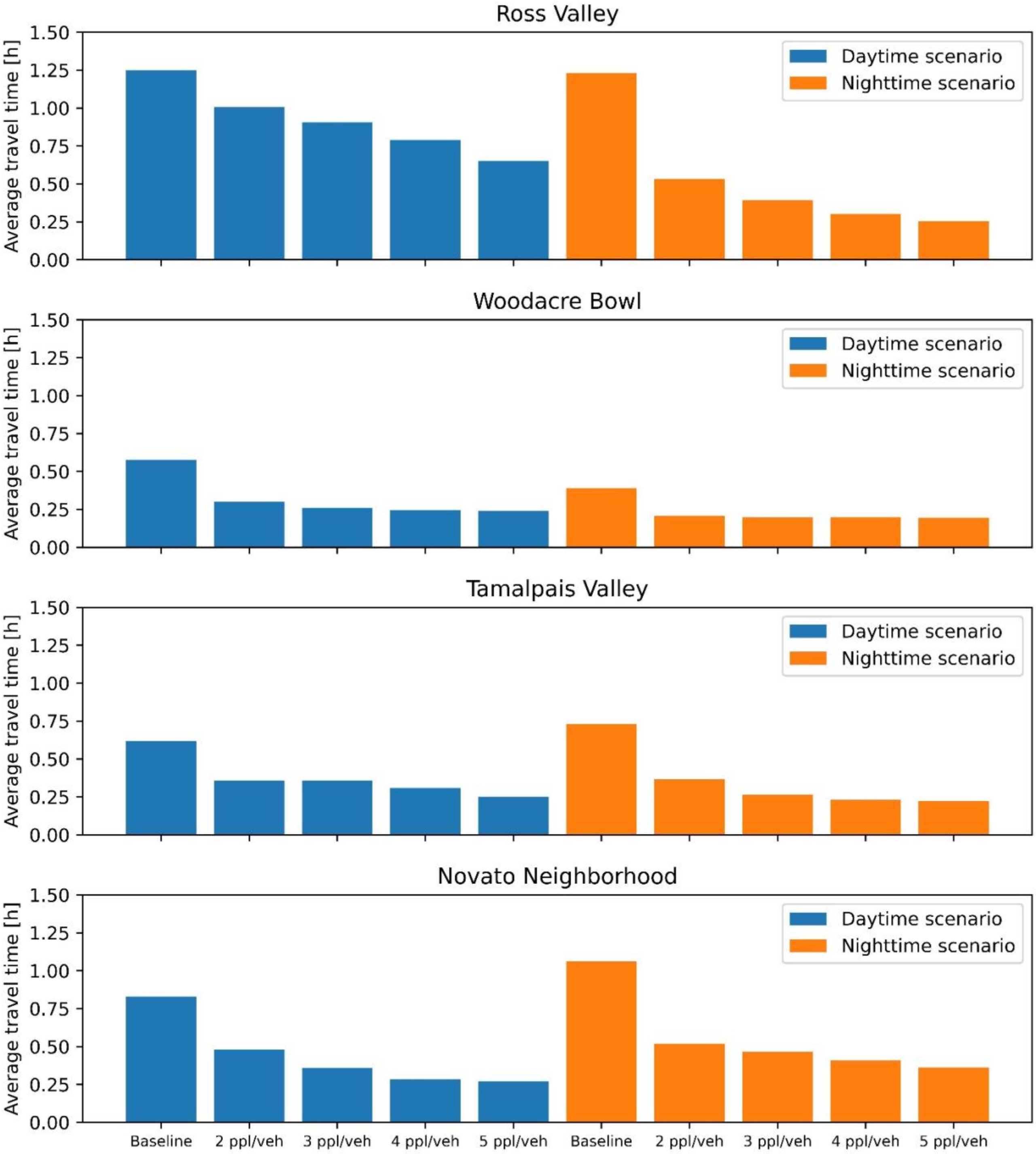


Figure 30. Average Evacuation Times for Different Carpooling Scenarios, All Case Studies

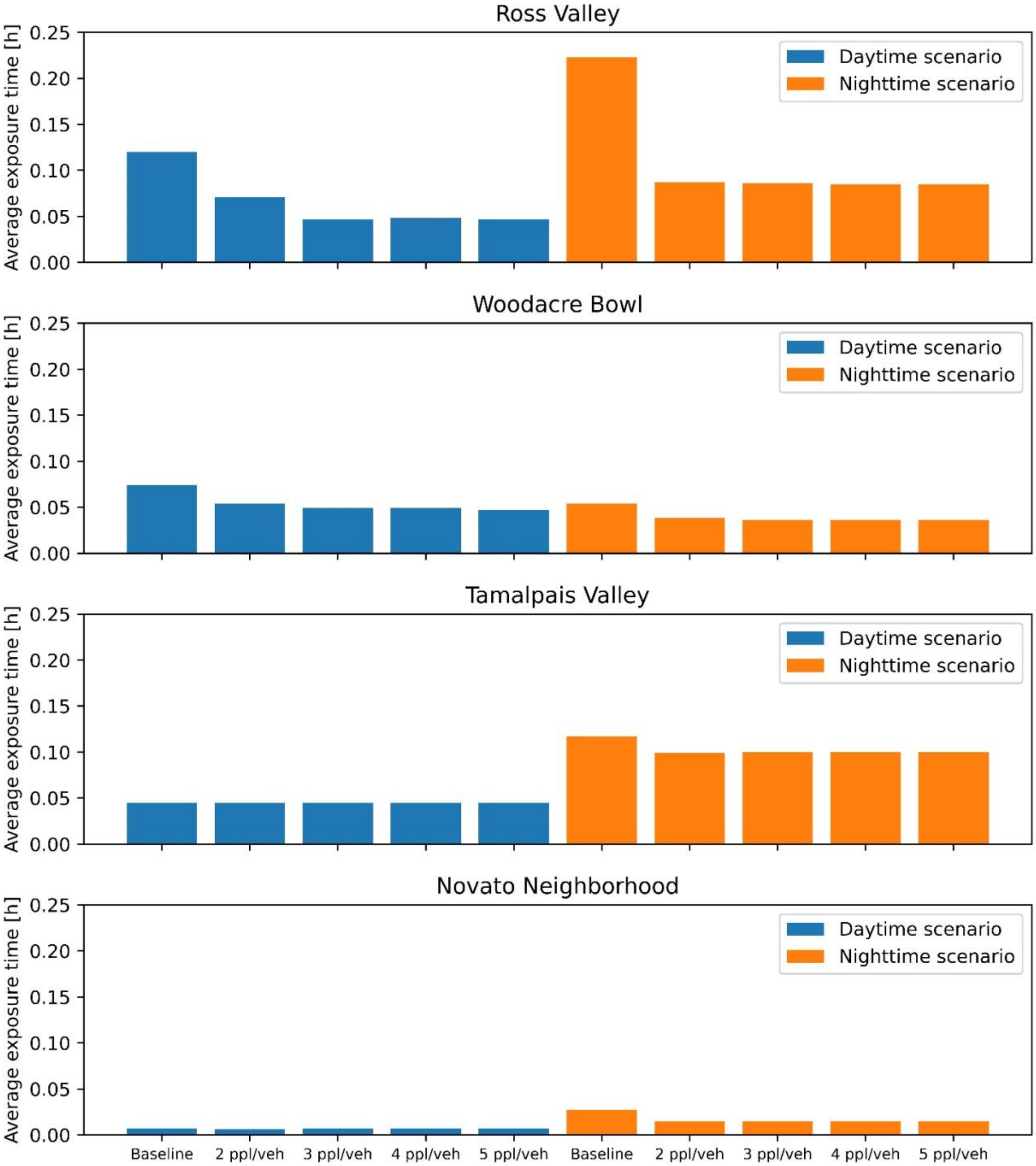


Figure 31. Average Exposure Times For Vehicle Reduction Strategy, All Case Studies

Phased Evacuation

This section analyzes the effects of a phased evacuation strategy. First, the four study areas were divided into smaller traffic analysis zones as designated by the Metropolitan Transportation Commission. These are seen in **Error! Reference source not found.**-**Error! Reference source not found.**. The zones in red (high-risk) are the closest zones to the modeled fire ignition point; therefore, residents in these zones would be the first to leave (Phase 1). Those in orange (middle-risk) and pink (low-risk) zones would be the second and third groups to leave (Phase 2 and Phase 3). Three scenarios with different phased intervals, described above in the "Scenario Development" section, were tested and the designated departure times for each Phase are shown in Table 9. In the daytime scenario evacuees from the designated zones depart at either 15, 30, or 45-minute intervals, while in the nighttime scenario, the intervals are 20, 40, or 60 minutes apart.

The results for each of the four locations are presented in Figures 36-39 which show the number of evacuees that reach a point at least two miles away from the fire area over time, number of evacuees within a half mile of the fire area over time, and cumulative fire exposure over time under each phased evacuation strategies for the four case studies. Table 10 and Figures 40-41 present the average travel time and average exposure time or each of the different alternatives.

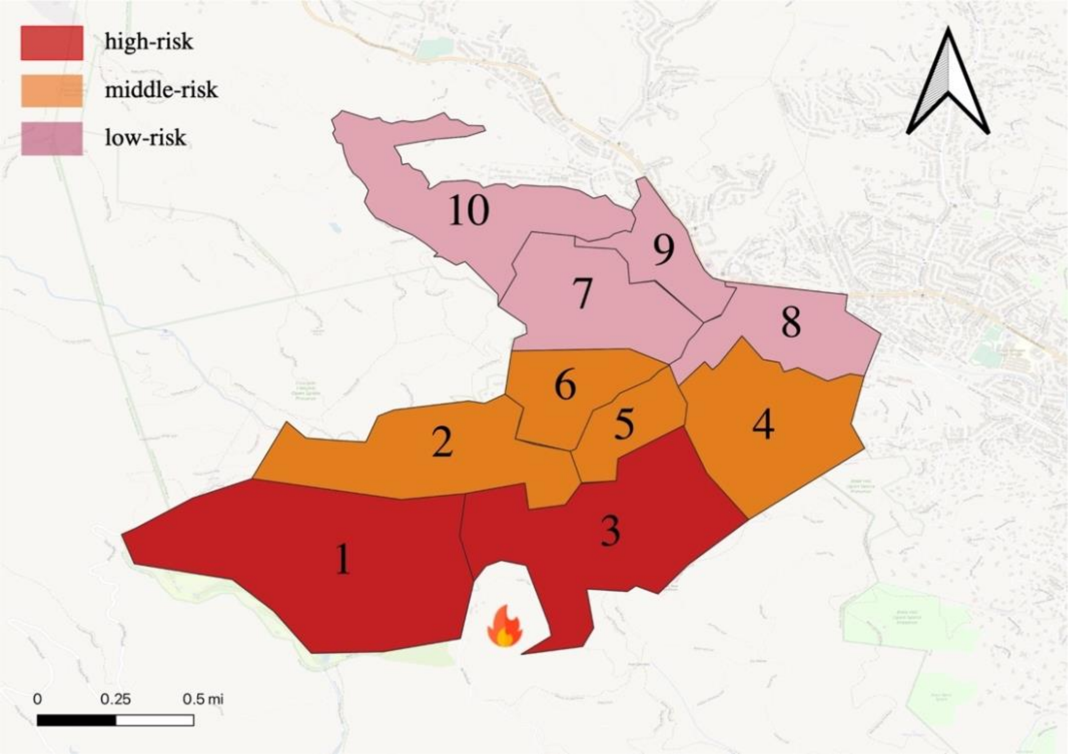


Figure 32. Evacuation Zones for Ross Valley

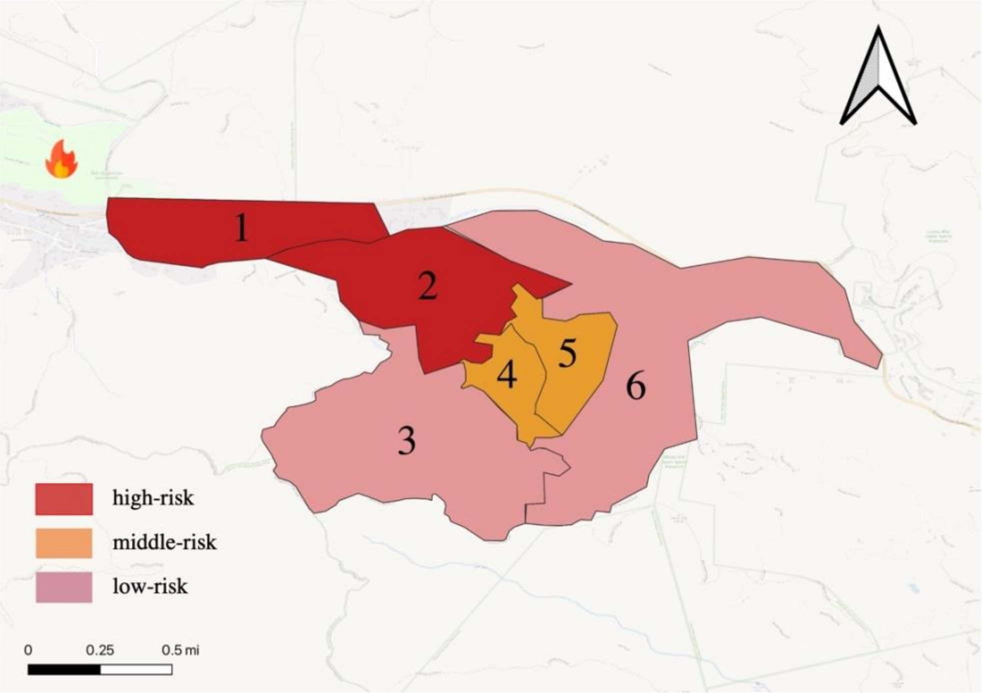


Figure 33. Evacuation Zones for Woodacre Bowl

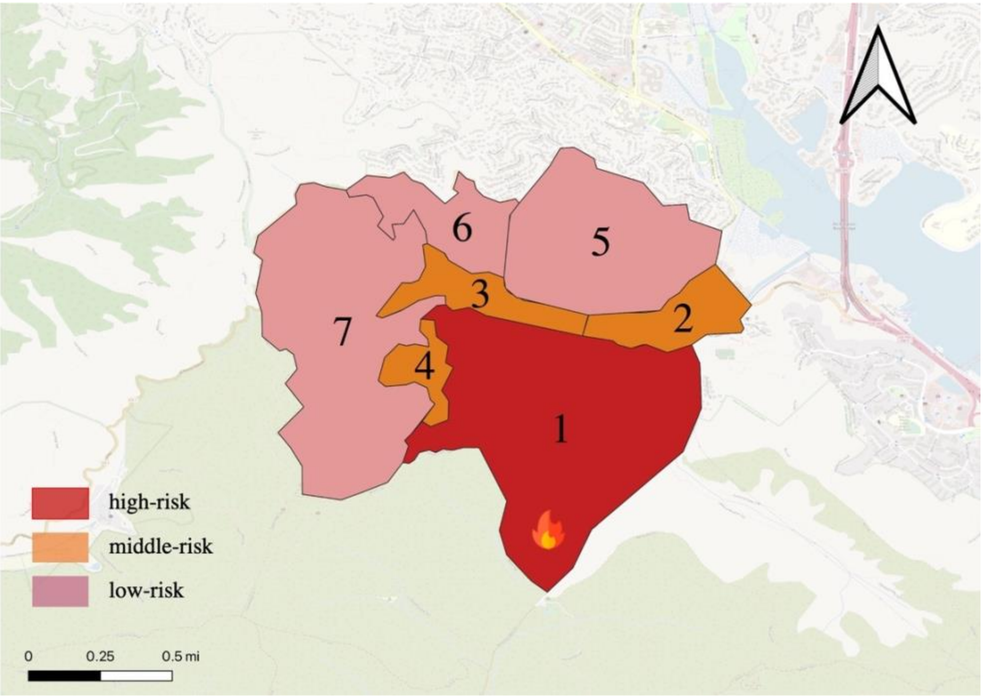


Figure 34. Evacuation Zones for Tamalpais Valley

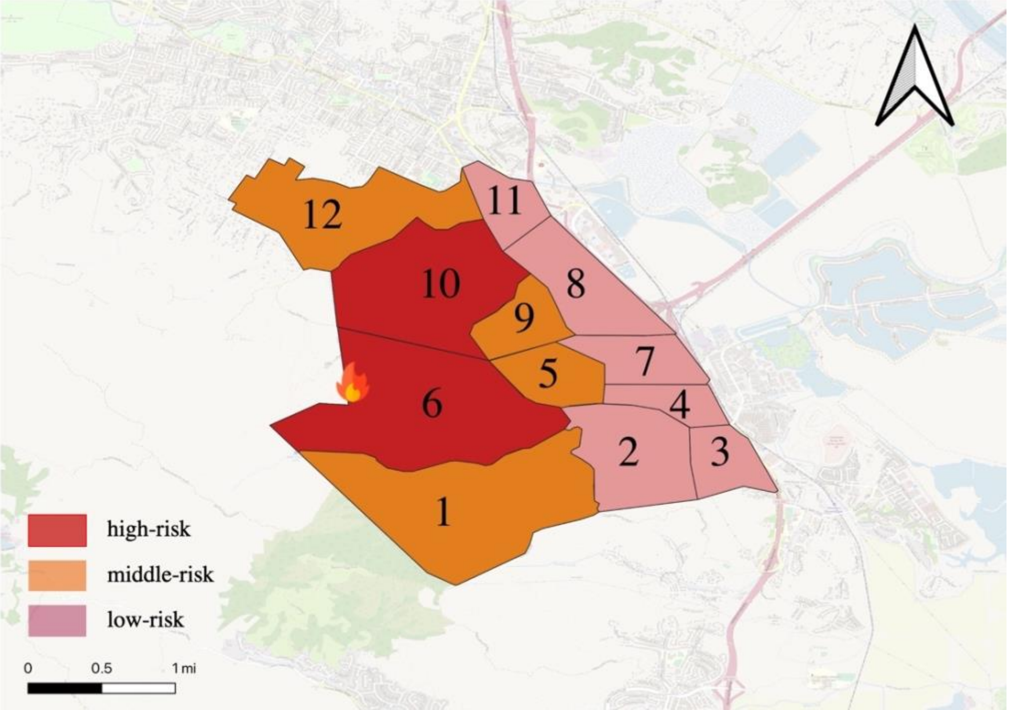


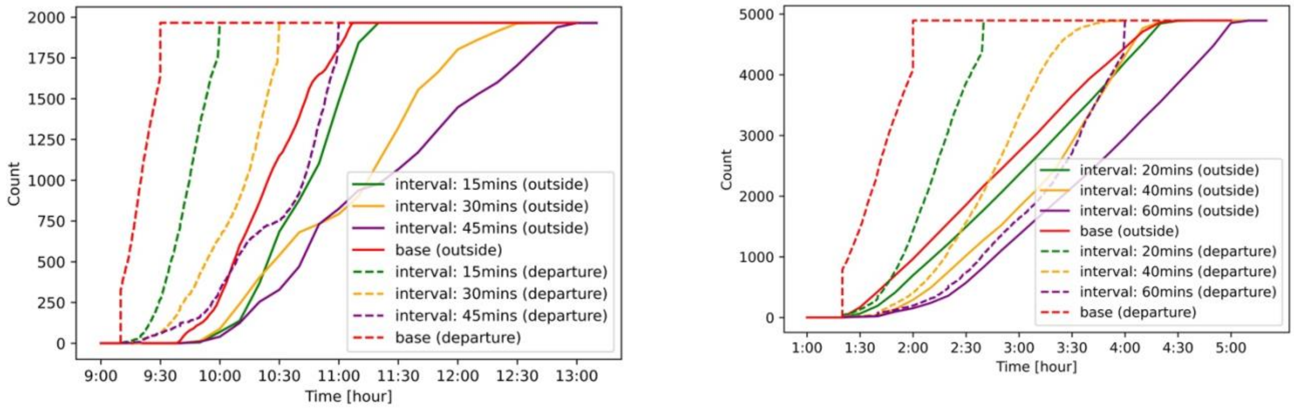
Figure 35. Evacuation Zones of Novato Neighborhood

Table 9. Departure Times for Phased Evacuation Strategy, All Case Studies

	Interval	Phase 1 (zones)	Phase 1 (departure time)	Phase 2 (zones)	Phase 2 (departure time)	Phase 3 (zones)	Phase 3 (departure time)
Day time	15 mins	Fairfax (1,3) Woodacre (1,2) Tamalpais (1) Novato (6,10)	9:20±10 mins	Fairfax (2,4,5,6) Woodacre (4,5) Tamalpais (2,3,4) Novato (1,5,9,12)	9:35±10 mins	Fairfax (7,8,9,10) Woodacre (3,6) Tamalpais (5,6,7) Novato (2,3,4,7,8,11)	9:50±10 mins
	30 mins		9:20±10 mins		9:50±10 mins		10:20±10 mins
	45 mins		9:20±10 mins		10:05±10 mins		10:50±10 mins
Night time	20 mins		1:40±20 mins		2:00±20 mins		2:20±20 mins
	40 mins		1:40±20 mins		2:20±20 mins		3:00±20 mins
	60 mins		1:40±20 mins		2:40±20 mins		3:40±20 mins

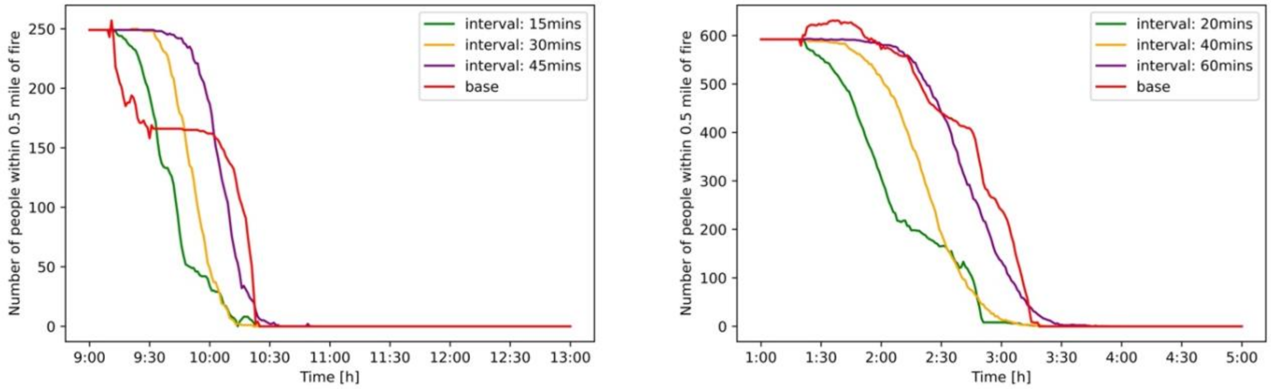
For the Ross Valley case, Figure 36 shows that in the daytime scenario when the interval between phases is 15 minutes it takes two hours to complete the evacuation. When the interval is increased to 30 minutes the evacuation takes three and a half hours and when it is increased to 45 minutes the evacuation is completed in four hours. In the nighttime scenario, if the phased intervals are 20, 40 and 60 minutes, the evacuation times last 3, 3, and 4 hours, respectively. Notably, longer lasting evacuation times do not necessarily represent high evacuation efficiency. From the perspective of people within 0.5 mile of the fire area and cumulative exposure time, the baseline leads to the lowest exposure (around 85 hours) and quick evacuation, and longer interval time leads to worse evacuation performance at the daytime scenario. In the nighttime scenario, the best option is the 20-minute interval (corresponding cumulative exposure time is 600 hours) and the worst is the interval of 60 minutes, of which the exposure time reaches over 700 hours.

Table 10 and Figures 40-41 show that the average evacuation time decreases as the phasing interval increases from one and a quarter hour when there is no phased interval to one hour when the interval is 45 minutes, a reduction of 23 percent. However, the longer interval time forces some people to stay longer in the fire danger area. When the interval time is 45 minutes, the average exposure time increases by 17 percent, compared to the baseline. However, when the interval time is 15 minutes, both average travel time and exposure time are reduced. Hence, the optimal interval for Ross Valley is 15 minutes. For the nighttime evacuation, a longer interval time leads to lower evacuation time, but higher exposure time. When the interval time is 20 minutes, the average evacuation time is 40 percent of the baseline and 60 percent of the time with a 40-minute interval. In addition, the average exposure time with a 40-minute interval is 27 percent less, compared with a reduction of 38 percent with a 20-minute interval and 6 percent with a 60-minute interval. Therefore, a 20-minute interval is the best option for the Ross Valley nighttime scenario.



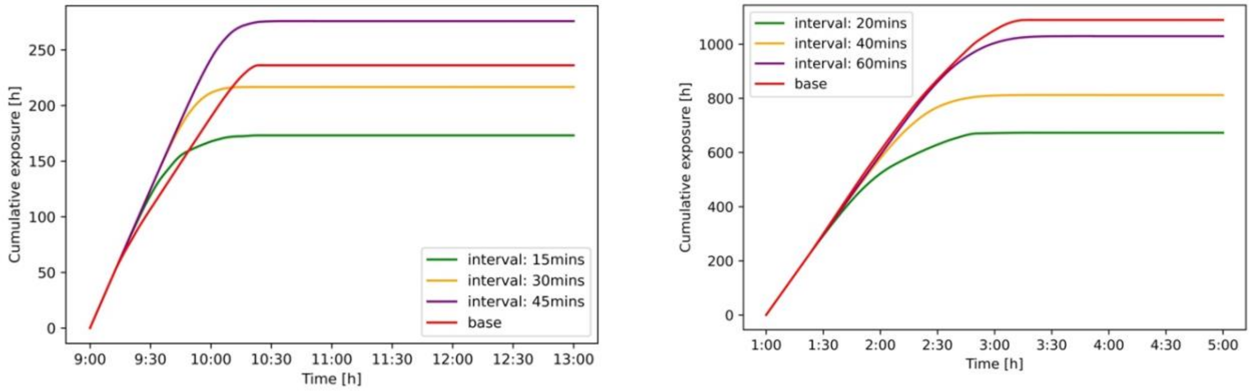
(a) #vehicles that reach 2 miles away from the fire area (daytime scenario)

(b) #vehicles that reach 2 miles away from the fire area (nighttime scenario)



(c) #persons within 0.5 mile of fire (daytime scenario)

(d) #persons within 0.5 mile of fire (nighttime scenario)



(e) Cumulative exposure (hours) (daytime scenario)

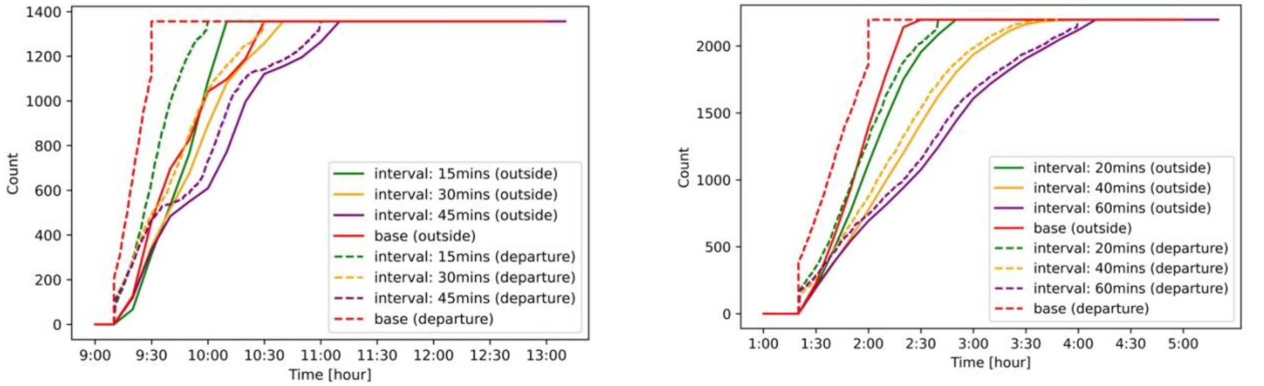
(f) Cumulative exposure (hours) (nighttime scenario)

Figure 36. Phased Evacuation Performance Measures for Ross Valley)

For the Woodacre Bowl case, Figure 37 shows that in the daytime scenario if the phased intervals are 15, 30, and 45 minutes, respectively, the evacuation takes one, one and a half, and two hours to complete. In the nighttime scenario if the phased intervals are 20, 40, and 60 minutes, respectively the evacuations last one and a half, two and a half, and three hours. Notably, longer evacuation time does not necessarily represent low evacuation efficiency.

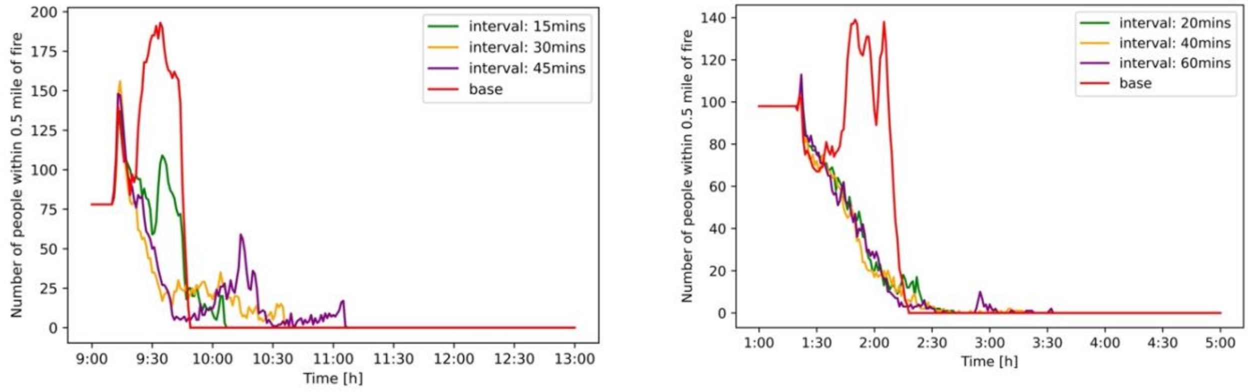
An interval of 30 minutes leads to the lowest exposure time (around 58 hours) and quick evacuation, while the baseline performs the worst in the daytime scenario (up to 100 hours of cumulative exposure time). In the nighttime scenario, all evacuation intervals perform similarly, with exposure time of around 80 hours, while for the baseline, the exposure time reaches 120 hours.

Table 10 and Figures 40-41 show that, similar to the Ross Valley case, the average daytime and nighttime evacuation times decrease as the phased evacuation interval time increases. However, the average exposure times of both scenarios first decrease and reach their lowest value with a 30/40-minute interval. However, as the interval time continues to increase, the average exposure times increase, and the speed of the evacuation becomes slower than the speed of the fire spread. Hence, the ideal interval time for the daytime evacuation is 30 minutes and 40 minutes for the nighttime evacuation.



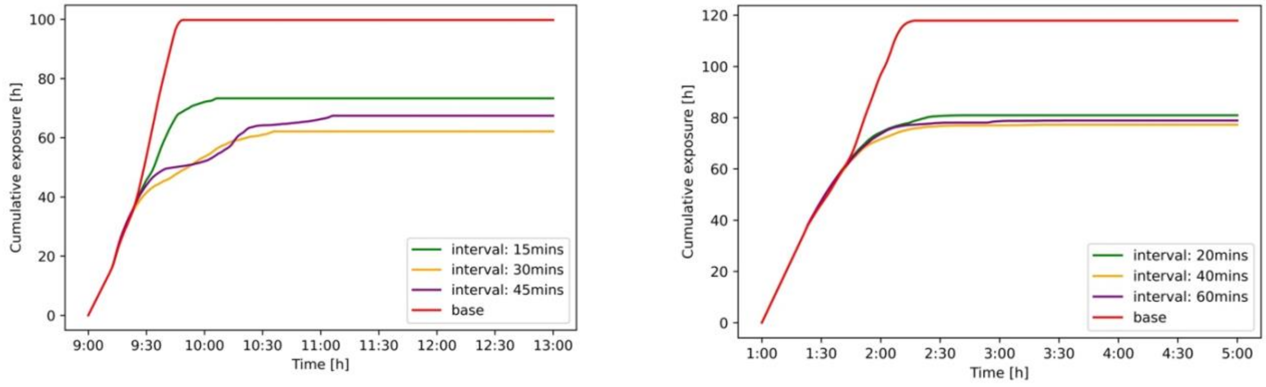
(a) #vehicles that reach 2 miles away from the fire area (daytime scenario)

(b) #vehicles that reach 2 miles away from the fire area (nighttime scenario)



(c) #persons within 0.5 mile of fire (daytime scenario)

(d) #persons within 0.5 mile of fire (nighttime scenario)



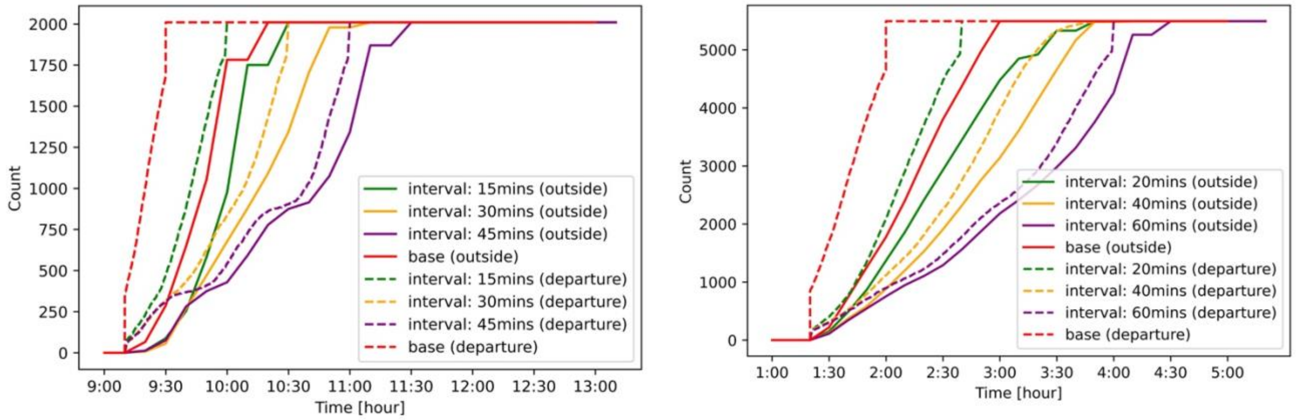
(e) Cumulative exposure (hours) (daytime scenario)

(f) Cumulative exposure (hours) (nighttime scenario)

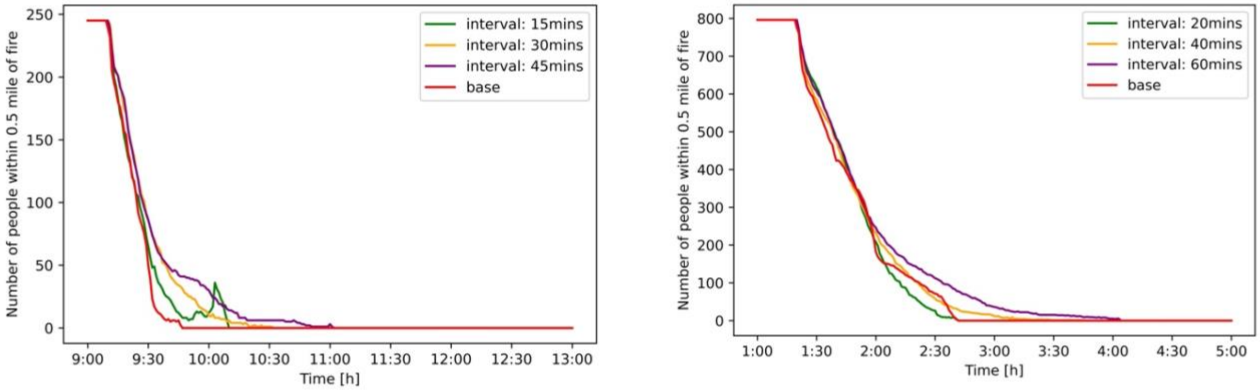
Figure 37. Phased Evacuation Performance Measures for Woodacre Bowl

For the Tamalpais Valley case, Figure 38 shows that in the daytime scenario when the interval between phases is 15 minutes it takes one and a half hours to complete the evacuation. When the interval is increased to 30 minutes the evacuation takes two hours and when it is increased to 45 minutes the evacuation is completed in two and a half hours. In the nighttime scenario, if the phased intervals are 20, 40 and 60 minutes, respectively, the evacuations last two and three-quarter hours two and three-quarter hours and three and a half. Notably, longer evacuation times does not necessarily represent low evacuation efficiency. For the daytime scenario, the baseline has the lowest fire exposure time (around 85 hours) and quick evacuation, and longer interval times reduce evacuation performance. For the nighttime scenario, the all-phasing intervals perform similarly, with exposure times around 600 hours, though the 60-minute interval exposure time reaches over 700 hours.

Table 10 and Figures 40-41 show that a larger interval time results in higher evacuation efficiency in terms of the average evacuation time for both the daytime evacuation and nighttime scenarios. However, average fire exposure time, even for the 15/20-minute interval is no better than the no-phase scenario. In the daytime evacuation, a 15-minute interval reduces the average evacuation time by 34 percent, while increasing the average exposure time by 16 percent. If the focus is on reducing fire exposure time as much as possible, then for the daytime evacuation, the best strategy is to let all evacuees leave at the same time. For the nighttime evacuation, applying a 20-minute interval reduces the average evacuation time markedly and reduces the exposure time somewhat. Therefore, this is the optimal strategy for the nighttime case.

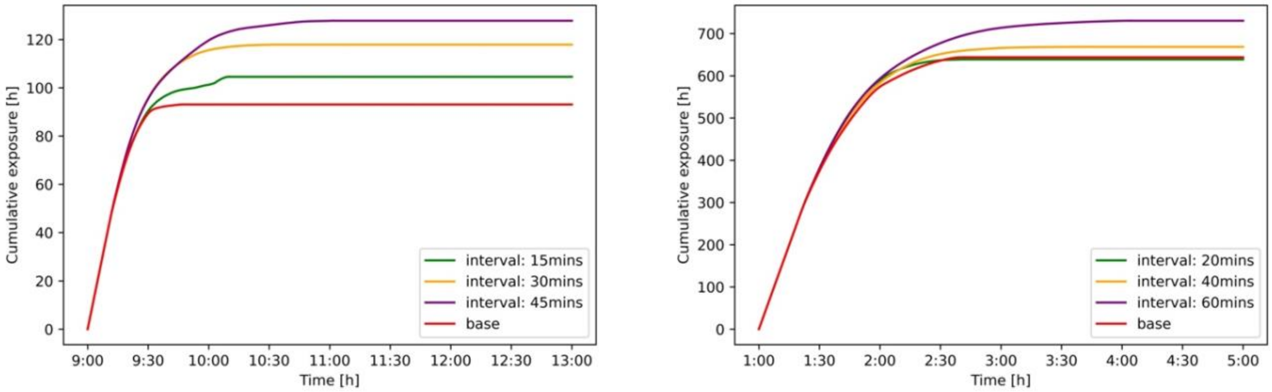


(a) #vehicles that reach 2 miles away from the fire area (daytime scenario) (b) #vehicles that reach 2 miles away from the fire area (nighttime scenario)



(c) #persons within 0.5 mile of fire (daytime scenario)

(d) #persons within 0.5 mile of fire (nighttime scenario)



(e) Cumulative exposure (hours) (daytime scenario)

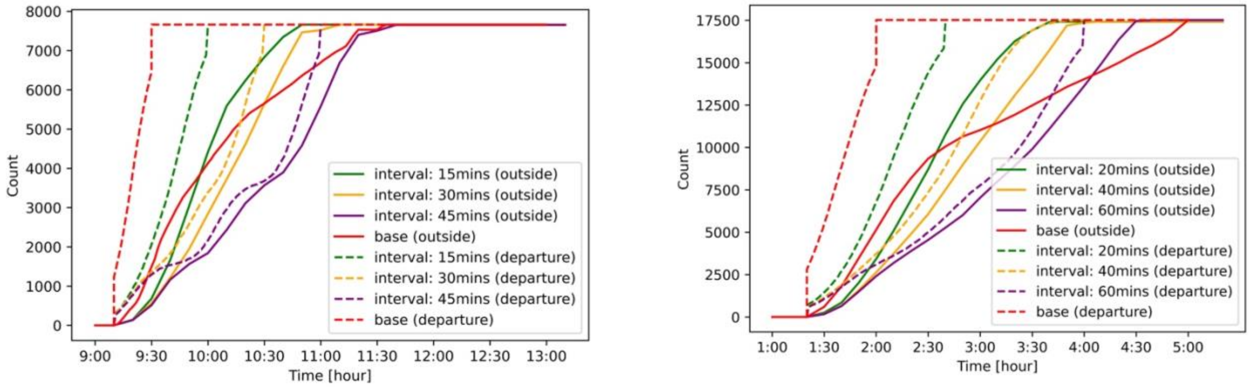
(f) Cumulative exposure (hours) (nighttime scenario)

Figure 38. Phased Evacuation Performance Measures for Tamalpais Valley

For the Novato Neighborhood case, Figure 39 shows that in the daytime scenario when the interval between phases is 15, 30 and 45 minutes, respectively the evacuation is completed in 1.75, two, and 2.5 hours. For the nighttime scenario if the phased intervals are 20, 40, and 60 minutes, respectively, the evacuations last two and a half, two and a half and four hours.

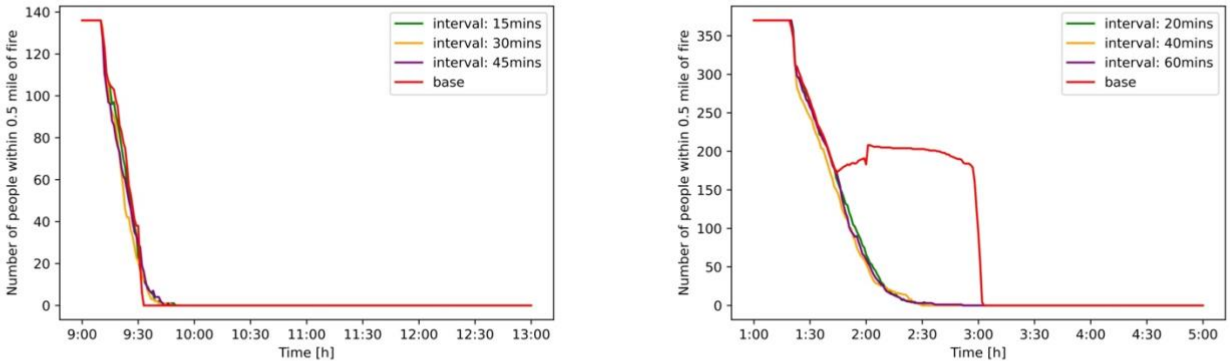
Longer evacuation times do not necessarily represent low evacuation efficiency. An interval of 30 minutes for the daytime scenario leads to the lowest cumulative fire exposure time (around 45 hours) and quick evacuation, while the baseline leads to the worst evacuation. For the nighttime scenario, intervals of 20, 40, and 60 minutes perform similarly, with exposure times around 250 hours while the baseline exposure time reaches around 500 hours. Table 10 and Figures 40-41 show that, as for the other three cases, average evacuation times decrease as the phasing interval is increased. Average exposure times are mostly unchanged across these three different intervals. Additionally, the performance of the 30/40-minute interval is close to that of a 45/60-minute interval. Therefore, 30/45-minute intervals for daytime evacuation and 40/60-minute intervals for nighttime evacuation are the best options according to the model.

In summary, as the phasing interval is increased, the evacuation takes longer, at least up to a point, because the traffic congestion almost disappears. When implementing a phased evacuation strategy, it is important not only to focus on travel time but also the duration of fire exposure; longer waiting times in high-risk areas can pose a significant threat to residents.



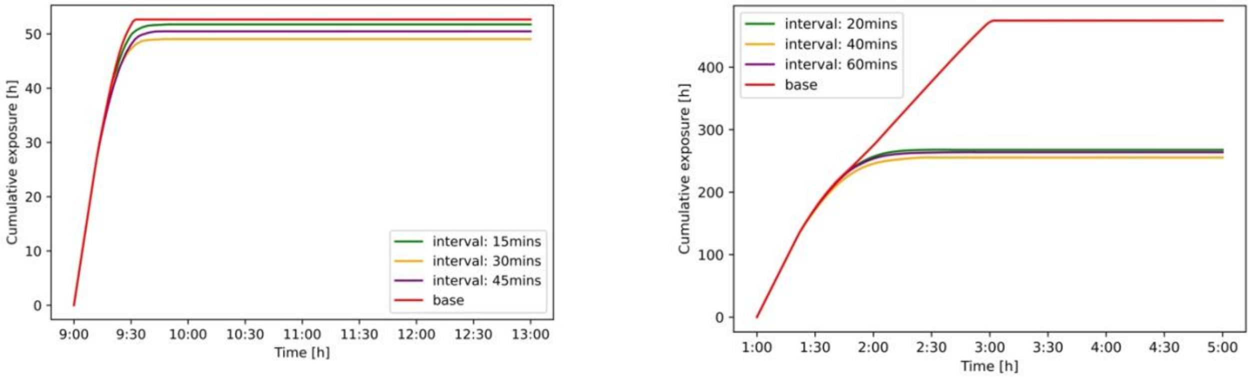
(a) #vehicles that reach 2 miles away from the fire area (daytime scenario)

(b) #vehicles that reach 2 miles away from the fire area (nighttime scenario)



(c) #persons within 0.5 mile of fire (daytime scenario)

(d) #persons within 0.5 mile of fire (nighttime scenario)



(e) Cumulative exposure (hours) (daytime scenario)

(f) Cumulative exposure (hours) (nighttime scenario)

Figure 39. Phased Evacuation Strategy Performance Measures for Novato Neighborhood

Table 10. Average Evacuation Time and Exposure Time for Phased Evacuation Strategy, All Case Studies

Indicators	Average travel time [h]	%change from baseline	Average exposure time [h]	%change from baseline	Average travel time [h]	%change from baseline	Average exposure time [h]	%change from baseline
Ross Valley	Daytime case				Nighttime case			
Baseline	1.250	-	0.120	-	1.230	0	0.223	-
15/20 mins	1.081	-13.5%	0.088	-26.7%	0.883	-28.2%	0.138	-38.1%
30/40 mins	1.079	-13.7%	0.110	-8.3%	0.505	-58.9%	0.166	-25.6%
45/60 mins	0.963	-23.0%	0.140	+16.7%	0.412	-66.5%	0.210	-5.8%
Woodacre Bowl	Daytime case				Nighttime case			
Baseline	0.577	-	0.074	-	0.389	-	0.054	-
15/20 mins	0.328	-43.2%	0.054	-27.0%	0.203	-47.8%	0.037	-31.5%
30/40 mins	0.236	-59.1%	0.046	-37.8%	0.197	-49.4%	0.035	-35.2%
45/60 mins	0.236	-59.1%	0.050	-32.4%	0.194	-50.1%	0.036	-33.3%
Tamalpais Valley	Daytime case				Nighttime case			
Baseline	0.618	-	0.045	-	0.731	-	0.117	-
15/20 mins	0.408	-34.0%	0.052	+15.6%	0.463	-36.7%	0.116	-0.9%
30/40 mins	0.308	-50.2%	0.059	+31.1%	0.301	-58.9%	0.122	+4.3%
45/60 mins	0.296	-52.1%	0.064	+42.2%	0.282	-61.4%	0.133	+13.7%
Novato Neighborhood	Daytime case				Nighttime case			
Baseline	0.830	-	0.007	-	1.061	-	0.027	-
15/20 mins	0.346	-58.3%	0.007	0.0%	0.502	-52.7%	0.015	-44.4%
30/40 mins	0.220	-73.5%	0.006	-14.3%	0.322	-69.7%	0.015	-44.4%
45/60 mins	0.220	-73.5%	0.007	0.0%	0.311	-70.7%	0.015	-44.4%

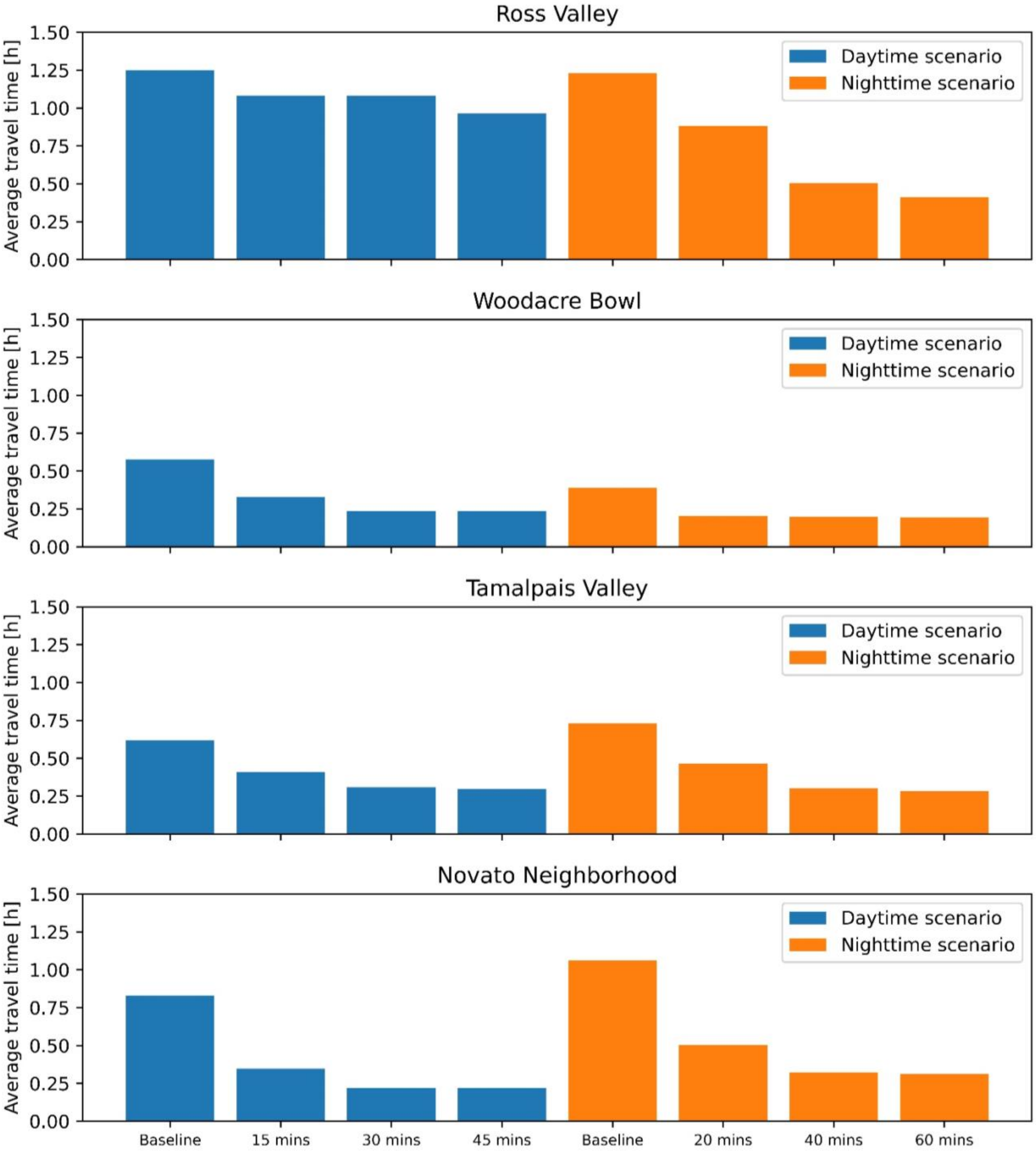


Figure 40. Average Travel Times for Various Departure Intervals for Phased Evacuation Strategy, All Case Studies

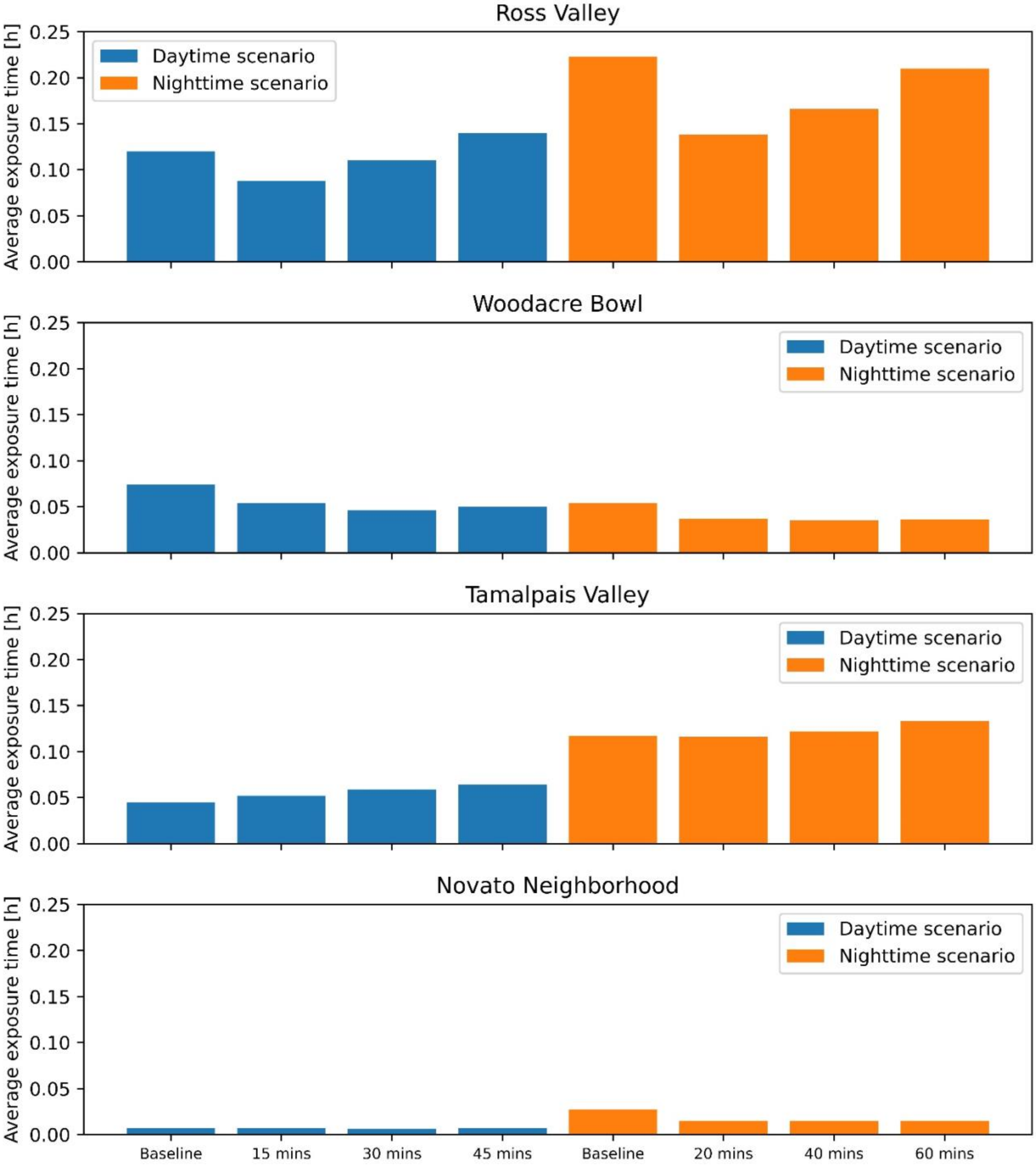


Figure 41. Average Exposure Times for Different Departure Intervals for Phased Evacuation Strategy, All Case Studies

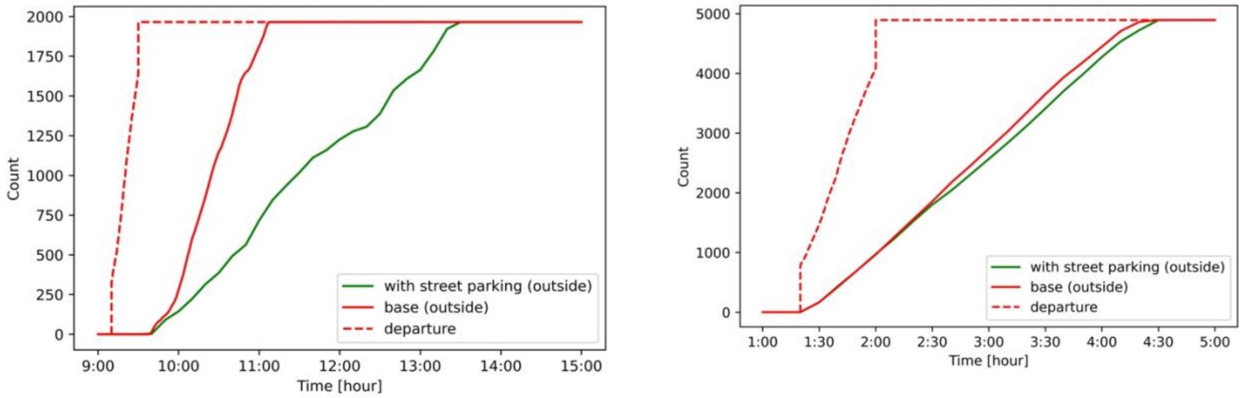
On-street Parking Prohibition

This section analyzes the impact of street-parking on evacuation efficiency. Figures 42-45 show the number of evacuees that reach a point two miles away from the fire area over time, number of evacuees within a half mile of the fire area over time, and cumulative exposure over time with and without street parking for all four cases. Table 11 and Figures 46-47 present the average evacuation time and average exposure time for each alternative parking prohibition strategy.

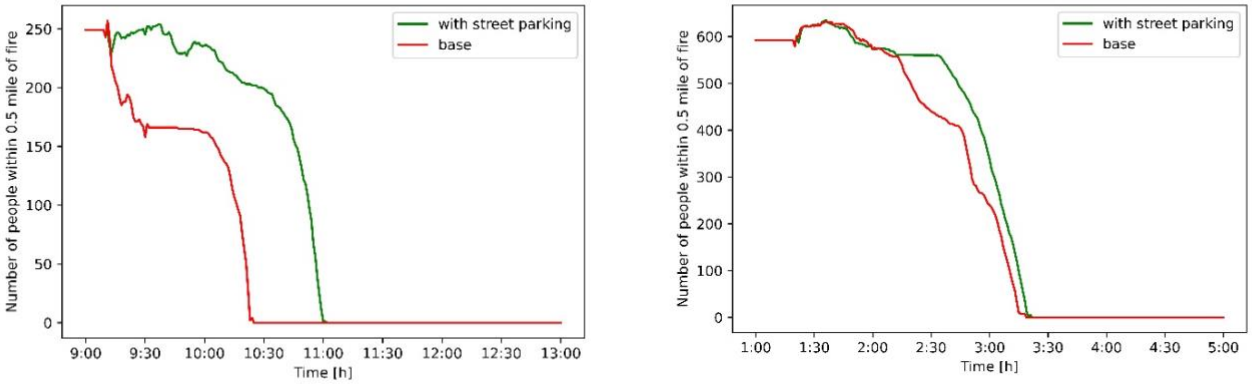
For the Ross Valley case, Figure 42 shows that if street parking is allowed, the evacuation lasts over four hours for the daytime scenario, compared with two hours if street parking is prohibited. However, for the nighttime scenario, there is no significant difference with evacuation time lasting around 3.5 hours.

Street parking leads to slower evacuations and increases the total cumulative exposure time in the daytime scenario to over 400 hours, which is double compared to the situation without street parking. For the nighttime scenario, the total exposure time when street parking is permitted is only 100 hours more than when it is prohibited.

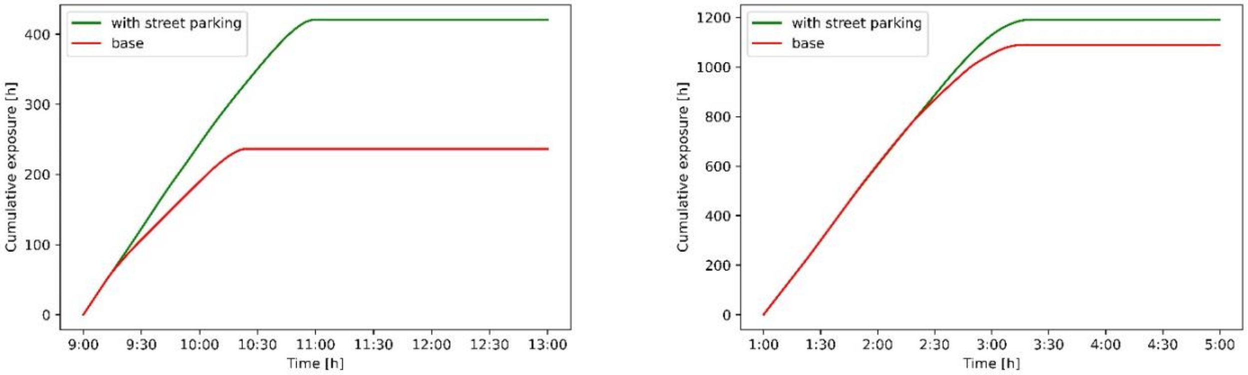
Table 11 and Figures 46-47 show that, if street parking is permitted during the daytime, the average evacuation time increase significantly by up to 88 percent and fire exposure time to over 78 percent. However, street parking does not affect nighttime evacuations as much, as there is little of background traffic in the way so even though permitting street parking reduces road capacity, vehicles can still evacuate smoothly.



(a) #vehicles that reach 2 miles away from the fire area (daytime scenario) (b) #vehicles that reach 2 miles away from the fire area (nighttime scenario)



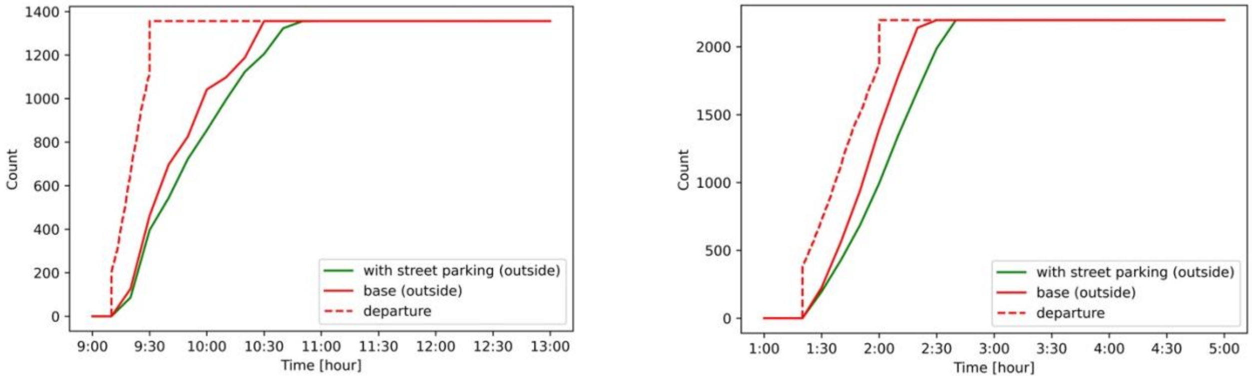
(c) #persons within 0.5 mile of fire (daytime scenario) (d) #persons within 0.5 mile of fire (nighttime scenario)



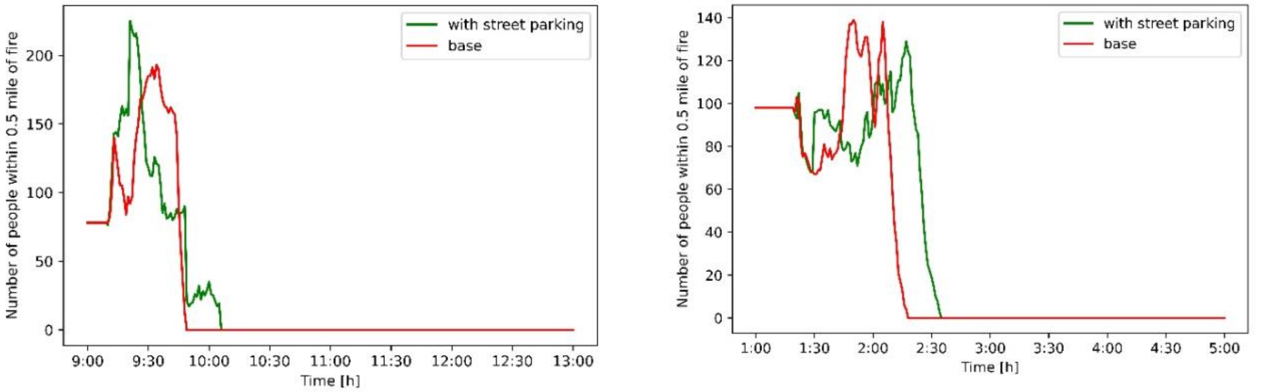
(e) Cumulative exposure (hours) (daytime scenario) (f) Cumulative exposure (hours) (nighttime scenario)

Figure 42. Street Parking Prohibition Strategy Performance Measures for Ross Valley

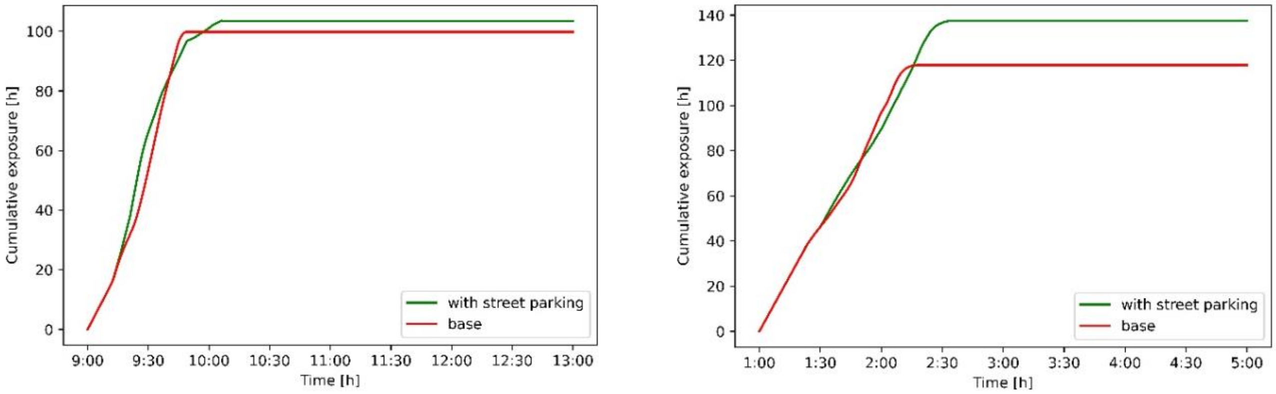
For the Woodacre Bowl case, Figure 43 shows that if street parking is allowed, the evacuation lasts for over one and a half hours for the daytime scenario, which is very close to the evacuation time when street parking is prohibited. For the nighttime scenario, street parking extends the evacuation time from one and a quarter hour to one and a half hours. In the daytime scenario, the cumulative exposure times are similar at around 100 hours; however, for the nighttime scenario, street parking increases the total exposure time by 20 hours to 140 hours and strands persons in the vicinity of the fire area for a longer duration. Table 11 and Figures 46-47 show the opposite result compared to the Ross Valley case. Street parking has a very small effect on the daytime evacuation, but a huge impact on the nighttime evacuation. During the daytime, there is little background traffic around that area and the number of evacuees is relatively small, so the evacuees can evacuate quickly. However, during the nighttime, the number of evacuees is nearly double the number of evacuees during the daytime. There are only two exits to leave this area and if evacuees want to leave, they need first to enter the fire danger area and then drive through these two exists. With the reduced road capacity caused by street parking, the fire danger area becomes congested which leads to longer exposure and evacuation times. Therefore, officials should consider notifying residents to move their vehicles off the streets in these situations.



(a) #vehicles that leave 2 miles away from the fire area (daytime scenario) (b) #vehicles that leave 2 miles away from the fire area (nighttime scenario)



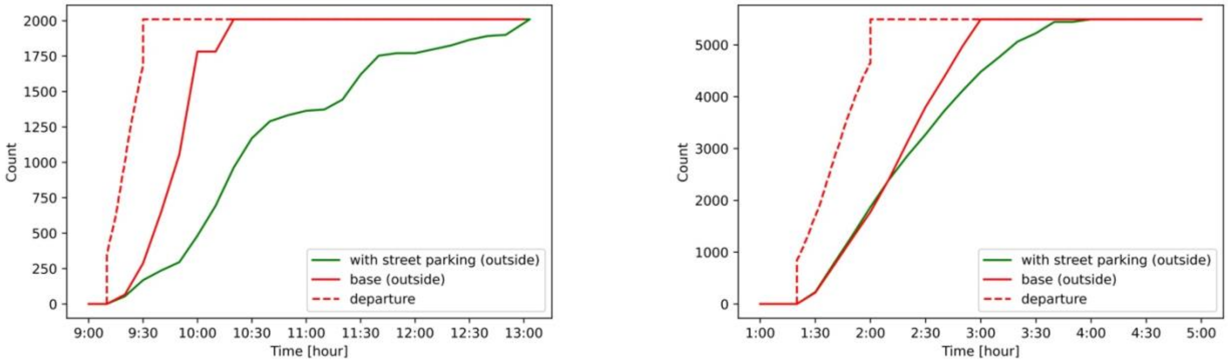
(c) #persons within 0.5 mile of fire (daytime scenario) (d) #persons within 0.5 mile of fire (nighttime scenario)



(e) Cumulative exposure (hour) (daytime scenario) (f) Cumulative exposure (hour) (nighttime scenario)

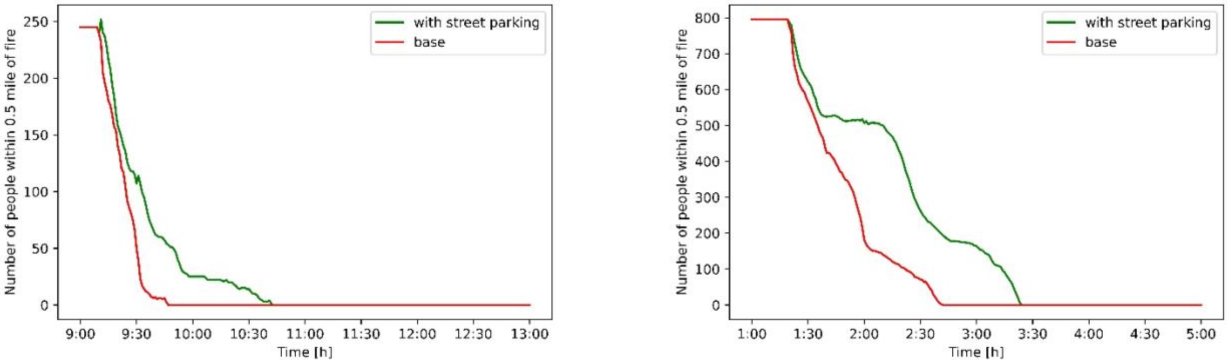
Figure 43. Street Parking Prohibition Strategy Performance Measures for Woodacre Bowl

For the Tamalpais Valley case, Figure 44 shows that if street parking is allowed, the evacuation lasts over five hours in the daytime scenario, four hours longer than without street parking. For the nighttime scenario, street parking only extends the evacuation time by one hour to around two and a half hours. Street parking extends fire exposure times in both scenarios by 40 hours and 400 hours, respectively. Table 11 and Figures 46-47 show that street parking has a significant influence on evacuation efficiency in both the daytime scenario and nighttime scenario, where the average evacuation times increase by 19 and 12 percent, respectively, and the average exposure times increase by 52 and 58 percent respectively. Based on the simulation results, officials should consider prohibiting on-street parking whenever fire danger in Tamalpais Valley is high.



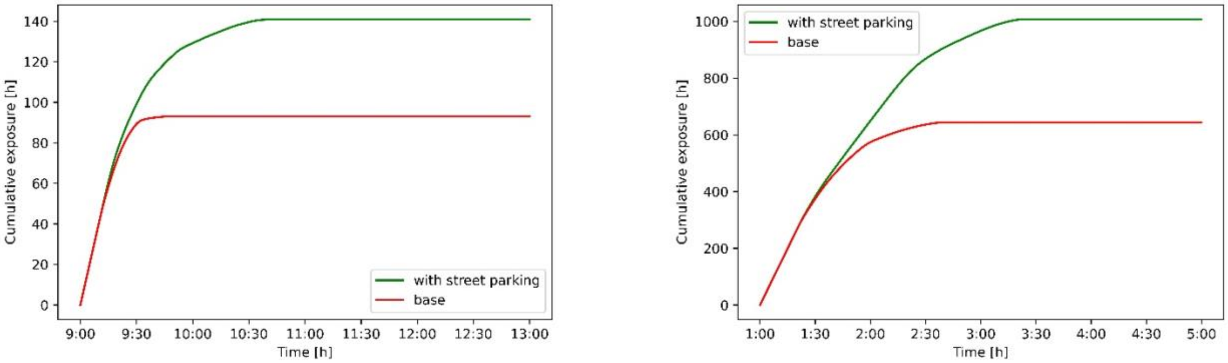
(a) #vehicles that reach 2 miles away from the fire area (daytime scenario)

(b) #vehicles that reach 2 miles away from the fire area (nighttime scenario)



(c) #persons within 0.5 mile of fire (daytime scenario)

(d) #persons within 0.5 mile of fire (nighttime scenario)



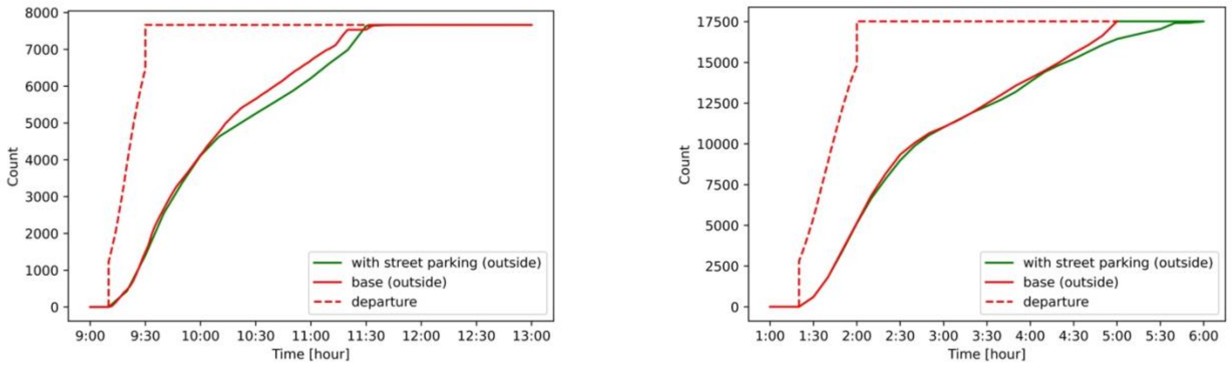
(e) Cumulative exposure (hours) (daytime scenario)

(f) Cumulative exposure (hours) (nighttime scenario)

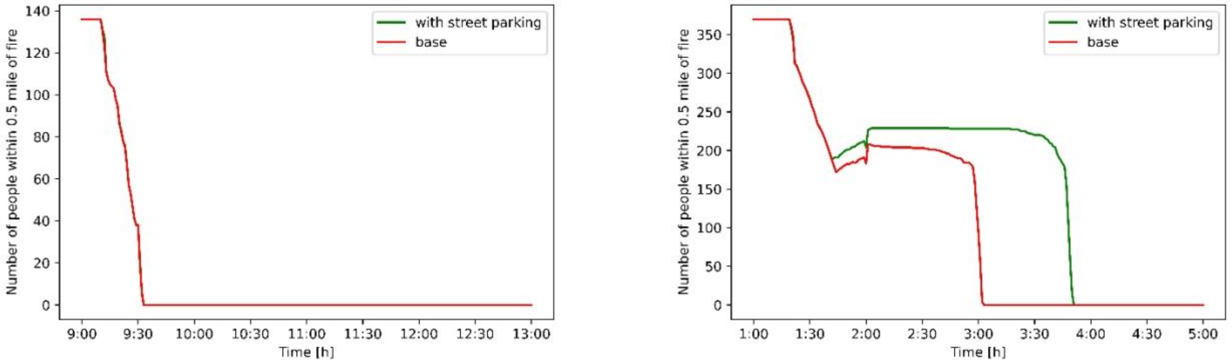
Figure 44. Street Parking Prohibition Performance Measures for Tamalpais Valley

For the Novato Neighborhood case, Figure 45 shows that if street parking is allowed, the evacuation lasts over two and a half hours for the daytime scenario, which is very close to the evacuation time when street parking is prohibited. For the nighttime scenario, street parking extends the evacuation time from four hours to four and a half hours. Street parking almost has no impact on the cumulative fire exposure time and number of persons within a half mile of the fire area in the daytime scenario. In the nighttime scenario, street parking hinders the evacuation process, causing the exposure time to increase to 700 hours, which is 250 hours more compared to the situation without street parking. Table 11 and Figures 46-47 show that street parking has a tiny effect on daytime evacuation, but a significant influence on nighttime evacuation. During the day, the number of evacuees is small, and there are many exits. Therefore, the reduced road capacity for residential roads does not influence the evacuation much. However, there are 17,519 evacuees during the night. Even though there is almost no background traffic, the dual effect of having so many evacuees and the fewer number of accessible lanes creates delays. These findings show how banning on-street parking at night when fires occur in the Novato Neighborhood could greatly increase evacuation efficiency.

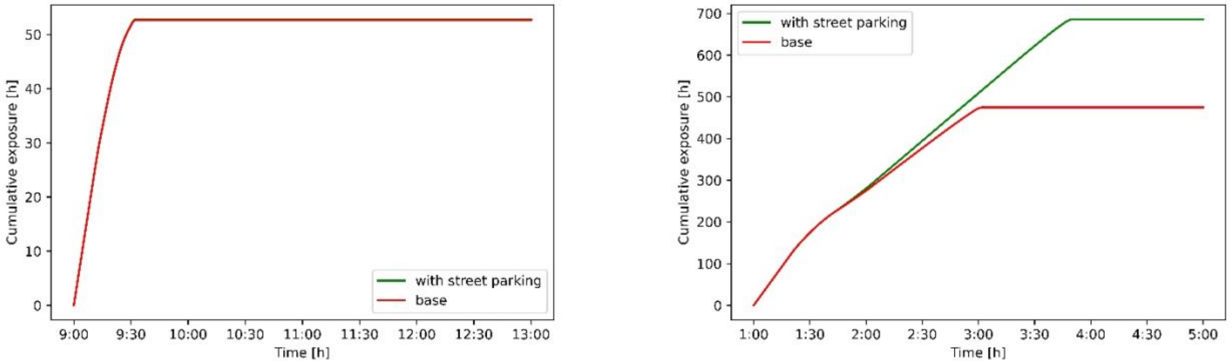
In evaluating banning on-street parking, we assumed that, if the road capacity is reduced by 25 percent, the average evacuation time would increase by around 25 percent. Yet, the results of many scenarios did not reflect this pattern. Instead, the evacuation times only increased about 10 percent in some scenarios (e.g., Ross Valley nighttime scenario and Woodacre Bowl daytime scenario), but rose by 50 percent in others (e.g., Ross Valley daytime scenario, Novato Neighborhood nighttime scenario). The impact depended on the different number of background vehicles and evacuee vehicles. Thus, the merits of this strategy depend on the characteristics of the local areas, including the ratio of number of evacuees to volume of background traffic, the spatial distribution of evacuees, and the number of exits.



(a) #vehicles that reach 2 miles away from the fire area (daytime scenario) (b) #vehicles that reach 2 miles away from the fire area (nighttime scenario)



(c) #persons within 0.5 mile of fire (daytime scenario) (d) #persons within 0.5 mile of fire (nighttime scenario)



(e) Cumulative exposure (hours) (daytime scenario) (f) Cumulative exposure (hours) (nighttime scenario)

Figure 45. Street Parking Prohibition Strategy Performance Measures for Novato Neighborhood ()

Table 11. Average Evacuation and Exposure Times for Street Parking Prohibition Strategy for All Case Studies

Indicators	Average travel time [h]	%change from baseline	Average exposure time [h]	%change from baseline	Average travel time [h]	%change from baseline	Average exposure time [h]	%change from baseline
Ross Valley	Daytime case				Nighttime case			
Without street parking (baseline)	1.250	-	0.120	-	1.230	-	0.223	-
With street parking	2.353	+88.2%	0.214	+78.3%	1.341	+9.0%	0.243	+9.0%
Woodacre Bowl	Daytime case				Nighttime case			
Without street parking (baseline)	0.577	-	0.074	-	0.389	-	0.054	-
With street parking	0.632	+9.5%	0.076	+2.7%	0.480	+23.4%	0.063	+16.7%
Tamalpais Valley	Daytime case				Nighttime case			
Without street parking (baseline)	0.618	-	0.045	-	0.731	-	0.117	-
With street parking	0.738	+19.4%	0.070	+52.2%	0.817	+11.8%	0.184	+57.3%
Novato Neighborhood	Daytime case				Nighttime case			
Without street parking (baseline)	0.830	-	0.007	-	1.061	-	0.027	-
With street parking	0.896	+8.0%	0.007	0.0%	1.327	+25.1%	0.039	44.4%

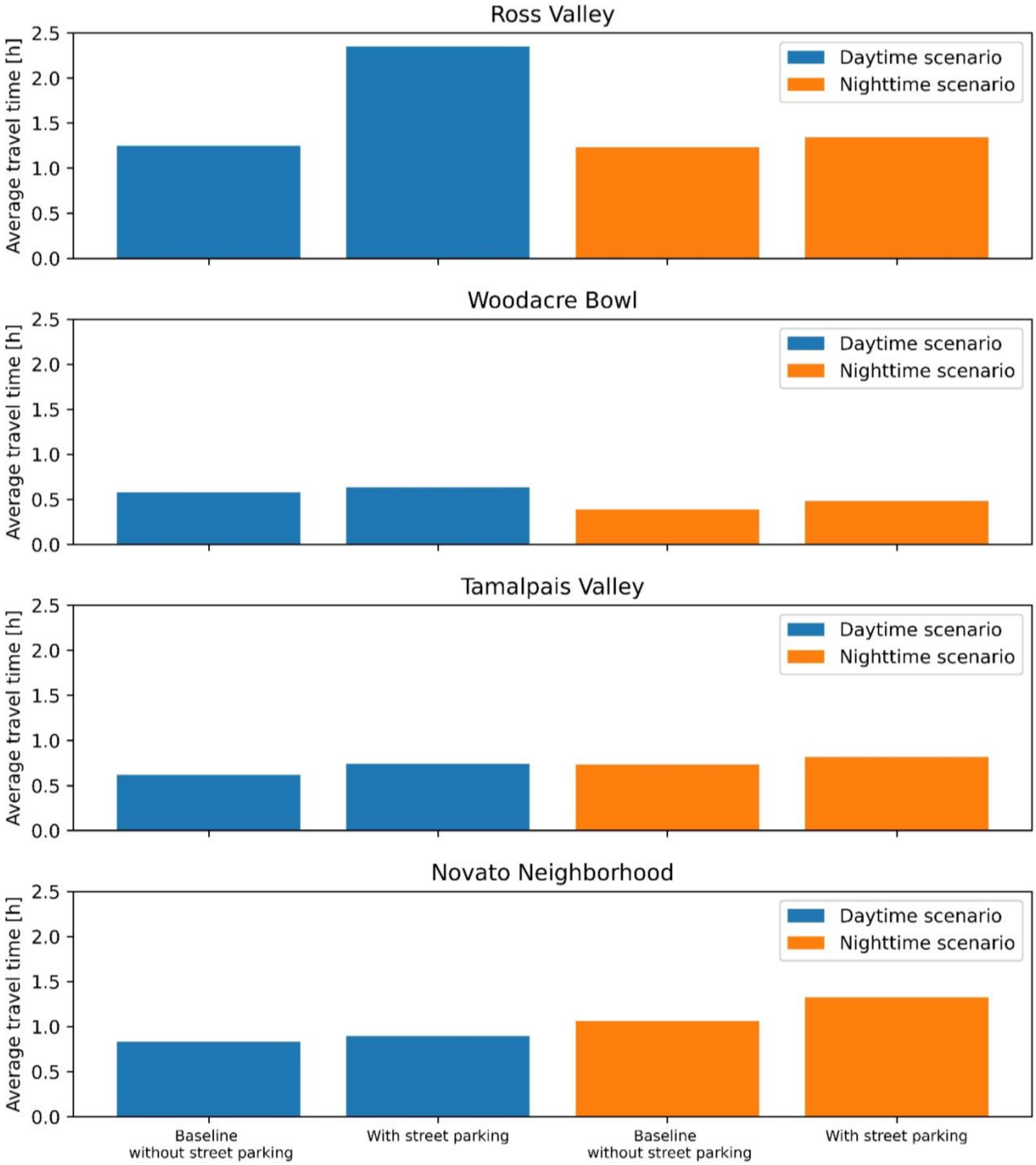


Figure 46. Average Evacuation Times With and Without Street Parking

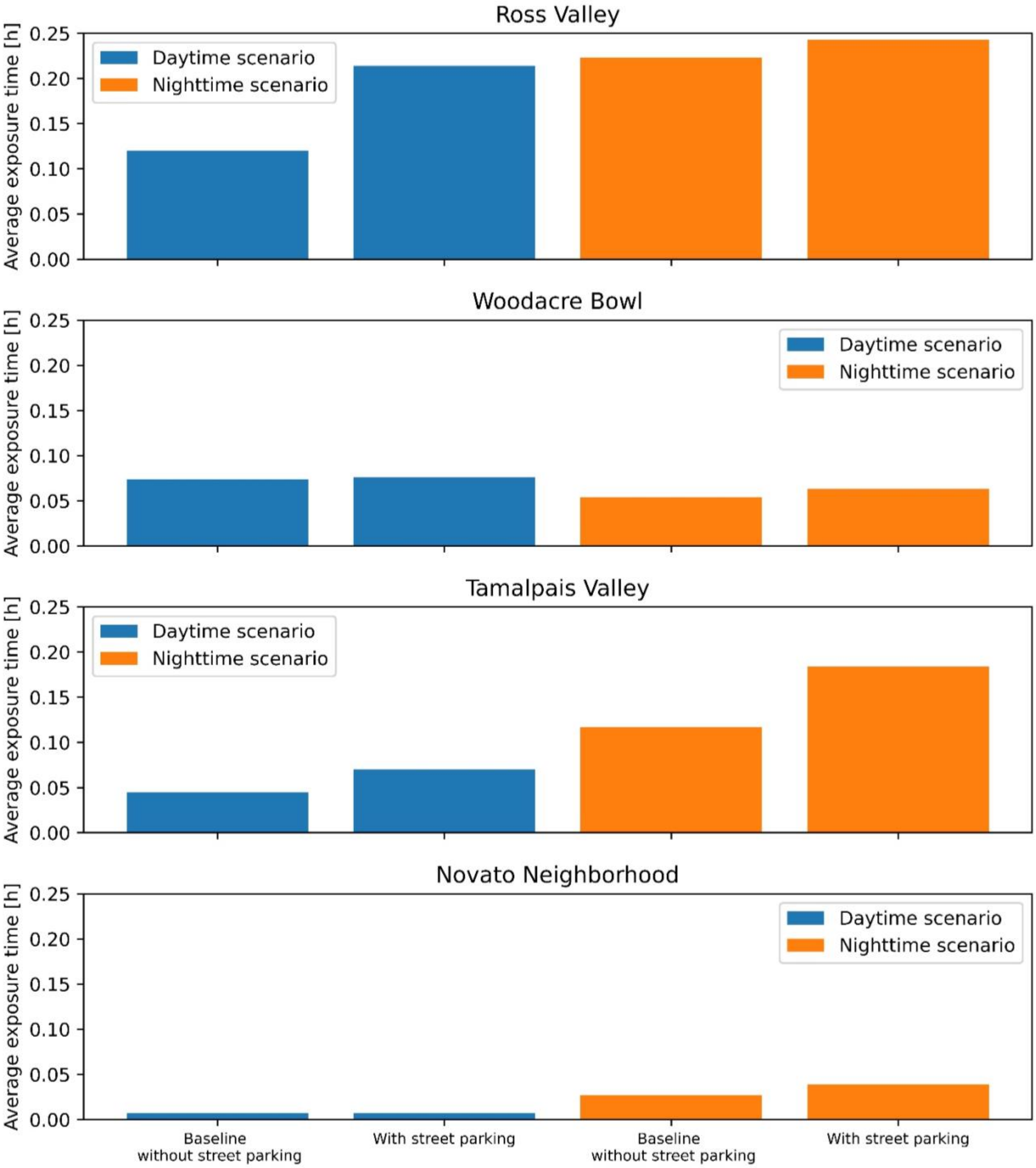


Figure 47. Average Fire Exposure Times With and Without Street Parking

Recommended Strategies

The previous section analyzed different evacuation strategies in terms of two summary statistics: (i) average time for evacuees to reach two miles away from the fire area; and (ii) average exposure time within a half miles of fire area. From the results shown in Tables 8, 10-11 and Figures 30-31, 40-41, and 46-47, different strategies exhibit varying performance in different areas and times. This is due to differences in road networks, fire ignition points and progression, the number of evacuees, and the normal traffic around the areas. Table 12 lists recommended strategies for each case.

Sharing a vehicle among multiple persons is a good strategy among these different cases, as sharing vehicles can greatly reduce traffic congestion and speed up the evacuation. However, it is difficult and time-consuming to coordinate having persons from different households share one vehicle in emergency situations. On the contrary, it is quite easy to encourage persons not to use all their cars, but to share one or two vehicles among family members. We recommend that at least two persons should share a car during fire evacuations.

We recommend cities consider adopting a phased evacuation strategy. However, longer departure intervals do not necessarily result in a more efficient evacuation. This is because over time fires can spread and approach zones that were initially far from the point of origin. Therefore, it is not advisable to make persons in these zones wait too long time before issuing an evacuation order.

The effect of street parking on evacuation varies with the circumstances. In some cases, such as the nighttime scenario for Ross Valley and the daytime scenario for Woodacre Bowl, street parking had little impact on the evacuation, while in the other cases, prohibiting street parking can result in a significant increase in evacuation efficiency. The difference results from varying numbers of evacuees and exit routes. When the number of evacuees is relatively small compared with the number of background vehicles and the number of exits is large, the effect of street parking is small. Yet, with are more evacuees and fewer exits, the impact of street parking is high. Overall, prohibiting street parking on fire days can effectively reduce evacuation times. This strategy would be advantageous in all cases, particularly Tamalpais Valley, and during the daytime for Ross Valley, and at night for Woodacre Bowl, and the Novato Neighborhood. Prohibiting street parking in these cases could significantly improve evacuation performance.

Table 12. Recommended Strategies

Case	Daytime Scenario	Nighttime Scenario
Ross Valley	i. ≥3 persons sharing one vehicle ii. 15-min departure interval iii. No street parking	i. ≥2 persons sharing one vehicle ii. 40-min departure interval
Woodacre Bowl	i. ≥3 persons sharing one vehicle ii. 30-min departure interval	i. ≥2 persons sharing one vehicle ii. 40-min departure interval iii. No-street parking
Tamalpais Valley	i. ≥2 persons sharing one vehicle ii. No phased evacuation iii. No-street parking	i. ≥2 persons sharing one vehicle ii. 20-min departure interval iii. No-street parking
Novato Neighborhood	i. ≥3 persons sharing one vehicle ii. 30/45-min departure interval	i. ≥3 persons sharing one vehicle ii. 40/60-min departure interval iii. No-street parking

Policy Recommendations

The following policy recommendations are based on our analysis of the three evacuation strategies.[1]

Vehicle Reduction

Based on the analysis presented in the previous sections, reducing the number of evacuating vehicles is a highly recommended strategy for Marin County. In Marin County, the average household size in 2019 was 2.45 and the number of vehicles per household was 1.9 (US Census Bureau, 2021). Due to the high level of vehicle ownership, there may be less incentive to carpool in emergency situations. The relevant benefits of carpooling have already been advocated on official websites (Firesafe Marin, 2019, 2020).

This strategy was also analyzed in Zhao and Wong (2021), and the relevant policy recommendations discussed there remain valid based on results from this study:

> - Recommend residents take as few vehicles as possible (just enough to transport people and key belongings) through an educational and informational campaign.
> - Suggest residents pre-pack their vehicle(s) during high fire danger periods so that vehicle space is used efficiently.
> - Develop an equitable insurance framework for protecting residents' vehicles in high-risk fire areas.
> - Develop plans for parking areas outside of potential evacuation zones for residents to take additional vehicles during high fire danger weather conditions as part of their emergency preparedness planning).
>
> Zhao and Wong (2021)

In addition, the following policies are also recommended:

- Establish a communication system to provide real-time updates on car-pooling opportunities, match drivers with potential passengers, and disseminate information about carpooling resources and schedules.
- Continuously monitor and evaluate the effectiveness of vehicle reduction/car-pooling policies after a wildfire. Collect feedback from users, measure the impact on transportation patterns, and make necessary adjustments to improve the effectiveness and operational feasibility of this strategy.

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[1] The analysis framework and some content of this section can be referred to Table 4 in Zhao and Wong (2021). Direct quotes are used for readability. References to the original content are given whenever applicable.

Phased Evacuation

The effectiveness of a phased evacuation strategy depends on the timing phases and size of the designated zones. However, this requires heavy communication and coordination tasks. Overall, when implementing a phased evacuation, it is essential to have an accurate assessment of the fire progression to prevent a situation where some people are exposed to the fire threat while waiting for the issuance of an evacuation order.

This strategy was also assessed in Zhao and Wong (2021), and their policy recommendations are still applicable based on results from this study:

- Research, develop, and distribute widely phased evacuation plans that create reasonable time bands.
- Use known boundaries and easy to identify landmarks and roads to set evacuation zones for phasing.
- Maintain relatively few potential zones to reduce confusion in the evacuation process and reduce the number of messages sent to evacuees.
- Convey emergency evacuation orders and warnings by zones.
- Prepare for contingencies (e.g., changes in time bands) if the fire spreads faster or slower than expected.

In addition, the following policy recommendations should be considered:

- Conduct public education campaigns to raise awareness about the phased evacuation strategy, the importance of preparedness, and the actions residents should take during each phase.
- Provide guidance on emergency kits, communication plans, and evacuation procedures to help individuals and communities prepare for evacuation in advance.

Street Parking Prohibition

The effectiveness of prohibiting street parking in in wildfire situations is highly context specific. In some areas, prohibiting street parking can effectively increase the road capacity and speed up the evacuation. However, this strategy requires active communication with residents before and during the evacuation, making it difficult to implement. To minimize trouble for residents, careful research should be conducted on where street parking has a significant impact on evacuation efficiency. Overall, this strategy is moderately recommended, but context-specific analysis is highly recommended.

Street parking has been demonstrated to have a great effect on the road capacity. It reduces road capacity by 16-30 percent (Wijayaratna, 2015; Cao et al., 2017). During evacuations, prohibiting street parking can greatly mitigate traffic congestion. Before wildfires occur, residents need to be notified to move their vehicles off the street. However, there may not be enough space off the street for vehicles to park. When formulating a street parking prohibition plan, it is essential to identify alternative parking spaces to ensure that vehicles have a place to park.

The following recommendations should be considered in developing a street parking prohibition policy:

- Judge the impact of street parking on the evacuation traffic.
- Develop street parking prohibition plans that focus on highly congested roads and neighborhoods with few exits to maximize effectiveness and minimize disruptions to residents along the roads.
- Notify residents along roads where street parking is prohibited on fire days ahead of time.

Summary and Conclusions

This study applied a spatial-queue-based dynamic traffic simulation model to analyze the impact of strategies for vehicle reduction, phased evacuation, and prohibiting street parking on the evacuation process. Background traffic was considered in conducting the simulations due to its effect on evacuation efficiency. These three strategies were tested on representative areas in Marin County, including Ross Valley, Woodacre Bowl, Tamalpais Valley, and a Novato neighborhood.

Simulation results show that vehicle reduction is a good strategy for evacuations based on the modeled average evacuation times and average wildfire exposure times. Road congestion is mitigated, and evacuation can be completed more quickly. Achieving an average of just two or three persons per vehicle can significantly reduce both average evacuation and exposure times, though beyond that improvements are only marginal. Carpooling should be recommended during evacuation in these four areas.

The phased evacuation simulation results show that this strategy reduces peak demand on the roadway by spreading out evacuees temporally and reduces traffic congestion. The optimal time interval between phases depends on the speed the fire spreads and the number of evacuees. Time intervals that are too short or too long will be less efficient, suggesting a need for thoughtful planning.

The effect of prohibiting street parking varies. In some cases, prohibiting street parking can make a greatly improve evacuation efficiency, while in the other cases, it makes little difference. This result suggests that a thorough analysis should be conducted before a wildfire occurs to determine whether this strategy is appropriate for implementation during fires.

The simulations presented in this study involve many assumptions regarding road networks and vehicle behavior due to the level of detail that the model can support. Nevertheless, the results show that the proposed wildfire-traffic simulation framework can offer broader application for preparedness analysis especially for resource-strapped communities in WUI areas to undertake the most cost-effective precautionary measures and implement corresponding policies.

However, there are some limitations to this research. This study only involved two fire scenarios for each case study, one in the morning and one in the evening. Additional fire scenarios could be explored in future research, as traffic patterns differ at different times of the day. It may also be possible to develop distinct evacuation strategies tailored to specific periods of the day when fires may occur. Additional evacuation strategies could also be analyzed, such as making narrow roads one-way during Red Flag Days to increase road capacity.

References

BISWAS, S., CHANDRA, S. & GHOSH, I. 2017. Effects of on-street parking in urban context: A critical review. Transportation in developing economies, 3, 1-14.

CALIFORNIA TRANSPORTATION COMMISSION. 2017. 2017 Regional Transportation Plan Guidelines for Regional Transportation Planning Agencies [Online]. https://dot.ca.gov/-/media/dot-media/programs/transportation-planning/documents/2017rtpguidelinesforrtpas-a11y.pdf [Accessed January 13, 2023].

CAO, Y., YANG, Z. & ZUO, Z. 2017. The effect of curb parking on road capacity and traffic safety. European Transport Research Review, 9, 1-10.

CHEN, X. & ZHAN, F. B. 2008. Agent-based modelling and simulation of urban evacuation: Relative effectiveness of simultaneous and staged evacuation strategies. Journal of the Operational Research Society, 59, 25-33.

CHEN, Y., SHAFI, S. Y. & CHEN, Y.-F. 2020. Simulation pipeline for traffic evacuation in urban areas and emergency traffic management policy improvements through case studies. *Transportation research interdisciplinary perspectives*, 7**,** 100210.

COHN, P. J., CARROLL, M. S. & KUMAGAI, Y. 2006. Evacuation behavior during wildfires: Results of three case studies. Western Journal of Applied Forestry, 21, 39-48.

COMFORT, L., SOGA, K., STACEY, M., MCELWEE, M., ECOSSE, C., DRESSLER, J. & ZHAO, B. 2019. Collective action in communities exposed to recurring hazards: The Camp Fire, Butte County, California, November 8, 2018. Natural Hazards Center Quick Response Grant Report Series, 300.

COVA, T. J. & JOHNSON, J. P. 2002. Microsimulation of neighborhood evacuations in the urban–wildland interface. Environment and Planning A, 34, 2211-2229.

COVA, T. J. & JOHNSON, J. P. 2003. A network flow model for lane-based evacuation routing. Transportation Research Part A: Policy and Practice, 37, 579-604.

COVA, T. J. 2005. Public safety in the urban–wildland interface: should fire-prone communities have a maximum occupancy? Natural Hazards Review, 6**,** 99-108.

DE ARAUJO, M. P., LUPA, M. R., CASPER, C. T. & WATERS, B. 2014. Wildfire evacuation scenario in colorado: Comparison of adapted four-step metropolitan planning organization modeling results and planning process findings with actual experience. Transportation Research Record, 2430, 133-144.

FEMA. 2021a. Integrated Public Alert \& Warning System [Online]. https://www.fema.gov/emergency-managers/practitioners/integrated-public-alert-warning-system [Accessed March 3, 2023].

FEMA. 2021b. Planning Considerations: Evacuation and shelter-in-place guidance for state, local, tribal, and territorial partner [Online]. https://www.fema.gov/sites/default/files/2020-07/planning-considerations-evacuation-and-shelter-in-place.pdf [Accessed February 4, 2023].

FINNEY, M. A. 1998. FARSITE, Fire Area Simulator--model development and evaluation, US Department of Agriculture, Forest Service, Rocky Mountain Research Station.

FINNEY, M. A. & ANDREWS, P. L. 1999. FARSITE—a program for fire growth simulation. Fire Management Notes, 59, 13-15.

GOLSHANI, N., SHABANPOUR, R., MOHAMMADIAN, A., AULD, J. & LEY, H. 2019. Analysis of evacuation destination and departure time choices for no-notice emergency events. Transportmetrica A: Transport Science, 15, 896-914.

KULIGOWSKI, E. 2021. Evacuation decision-making and behavior in wildfires: Past research, current challenges and a future research agenda. Fire Safety Journal, 120, 103129.

LI, P., ZHAO, B., JIANG, M., SOGA, K. & ZHANG, Y. 2022. Assessing the effectiveness of phased evacuation strategies under slow and fast fire scenarios with a real case study in Paradise, California. CICTP 2022.

LIM, G. J., ZANGENEH, S., BAHARNEMATI, M. R. & ASSAVAPOKEE, T. 2012. A capacitated network flow optimization approach for short notice evacuation planning. European Journal of Operational Research, 223, 234-245.

LOVREGLIO, R., KULIGOWSKI, E., GWYNNE, S. & STRAHAN, K. 2019. A modelling framework for householder decision-making for wildfire emergencies. International Journal of Disaster Risk Reduction, 41, 101274.

MARIN, F. 2020. Wildfire evacuation preparedness [Online]. https://firesafemarin.org/prepare-yourself/evacuation-guide/#gsc.tab=0 [Accessed February 2, 2023].

MCCAFFREY, S., WILSON, R. & KONAR, A. 2018. Should I stay or should I go now? Or should I wait and see? Influences on wildfire evacuation decisions. Risk Analysis, 38, 1390-1404.

MCLENNAN, J., RYAN, B., BEARMAN, C. & TOH, K. 2019. Should we leave now? Behavioral factors in evacuation under wildfire threat. Fire Technology, 55, 487-516.

MOZUMDER, P., RAHEEM, N., TALBERTH, J. & BERRENS, R. P. 2008. Investigating intended evacuation from wildfires in the wildland–urban interface: Application of a bivariate probit model. Forest Policy and Economics, 10, 415-423.

MURRAY-TUITE, P. M. & MAHMASSANI, H. S. 2003. Model of household trip-chain sequencing in emergency evacuation. Transportation Research Record, 1831, 21-29.

MURRAY-TUITE, P. M. & MAHMASSANI, H. S. 2004. Transportation network evacuation planning with household activity interactions. Transportation Research Record, 1894, 150-159.

NOH, H., CHIU, Y.-C., ZHENG, H., HICKMAN, M. & MIRCHANDANI, P. 2009. Approach to modeling demand and supply for a short-notice evacuation. Transportation Research Record, 2091, 91-99.

ONSOLVE. 2021. CodeRED for IPAWS [Online]. https://www.onsolve.com/landing/codered-for-ipaws [Accessed February 21, 2023].

PAVEGLIO, T. B., BOYD, A. D. & CARROLL, M. S. 2012. Wildfire evacuation and its alternatives in a post-Black Saturday landscape: Catchy slogans and cautionary tales. Environmental Hazards, 11, 52-70.

RADELOFF, V. C., HELMERS, D. P., KRAMER, H. A., MOCKRIN, M. H., ALEXANDRE, P. M., BAR-MASSADA, A., BUTSIC, V., HAWBAKER, T. J., MARTINUZZI, S. & SYPHARD, A. D. 2018. Rapid growth of the US wildland-urban interface raises wildfire risk. Proceedings of the National Academy of Sciences, 115, 3314-3319.

ROHAERT, A., KULIGOWSKI, E. D., ARDINGE, A., WAHLQVIST, J., GWYNNE, S. M., KIMBALL, A., BENICHOU, N. & RONCHI, E. 2023. Traffic dynamics during the 2019 Kincade wildfire evacuation. Transportation Research Part D: Transport And Environment, 116, 103610.

SBAYTI, H. & MAHMASSANI, H. S. 2006. Optimal scheduling of evacuation operations. Transportation Research Record, 1964, 238-246.

SHAHPARVARI, S., ABBASI, B. & CHHETRI, P. 2017. Possibilistic scheduling routing for short-notice bushfire emergency evacuation under uncertainties: An Australian case study. Omega, 72, 96-117.

SO, S. K. & DAGANZO, C. F. 2010. Managing evacuation routes. Transportation Research Part B: Methodological, 44, 514-520.

SOGA, K., COMFORT, L., ZHAO, B., LORUSSO, P. & SOYSAL, S. 2021. Wildfire Evacuation Planning Can Be Greatly Enhanced by Considering Fire Progression, Communication Systems, and Other Dynamic Factors. UC Office of the President: University of California Institute of Transportation Studies.

STRAHAN, K. 2017. Factors influencing householder self-evacuation in two Australian bushfires. Doctoral Dissertation, RMIT University.

THOMAS, D. S. & BUTRY, D. T. 2014. Areas of the US wildland–urban interface threatened by wildfire during the 2001–2010 decade. Natural Hazards, 71, 1561-1585.

TOLEDO, T., MAROM, I., GRIMBERG, E. & BEKHOR, S. 2018. Analysis of evacuation behavior in a wildfire event. International Journal of Disaster Risk Reduction, 31, 1366-1373.

US CENSUS BUREAU. 2021. Marin County Household Survey [Online]. https://data.census.gov/table?q=marin+%2B+household&tid=ACSST1Y2021.S1101 [Accessed Feburary 1, 2023].

VORST, H. C. 2010. Evacuation models and disaster psychology. Procedia Engineering, 3, 15-21.

WIJAYARATNA, S. Impacts of on-street parking on road capacity. Australasian Transport Research Forum, 2015. 1-15.

WIJAYARATNA, S. & WIJAYARATNA, K. P. 2016. Quantifying the impact of on-street parking on road capacity: A case study of Sydney arterial roads.

WILMOT, C. G. & MEDURI, N. 2005. Methodology to establish hurricane evacuation zones. Transportation Research Record, 1922, 129-137.

WONG, S. & SHAHEEN, S. 2019. Current State of the Sharing Economy and Evacuations: Lessons from California. *UC Office of the President: University of California Institute of Transportation Studies*.

WONG, S. D., BROADER, J. C. & SHAHEEN, S. A. 2020. Can sharing economy platforms increase social equity for vulnerable populations in disaster response and relief? A case study of the 2017 and 2018 California wildfires. Transportation Research Interdisciplinary Perspectives, 5, 100131.

WONG, S. D., BROADER, J. C., WALKER, J. L. & SHAHEEN, S. A. 2022. Understanding California wildfire evacuee behavior and joint choice making. Transportation, 1-47.

WONG, S. D., WALKER, J. L. & SHAHEEN, S. A. 2021. Trust and compassion in willingness to share mobility and sheltering resources in evacuations: A case study of the 2017 and 2018 California Wildfires. International Journal of Disaster Risk Reduction, 52, 101900.

ZHAO, B. & WONG, S. D. 2021. Developing transportation response strategies for wildfire evacuations via an empirically supported traffic simulation of Berkeley, California. Transportation Research Record, 2675, 557-582.

ZHAO, X., XU, Y., LOVREGLIO, R., KULIGOWSKI, E., NILSSON, D., COVA, T. J., WU, A. & YAN, X. 2022. Estimating wildfire evacuation decision and departure timing using large-scale GPS data. Transportation Research Part D: Transport and Environment, 107, 103277.