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Microsimulation of neighborhood evacuations in the urban – wildland interface

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Abstract. Residential development in fire-prone wildlands is occurring at an unprecedented rate. Community-based evacuation planning in many areas is an emerging need. In this paper we present a method for using microscopic traffic simulation to develop and test neighborhood evacuation plans in the urban – wildland interface. The method allows an analyst to map the subneighborhood variation in household evacuation travel times under various scenarios. A custom scenario generator manages household trip generation, departure timing, and destination choice. Traffic simulation, route choice, and dynamic visualization are handled by a commercial system. We present a case study for a controversial fire-prone canyon community east of Salt Lake City, Utah. GIS was used to map the spatial effects of a proposed second access road on household evacuation times. Our results indicate that the second road will reduce some household travel times much more than others, but all evacuation travel times will become more consistent.

1 Introduction

Residential development in fire-prone wildlands is occurring at an unprecedented rate (GAO, 1998; 1999). Fire managers refer to the area where urban growth encroaches into fire-prone wildlands as the *urban – wildland interface* (or *wildland – urban interface*) (Cortner and Gardner, 1990; Davis, 1990; Ewert, 1993; Greenberg and Bradley, 1997). Given this trend, wildfire-induced evacuations and property loss are likely to increase in frequency and magnitude into the foreseeable future. The nature of much of this development is incremental, where structures are added to existing neighborhoods over decades. In other cases, new hillside and canyon communities may appear in a matter of years. Residents and planners are beginning to recognize that transportation networks in many neighborhoods were not designed to serve the elevated travel demand during an urgent wildfire evacuation (*San Francisco Chronicle* 1991). Adding to this problem, network improvements generally lag behind residential densification, leading to a gradual decline in neighborhood egress over time. In short, a grand experiment in developing low-egress communities in historically fire-prone wildlands is currently underway.

An emerging need in many fire-prone areas is community-based evacuation planning. Evacuation planning increases public safety, by educating residents and local planners on options and potential problems, in advance of an event (Johnson and Ziegler, 1986; Perry, 1985). The neighborhood scale is most appropriate in this context because wildfires generally induce small-scale evacuations. For this reason, wildfire evacuations are managed locally, although large urban firestorms may involve many agencies (OES, 1992). At the opposite end of the process scale are mass evacuations that involve entire urban areas. Simulation modeling and spatial decision support systems for managing mass evacuations have advanced significantly over the last twenty years in the context of many hazards (Hobeika et al, 1994; Pidd et al, 1997; Sheffi et al, 1982; Southworth, 1991; Southworth and Chin, 1987; Tufecki and Kisko, 1991); but simulating neighborhood-scale evacuations under the threat of wildfire has not been a focus.

Neighborhood-evacuation analysis requires a relatively fine level of geographic detail. At this process scale, important questions can arise regarding the relative egress of individual structures or street segments. *Microscopic traffic simulation* (or *microsimulation*) is the most detailed level of transportation simulation modeling. For this reason, it represents a promising strategy for meeting the scale requirements of this problem domain. Microsimulators model the movement and interaction of individual vehicles in a transportation network. They are increasingly used to address problems such as intersection design (Hossain, 1999) and traffic management system evaluation (Yang and Koutsopoulos, 1996). Microsimulation in transportation modeling can be distinguished from macrosimulation, where traffic is modeled as aggregate flows (Southworth and Chin, 1987), and mesosimulation, where vehicles are grouped into platoons simulated as separate entities (de Silva and Eglese, 2000).

In this paper we present a method for using microsimulation to design and test neighborhood-evacuation plans in the urban – wildland interface. A central goal was to develop a method that can be applied by community planners and consultants without requiring a large-scale software-development campaign. For this reason, we developed the method to work with existing, off-the-shelf microsimulation software. We begin the paper with a review of microsimulation approaches in regional evacuation modeling, and then describe the proposed method. In the next section we present a case study for a controversial community in a fire-prone canyon east of Salt Lake City, Utah and raise a number of issues on how to model and plan neighborhood evacuations in fire-prone areas. Finally, the paper concludes with a discussion of the results and limitations of the approach.

2 Background

Southworth (1991) defines regional evacuation modeling as a five-step process, similar to the four-step urban transportation modeling system (Meyer and Miller, 1984). The main steps include trip generation, departure timing, destination choice, route choice, and evacuation plan set-up and analysis procedures. Mode choice may also be an important step when more than one travel mode is available. The concern in trip generation is estimating the number of vehicles that will enter a transportation network at various source locations. This may require the costly proposition of gathering data on daytime population fluctuations. The focus in the departure-timing step is estimating the rate at which these vehicles will enter the network. The destination choice step assigns each evacuating vehicle to an emergency planning zone exit or shelter. The concern in the route choice step is modeling en route driver decisionmaking. In the plan set-up and analysis step a set of performance measures are developed and tested, often with the aid of visualization, to develop and evaluate an evacuation plan.

There are few examples of microsimulation in regional evacuation analysis. Historically, arguments for its use have not been able to offset the added computational burden in modeling the movement and interaction of a large number of autonomous vehicles. In recent years, this limitation has been greatly reduced (if not eliminated) by increases in computational power and advancements in software engineering. The earliest application of microsimulation in evacuation modeling relied on tailoring the general-purpose microsimulator NETSIM™ to manage an evacuation (Peat, Marwick, Mitchell and Company, 1973; Rathi and Santiago, 1990). Moeller et al (1981) developed the CLEAR (calculated logical evacuation and response) model for the Nuclear Regulatory Commission that simulated vehicle movement only along primary arteries, thereby reducing the computational burden. Tweedie et al (1986) developed a probabilistic method for calculating evacuation times that involved preselecting major evacuation routes for traffic simulation. Stern and Sinuany-Stern (1989) presented a behavioral-based microsimulation model, based on the SLAM II simulation language for small-city evacuations, that included pedestrian flows (see also Sinuany-Stern and Stern, 1993).

As Southworth (1991) notes, the focus in most microsimulation studies is traffic delays at intersections because this is where the majority of delays occur. Route choice is generally either myopic (drivers select the least congested link at each intersection) or restricted, as a result of emergency managers controlling the flow at each intersection. They have been used primarily in geographically limited urban network studies (for example, primary roads only), or in relatively small urban and urban – rural area studies. Despite its limited use in regional evacuation analysis, microsimulation has seen rapid growth in transportation studies in recent years. Current off-the-shelf desktop microsimulators are capable of modeling and visualizing thousands of vehicles in complex urban road networks with many features that would be useful in modeling evacuations.

3 Methods

Evacuation analysis and planning at a neighborhood scale raise a number of interesting questions. Foremost is the nature of the spatial variation in expected evacuation times for households within a neighborhood. For example, in congested scenarios, evacuees starting deep in a densely populated canyon with a limited number of exits will take significantly longer to clear the canyon than those at the canyon mouth. This is important in characterizing and communicating wildfire evacuation vulnerability at a disaggregate (household) level. To date, evacuation researchers have emphasized aggregate network performance metrics such as *network clearing time* or *average vehicle delay* rather than disaggregate metrics such as *household evacuation travel time*. Disaggregate metrics hold the potential to be very telling because they can be mapped to examine evacuation scenarios and management options in a spatial light. For example, although it is routine to identify the location of potential traffic bottlenecks in an evacuation, little attention has been paid to identifying which evacuees will experience these delays. The method presented herein allows an analyst to reveal this subneighborhood spatial variation in evacuation travel times and, thus, human vulnerability.

As noted, a new generation of desktop microtraffic simulators has emerged that include many features that would be useful in evacuation modeling and planning. Although these systems are not specifically designed for modeling evacuations, a regional evacuation can be viewed as a special case of urban transportation. Example differences include the motivation behind trip making, the elevated level of travel demand on the network, traffic management strategies, and the potential loss of critical links to a hazard. Many of these new systems include sophisticated intersection design and coding capabilities, public transportation routing features, 3D dynamic visualization, and the ability to model thousands of interacting vehicles in complex urban networks to lane-level detail. There are a number of competing microsimulators (SMARTEST, 1999), and we selected Paramics™ (Quadstone, 2002) as representative of this generation (Cameron and Duncan, 1996). Paramics™ has exceptional 3D dynamic visualization capabilities that would be useful in viewing evacuation scenarios. Also, it has recently gained acceptance in the United States by state Departments of Transportation such as the California Department of Transportation. This should not overshadow the fact that the method we describe in this paper can be used with any simulator that accepts a traffic scenario in the form of text files, which is standard practice.

Augmenting a microsimulator to model an evacuation requires a preprocessing step to generate a realistic scenario and a postprocessing step to assess any relevant

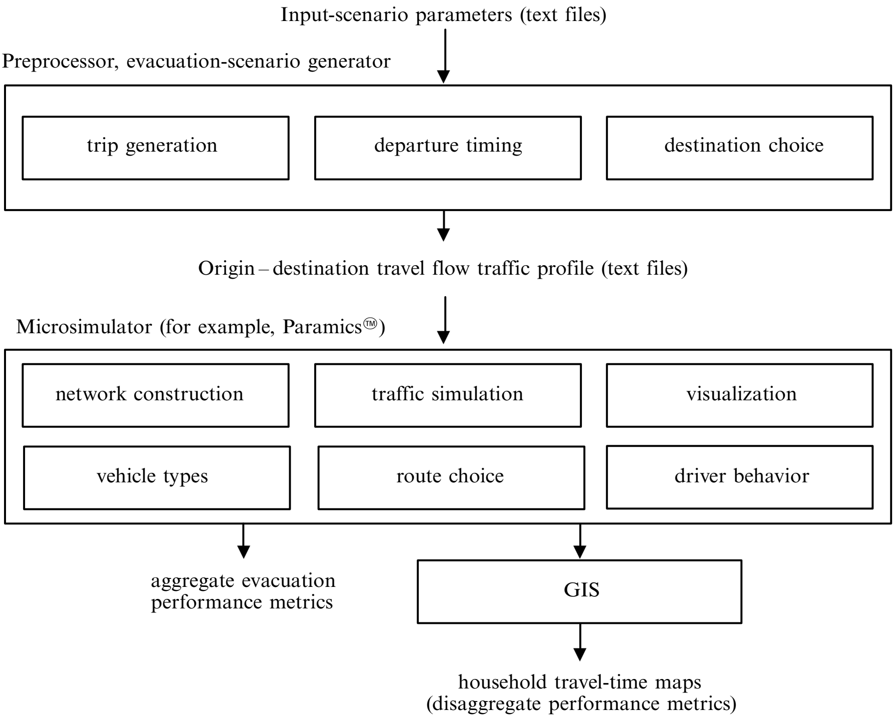

Figure 1. A diagram of the microsimulation evacuation method.

evacuation metrics. This approach was used in the original work with NETSIM (Peat et al, 1973). Figure 1 is a conceptual diagram of the proposed method. A preprocessor receives a set of input parameters that define the characteristics of an evacuation scenario. This program translates the scenario into a specific case of origin – destination (OD) travel flow for input into a general-purpose microsimulator. OD demand is expressed as a temporal profile that defines the rate of demand from each origin zone to destination zone within a specified time interval. In addition to defining an evacuation scenario in the preprocessing step, there are also direct inputs into the microsimulation software, most notably the one-time coding of the road network for a given study area. Other direct parameters to the microsimulator serve to define characteristics such as vehicle types and speeds. The next few sections review the steps in the proposed method.

3.1 Network coding

At the most detailed network data-modeling level, each structure is represented by an origin zone. To perform a study at this level, spatial information is required on all roads and residential structures (or parcels) within a study area. This information has a number of sources. For example, many local planning agencies maintain up-to-date digital spatial data regarding the location of structures or parcels for tax purposes. If this information is not available, air photographs are a source of spatial information available at very large map scales. In the United States, US Geological Survey digital orthophoto quads (DOQs) are a valuable resource in this regard (one-meter resolution rectified to Universal Transverse Mercator). However, in many rapidly developing areas, fieldwork may also be necessary to identify all current structures. Given a source of this information, Paramics™ allows a graphic image to be input from which a vector-based network can be directly digitized. The network coding functionality is similar to a network-based GIS (for example, ArcEdit®). Link speed and other network attributes must be entered manually. Coding a network is a time-consuming step; proportional to the number of structures (that is, origin zones), links, and intersections in the study area. Nonetheless, the graphical interactive input tools are a quantum leap over the text file network coding of first-generation traffic-simulation software.

3.2 Trip generation

The concern in trip generation is estimating the number of departing vehicles from each origin zone. In the context of this research, each origin zone represents a separate household. As the number of households in a neighborhood with $0, 1, 2, \ldots, n$ originating vehicles is a discrete count, we can make a statistical assumption that the aggregate distribution of originating vehicles in a neighborhood follows a Poisson distribution (figure 2, step 1). The Poisson distribution is most appropriate in this case because

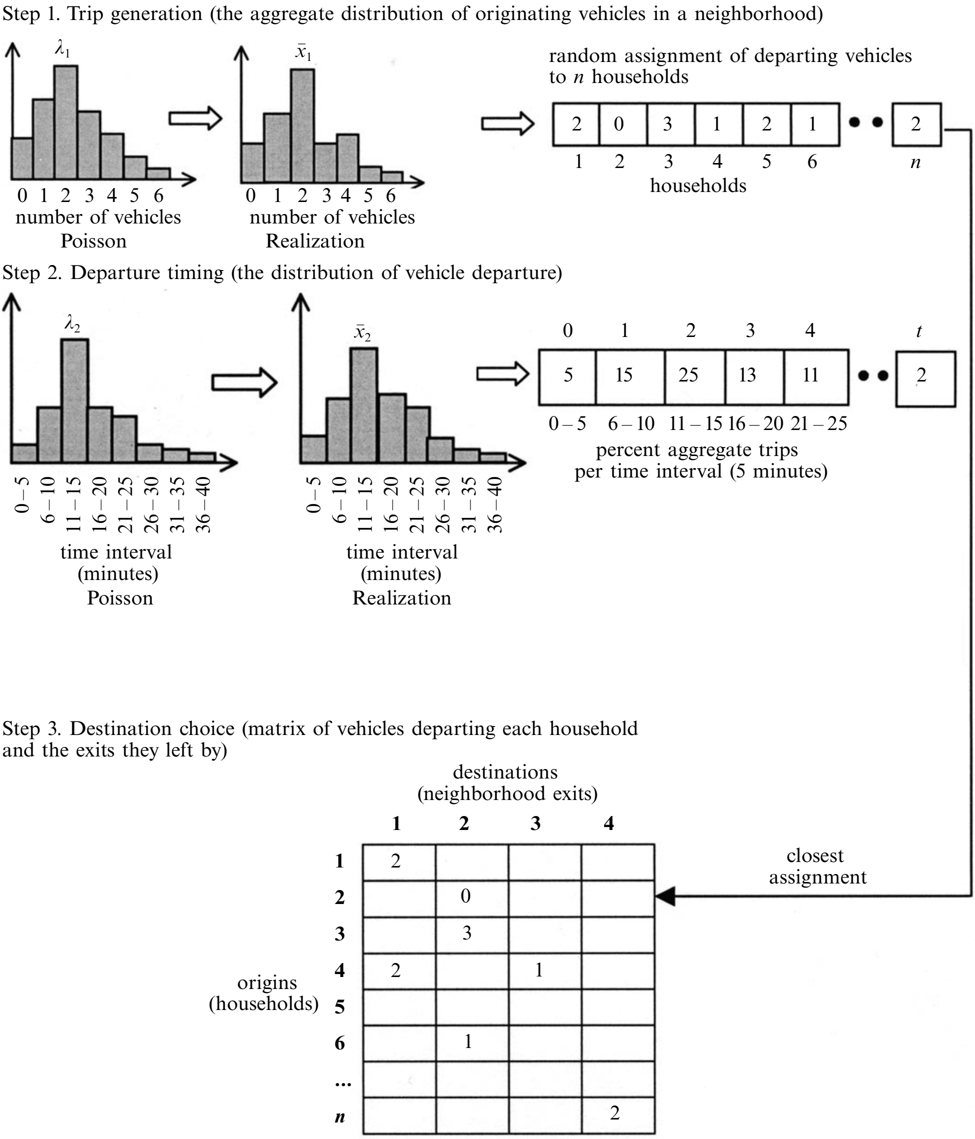

Figure 2. The three-step evacuation scenario-generation method.

some homes will have few or no evacuating vehicles at a given time of day, most will have some, and a few will have many. A house may have no evacuating vehicles because the residents are conducting activities elsewhere at the time of the evacuation or they opted to shelter-in-place during an emergency. Households with many vehicles may have large families, renters, or guests.

The mean and variance of a Poisson distribution are equal. In this context, this refers to the mean number of vehicles departing from each household and the variance in the number of vehicles. The main factors that affect the mean are the number of available vehicles at each household and their subsequent use by household members. This parameter fluctuates throughout the diurnal cycle as residents conduct activities away from home and return. At midday in a residential neighborhood, there may be as few as 0.5 vehicles, on average, departing from each household, because most residents are at work or conducting activities elsewhere. This is equivalent to saying that every other house will generate 1 vehicle, on average, during an evacuation. However residential neighborhoods also employ many transient people such as house cleaners, contractors, gardeners, delivery people, and utility workers who will also play a role in a daytime evacuation (Drabek, 1996). The mean can be adjusted; lower to assess the effect of fewer vehicles per household and higher for times when most residents are at home.

The Poisson distribution can be used to simulate (Ross, 1989) a *realization* of originating vehicles within a neighborhood. The steps in this process are as follows:

1. select the next household h;
2. use the mean number of vehicles per household in a Poisson random number generator to obtain a random integer v that represents the number of vehicle trips from the household (Kruse and Ryba, 1999, page 670);
3. assign the number of departing vehicles v to household h;
4. if there are more households, go to step 1;
5. done.

This process can be repeated any number of times for a given scenario to assess the sensitivity of all evacuation-analysis metrics. The benefit of this approach is that it does not place too much weight on a single distribution of trips. Household occupancy, vehicle ownership, and neighborhood demographics will vary significantly across all time scales in a community. In this way the goal is to test the longer term performance of a neighborhood configuration (residential and road network), across a range of scenarios, rather than attempt to produce an accurate estimate of the evacuation time for a particular scenario. We do not know where everyone will be in a community during an evacuation, so statistical simulation of the scenario is appealing because it incorporates this uncertainty. This approach also avoids privacy violations, which are a significant concern at this level of geographic detail. For example, it should not be necessary to know individual household demographics, how many vehicles a household owns, or when a household's occupants are home or not. This method assumes stationarity in the mean number of evacuating vehicles per household throughout the neighborhood. In some study areas, there may be enclaves within the neighborhood with a much higher or lower average number of evacuating vehicles per household. However, for small areas this assumption is not too egregious.

3.3 Departure timing

The concern in the departure-timing step is modeling the rate at which vehicles will enter the network following an evacuation order or recognition of a threat. A temporal profile of travel demand must be generated. This can be performed at an aggregate level where the percentage of evacuating vehicles entering the network in discrete time steps is specified. Time 'zero' can be viewed either as the time an evacuation order is issued or when the community perceives the hazard as a threat. In the context of this research, we are not concerned with decision time, or the time between incidence detection and the decision to order an evacuation (Urbanik et al, 1980). Departure time, in our context, refers to the point in time when a vehicle leaves a household; it includes both notification time and household preparation time. For example, if a vehicle is assigned a departure time of 25 minutes, then 25 minutes were required to notify the household and for the occupants to prepare to evacuate.

The diffusion of emergency warning has been studied for many hazards (Rogers, 1989; Rogers and Sorensen, 1991; Sorensen, 1988; 1991). Stern and Sinuany-Stern (1989) proposed modeling this process for nuclear power plant evacuations in a behavioral-based fashion using decision trees that include many factors such as the location of the head of household and available communication modes (for example, television, radio, neighbor). Despite the many theoretical and empirical advancements in this area, Southworth (1991) notes that this is still the weakest link in the evacuation modeling process. In the context of modeling wildfire-induced evacuations at the neighborhood scale, the process is further complicated by the fact that this particular topic has not been studied. Thus, the only option at this time is to rely on planner judgment about how evacuees might respond in an emergency.

In this method, there are t discrete vehicle trips from all households that must be assigned a departure time. The distribution of these events in an actual emergency can take many forms depending on myriad idiographic factors. In general, it is likely that few evacuees will depart at the onset of an emergency, as most will be preparing to leave or still receiving warning. This rate should increase to a peak and then gradually taper off. The most common approach to this problem is to model the cumulative distribution of these trips (rather than a probability density function) with a logistic curve (Southworth, 1991). Within the context of this method, we decided to use the Poisson distribution to represent the probability density function of departure events. The Poisson distribution is commonly used in queuing theory to model random arrivals because it describes the probability of n events occurring within a given time period, given that the time between arrivals is a random number that is independent of the time of the previous arrivals (Meyer and Miller, 1984). Here, we simply reverse the common use of this distribution to model a random *departure* process.

It is also simple to simulate a Poisson distribution to be used in Paramics™ as a traffic demand profile. For each discrete time period (0–5 minutes, 6–10 minutes, 11–15 minutes, ...), the percentage of evacuating vehicles from the neighborhood must be estimated. In a Poisson distribution, this can be specified with a single parameter—the mean vehicle departure time (in 5-minute increments) after an order to evacuate or recognition of a threat. In cases where the neighborhood mobilizes relatively quickly, this mean will be low and the distribution will be skewed. In cases where the response to an order is very slow (high preparation time), the mean departure time will be relatively high and the distribution will take on a Gaussian shape. Similar to the trip-generation step, the Poisson distribution is used as a statistical method to simulate departure timing realizations n times for a given mean—to incorporate a dimension of uncertainty (figure 2, step 2).

3.4 Destination choice

The concern in the destination choice step is assigning each evacuating vehicle to a neighborhood exit or shelter. The most straightforward approach is a closest-assignment assumption—where vehicles are assigned to their closest exit or shelter by using the network distance. In some neighborhood contexts this may be a very good estimate of where people will travel, whereas in others it may not. Another approach is to use traffic counting data to assess neighborhood-exit use and assume that destination choice can be approximated with this information. In other words, the assignment of vehicles to exits can be a modified version of closest assignment—where the allocation of vehicles to exits is adjusted to represent the actual use of exits in the neighborhood. A third approach is to establish boundaries manually as if the residents are following a set evacuation destination choice plan. The alternative to a deterministic approach is a probabilistic approach where the likelihood that a driver chooses a particular destination is a function of distance and other factors (Southworth, 1991). In this research, we opted for the closest-assignment method because it is straightforward to implement; and, as Southworth (1991) notes, it is a good assumption in small urban systems or rural evacuations—which is our focus (figure 2, step 3). A more comprehensive study would evaluate the effects of various destination-choice heuristics on evacuation times. However, all approaches must rely to a large degree on planner judgment.

3.5 Route choice

The concern in the route-choice step is modeling en route driver decisionmaking. The strategy adopted here is to take advantage of existing off-the-shelf microsimulation software. This means that route choice is handled by the commercial microsimulator, and in some cases will not be amenable to alternative modeling strategies unless source code or route-choice options are available. Thus, it is important to understand the route-choice strategy employed by an existing system to assess whether the approach is suitable for experimental purposes. In our case, Paramics™ relies on a myopic route-choice strategy; and is generally considered appropriate in urban–rural and rural evacuation analysis (Southworth, 1991). Next, we briefly describe the microsimulation route-choice method employed by Paramics™.

Vehicles in Paramics™ use a route-choice heuristic based on individual decisions at intersections. Each vehicle is assigned a destination, but a route is not assigned at the origin zone. Tables are constructed and stored at each intersection when the network is loaded. Each table holds, for a given set of vehicle types and driver familiarity settings, the travel costs to destinations indexed by exit number. Table 1 depicts an example route-choice table at a four-leg intersection, for drivers familiar with the network, using a given vehicle type when the network has six zonal destinations A–F.

Table 1. Travel costs to each destination (A–F) using links at an intersection.

Link	Destination					
	A	B	C	D	E	F
1	14	87	36	92	46	91
2	60	99	13	18	98	67
3	23	87	39	94	43	54
4	12	37	43	68	98	97

The rows of the matrix are indexed by the four departing links, and the six columns—reference the destination zones. The table entries can be used to identify which link will result in the least travel cost for reaching the given destination. For example, a vehicle with destination *D* would use the table to identify link 2 as the least-cost departing option at this intersection. Using the tables at each node, a vehicle takes the least-cost option to its destination. The decision of which link to take at an intersection is generally made two links ahead of time, so a vehicle can 'look ahead' because the travel cost values in the table above are adjusted dynamically according to congestion. That is, vehicles currently traversing the link are used to update the table. These costs are also slightly perturbed to avoid deterministic route choice. In other words, if the costs of two links leaving an intersection are close, one vehicle might take one alternative, and the next vehicle might take the other. Driver-familiarity parameters are available in Paramics™ to adjust the degree to which a driver can look ahead in making route decisions. The overall effect is traffic behavior that is near in appearance to real traffic.

4 Case study: Emigration Canyon, Utah

Emigration Canyon is a rapidly developing area immediately east of Salt Lake City, Utah. The primary vegetation in the canyon is Gamble Oak (*Quercus gambelli*), which is capable of supporting flames with a height ranging from 50 to 100 feet moving at 8 to 10 miles per hour in high winds. The main road follows the canyon floor, but our study focuses on an offshoot planned urban development called Emigration Oaks (figure 3). Emigration Oaks has been the source of an ongoing debate about the proposed construction of a second access road to improve emergency access. The controversy stems from the fact that the road will increase through-traffic and potentially compromise ecological resources such as the creek. Without the second access road, approximately 250 homes along a 6-mile long dendritic road network will rely on one exit (250 homes per network exit). For comparison purposes, the neighborhood at the origin of the Oakland – Berkeley Fire in 1991 that resulted in significant evacuation problems and 25 fatalities (OES, 1992) had approximately 300 homes and 4 exiting roads (75 homes per exiting lane)—although some exits were blocked by the fire.

In the last few years, residents in Emigration Oaks have become increasingly concerned about possible evacuation problems as new homes are constructed. In addition to the limited access, cellular phones do not work well in the canyon, and there is no installed notification system. This makes notifying the residents an equally

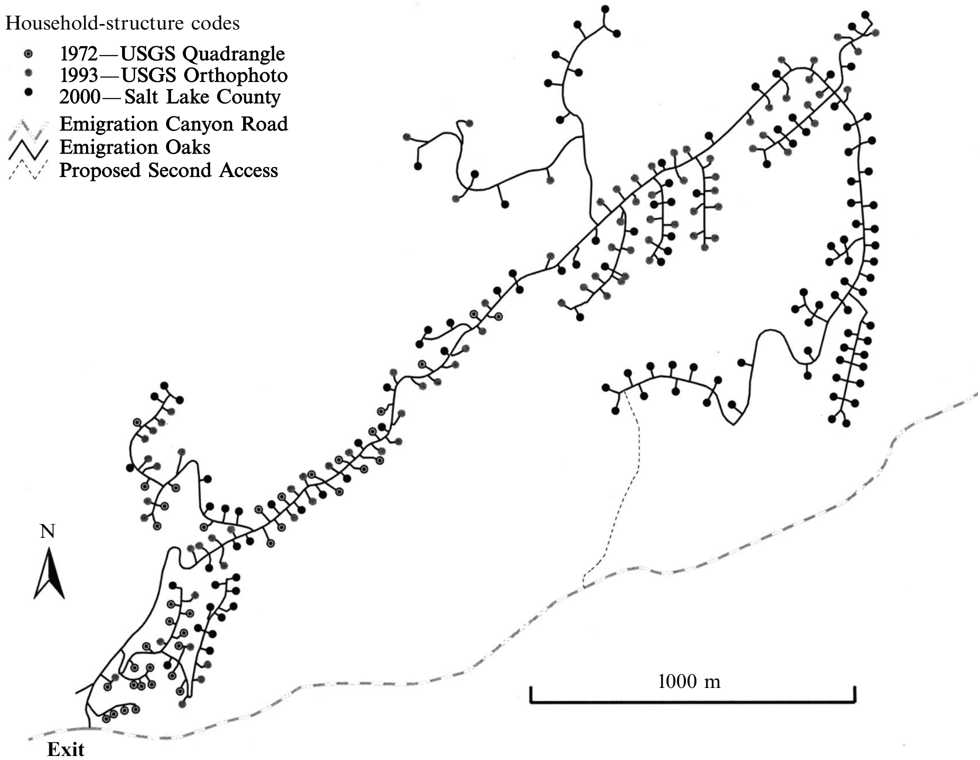

Figure 3. The Emigration Oaks neighborhood in Emigration Canyon (250 homes, 1 exit).

challenging problem. The evacuation order during a regional fire will likely be issued using a mobile siren and door-to-door notification. Currently, the community has no formal evacuation plan, but efforts are being made toward this end, of which this study is part. At this point, residents and emergency managers have many questions. For example, how long might it take to clear the neighborhood under various vehicle-use and departure-timing scenarios? What sort of traffic congestion might occur and where? What effect will the second access road have on alleviating potential congestion and reducing evacuation times?

To code the transportation network and household structures, a US Geological Survey digital orthophoto quad (DOQ) was acquired from the State of Utah Automated Geographic Reference Center. The DOQ predated much of the residential development, and we acquired a CAD drawing of the planned final development from the Salt Lake County Planning Office. Coding the road network and the 250 residential structures required 20 to 25 hours of digitizing time.

4.1 Experimental design

The principal independent variables were the mean number of evacuating vehicles per household and the mean vehicle departure time. An evacuation scenario in this context was comprised of a combination of these two variables. For example, a given scenario might be one in which few residents are at home at the time of the event (few vehicles per household) and evacuees have a low preparation time (quick response). Each scenario was run *n* times (realizations) before assessing any metrics to account for variations in the trip distribution, as well as the stochastic nature of traffic flow, in Paramics™. The dependent variables included both aggregate and disaggregate evacuation metrics. The principal aggregate metrics were mean evacuation time and mean vehicle travel time. The disaggregate metrics were the mean and standard deviation of the household-evacuation travel times. Disaggregate metrics are amenable to visualization in a map-based form to analyze spatial patterns. Each combination of mean vehicles per household and mean departure time was performed with and without the proposed second access road, which doubled the number of scenarios.

For each scenario, enough realizations were generated (OD matrix generations) to guarantee that at least 30 (*n*) trips were made from each household for the given scenario. This is necessary to ensure the statistical reliability of a household's mean and standard deviation travel time. In some scenario realizations, a house may not produce any trips because the Poisson realization did not assign it any departing vehicles (that is, no one was home or they sheltered-in-place). Thus, the lower the mean number of evacuating vehicles per household in a neighborhood, the fewer vehicles each household generates, and the more simulation runs it takes to ensure a sample of at least 30 vehicle trips from each household. For the two-exit case, destination choice was implemented by using a closest-exit assumption. Finally, aggregate clearing time of the neighborhood was defined as the time when the last vehicle reached the main canyon road using either exit.

4.2 Results

Figures 4 and 5 depict the aggregate metrics, mean evacuation time, and mean vehicle travel time, as a function of the two independent variables. Each point in the figures represents the mean of 30 simulations for the given scenario. The first independent variable, the mean number of vehicles per household, ranged from 0.5 vehicles per household to 3.0—at increments of 0.5. The second independent variable, the mean household departure time, ranged from 5 minutes (extremely urgent evacuation) to 25 minutes in 5-minute increments. Figure 4 shows that the sooner the evacuees depart, on average, the less time it will take to clear the entire neighborhood regardless

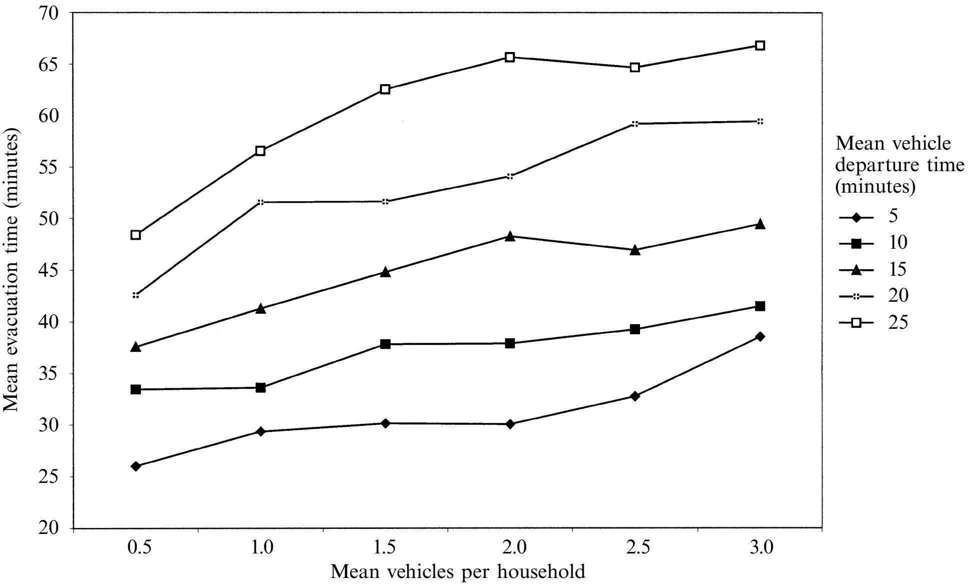

Figure 4. Mean total evacuation time for the neighborhood.

of how much traffic congestion the scenario might generate. In other words, the *y*-column order is preserved for each *x*-axis value. This means that there is no case where a more gradual departure rate might alleviate congestion and result in a quicker aggregate evacuation. Also, in general, as the mean number of vehicles per household increases, so does the evacuation time. This did not hold in all cases, and we attribute this to the sensitivity of this metric to the departure time of the last vehicle.

In general, varying the mean number of vehicles per household had less effect on the total evacuation time than does the departure rate. This is to say that the most important factor in clearing the neighborhood quickly is the mean vehicle departure rate—with vehicles per household having much less effect. It was surprising that, given an extremely short mean vehicle departure rate of 5 minutes and very low household vehicle use of 0.5 per home (almost no one at home), the average time to clear the canyon of all residents was still approximately 25 minutes. Thus, 25 minutes stands as an estimate of a best-case evacuation time for the canyon. Under a more realistic scenario of a mean departure rate of 20 minutes following warning and a mean of 2 vehicles per household, the average time to clear the canyon was nearly an hour. This is important because a large wildfire traveling at 8–10 miles per hour in high winds could consume this community in 30 minutes. Thus, sheltering-in-place would be advised unless emergency managers have at least an hour to conduct the evacuation. If there is not enough time, evacuees stand the chance of being overcome by the fire in traffic, and vehicles provide much less protection from a large-scale fire than a structure.

Figure 5 (see over) depicts the mean vehicle travel time for the simulation scenarios. This plot shows that the mean number of vehicles per home has little effect if the mean household departure rate is relatively slow (that is, 20 or 25 minutes) but has a very significant effect if the mean departure rate is very quick (for example, 5 or 10 minutes). In short, although the total time to evacuate the neighborhood was much less with a quicker departure rate (figure 4), the time that evacuees spent in their cars because of congestion was much greater (figure 5). This was not evident in the total-evacuation-time plots. This is important because the total-evacuation-time metric alone would imply that the evacuation scenario was quicker and, thus, safer, but the

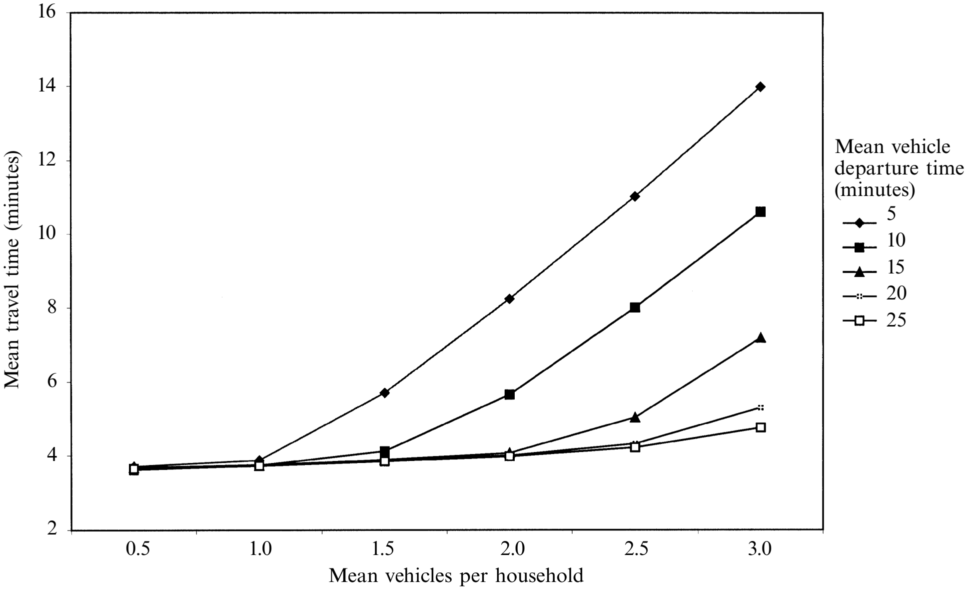

Figure 5. Mean vehicle evacuation travel time.

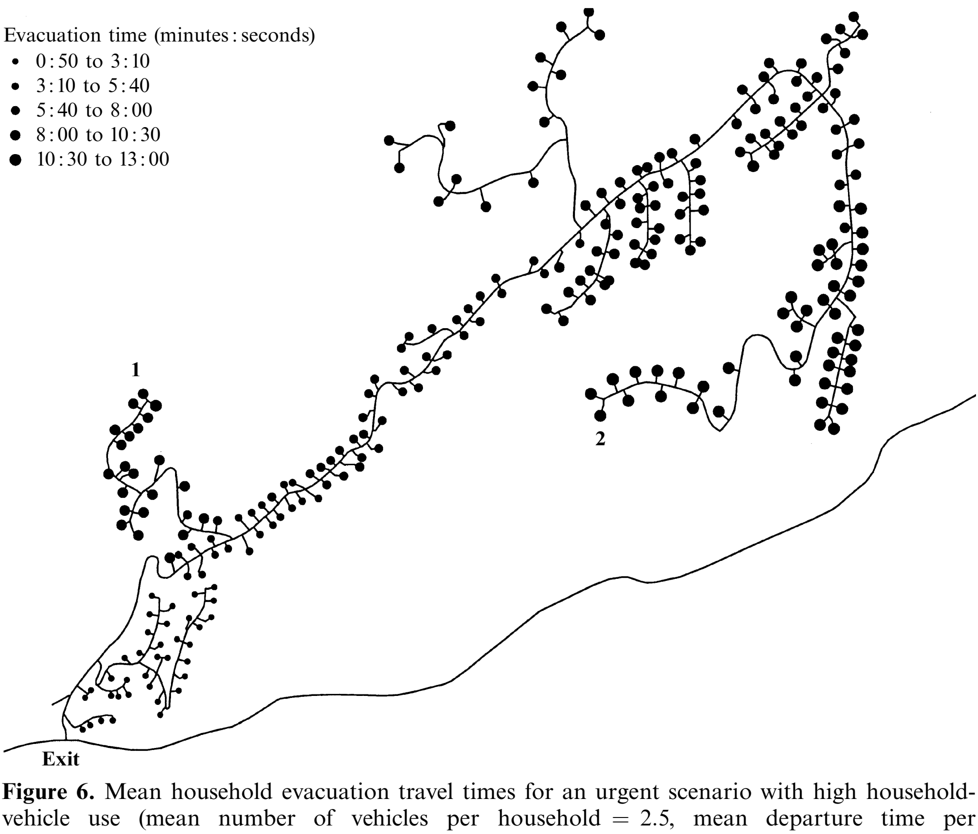

Figure 6. Mean household evacuation travel times for an urgent scenario with high household-vehicle use (mean number of vehicles per household = 2.5, mean departure time per vehicle = 10 minutes).

mean vehicle travel time is much higher, leading to a greater aggregate vehicle exposure to wildfire.

The disaggregate metrics were calculated for each household and mapped using GIS. GIS has increasingly been applied in evacuation analysis (Cova and Church, 1997; de Silva and Eglese, 2000; Gatrell and Vincent, 1991). Figure 6 depicts the mean evacuation household travel times under the assumption that the mean number of vehicles originating from each household (λ_1) was 2.5 and the mean departure time per vehicle following an evacuation order (λ_2) was 10 minutes. This scenario can be characterized as an urgent evacuation where evacuees leave almost immediately following warning (or recognition of a threat), with high vehicle-use per household similar to that of the 1991 Oakland Fire evacuation (OES, 1992). For this scenario the map shows that households in the back of the canyon can expect a mean evacuation travel time approximately 10 minutes longer than households close to the exit. Although this general pattern is intuitive for a network this simple, the method allows an analyst to quantify the difference in mean evacuation times between households in the back of the canyon from those in the front. Also, there are pockets where the evacuation time is not a linear function of the distance to the exit. For example, a household at location 1 in figure 6 is not very far from the exit but must merge with traffic that may be backed up on the main road. Households in this neighborhood have a much greater evacuation travel time than expected. Also, the map depicts mean household evacuation travel times, and in one case the evacuation travel time for a household at location 2 was 21 minutes. This is three to four times as long as it would take to leave the neighborhood from the same home if the network were empty of traffic. Figure 7 depicts the standard deviation in household evacuation

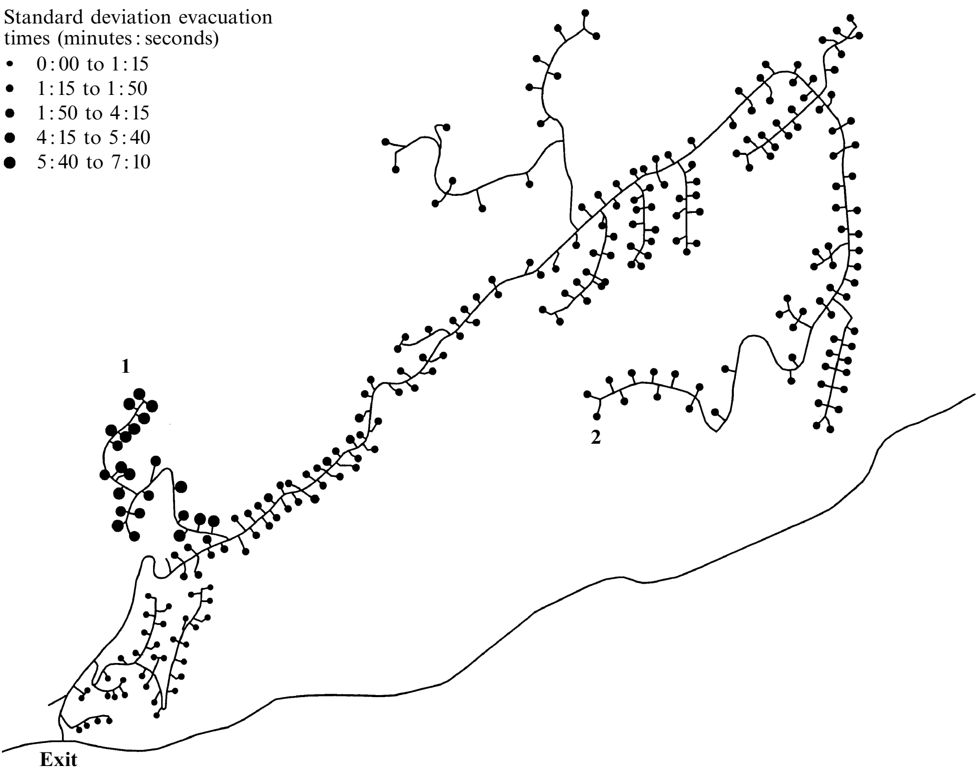

Figure 7. Standard deviation in household evacuation travel times for the same scenario as figure 6.

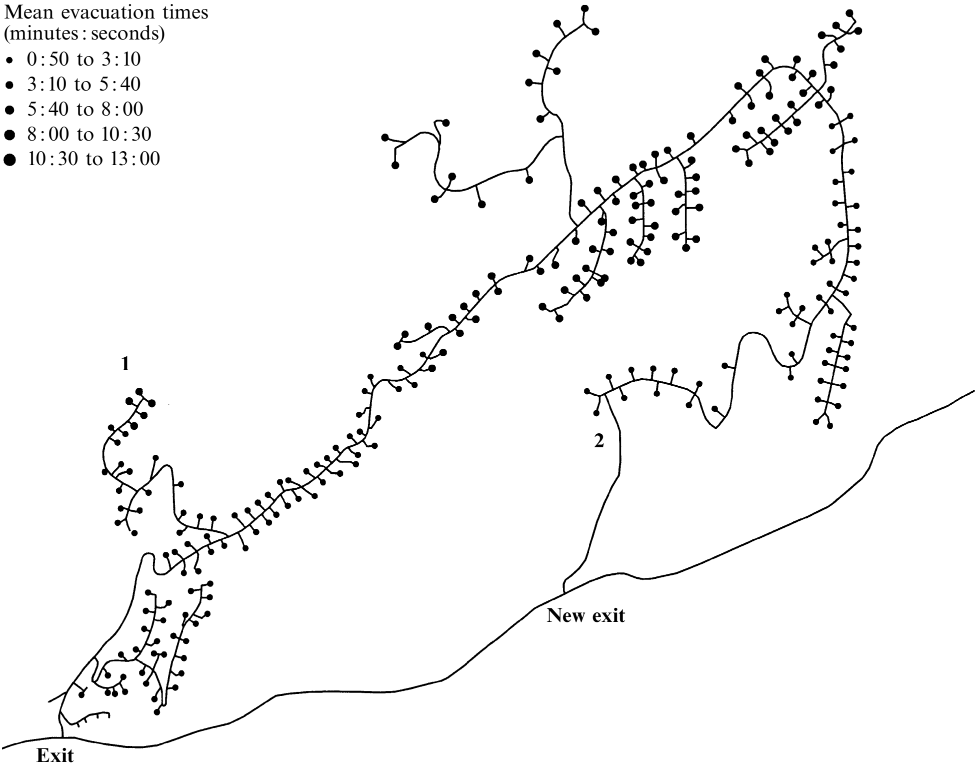

Figure 8. Mean household evacuation travel times—for an urgent scenario with high household-vehicle use—including the second access road.

times within the neighborhood for the same scenario. Note that, for most homes, the standard deviation in household evacuation travel times for this scenario is about 2 to 4 minutes.

Figure 8 depicts the mean household evacuation travel times for the same scenario ($\lambda_1 = 2.5$ minutes, $\lambda_2 = 10$ minutes) but with the addition of the proposed second access road. This map shows that homes in the back of the canyon will have a substantially lower mean evacuation travel time than in the one-exit case. After the construction of the second road, homes equidistant from each exit will have the highest mean evacuation travel times. Figure 9 shows the standard deviation in household evacuation travel time for the neighborhood given the second access road. The standard deviation in these travel times has decreased substantially for the neighborhood, on the whole, given the second access road. This implies that for this scenario all homes will have more consistent travel times with the second access road. This is because the second access road alleviates much of the traffic congestion associated with trying to get everyone out using a single exit. Viewed another way, two exits reduce the average number of homes per exit from 250 to 125.

Figures 10 and 11 (see over) show the effect of the new road on the distribution of household evacuation times for a house at the current exit (lower canyon) and one at the back of the development (upper canyon). The scenario in this case was a mean number of vehicles per household of 2.5 and a mean departure time of 10 minutes. It is clear from these figures that the shift (decrease) in the distribution of household evacuation times under an urgent evacuation scenario is much greater for a home in the back of the canyon than one at the canyon entrance, when the second access road is taken into account. The occasional higher evacuation time for a household at the entrance of the development occurs when a household delays departure and encounters a prolonged queue on the main road.

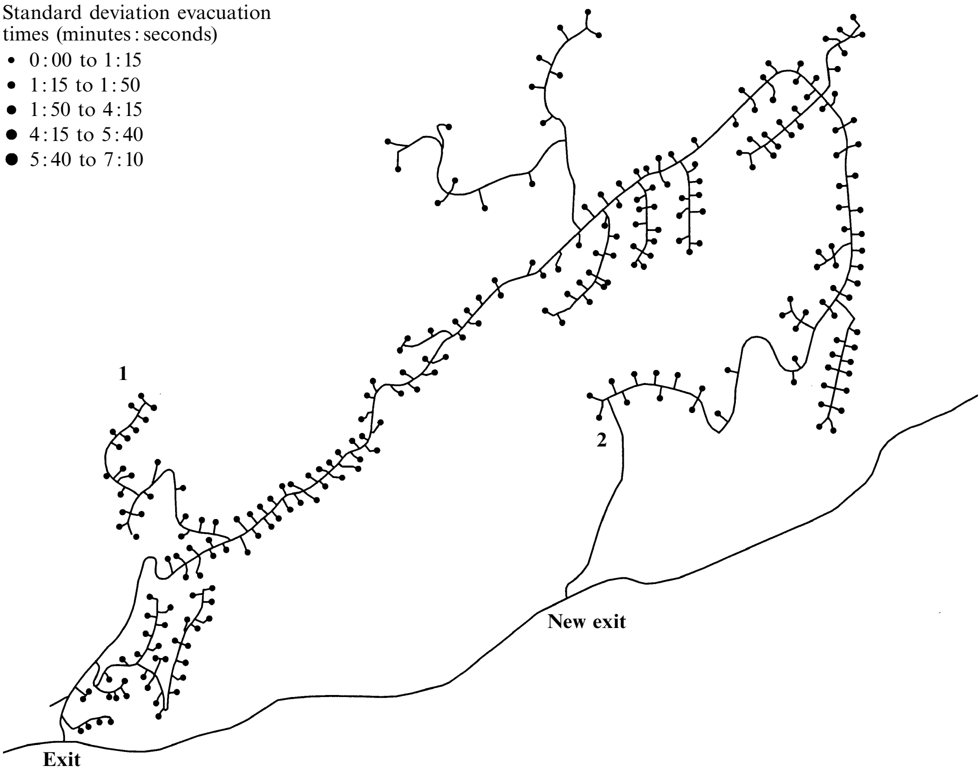

Figure 9. Standard deviation in household evacuation travel times with the second access road, for the same scenario as figure 8.

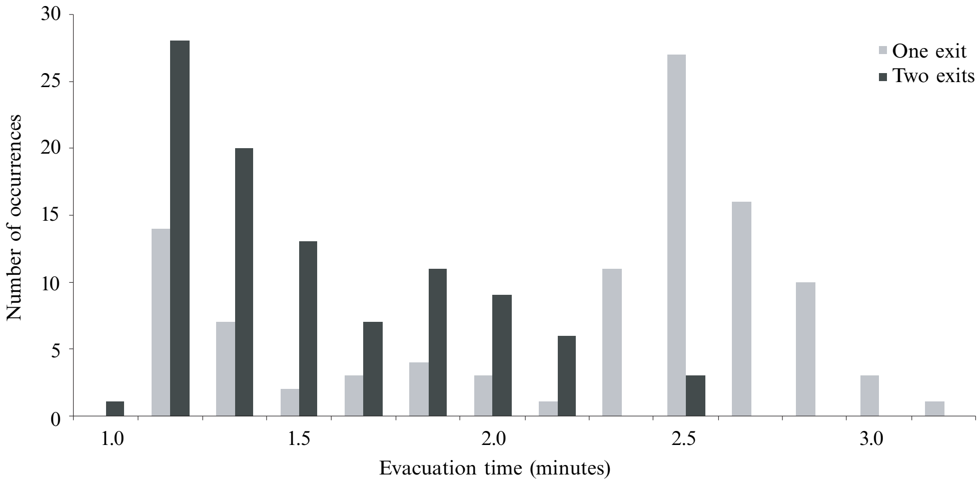

Figure 10. The distribution of evacuation travel times for a household at the entrance to the development (lower canyon).

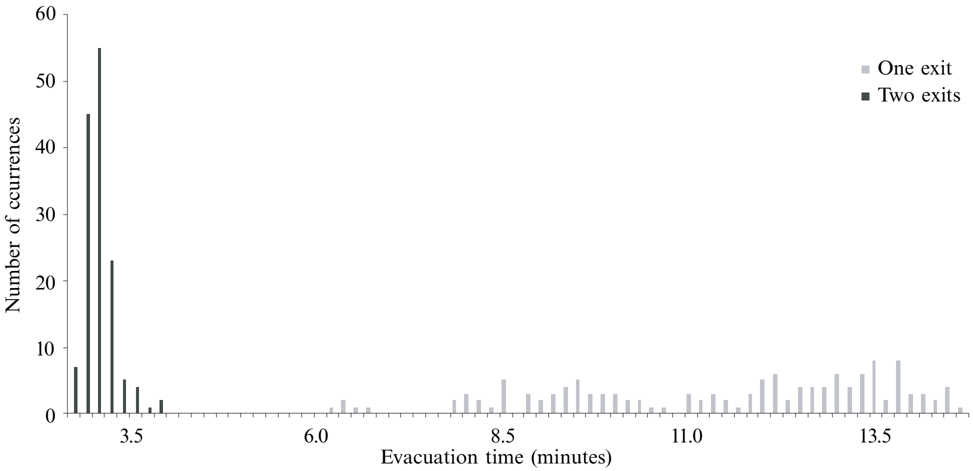

Figure 11. The distribution of evacuation travel times for a household in the back of the development (upper canyon).

5 Discussion and limitations

The results in the prior section demonstrate that shorter household preparation times and, thus, departure times always result in a quicker aggregate evacuation for the study area. However, very urgent evacuations can result in significant traffic congestion and a sharp increase in mean vehicle travel times, particularly if there are a lot of people at home during the evacuation and household vehicle use is relatively high. This is very important in assessing human vulnerability (Cutter, 1996) because vehicles provide much less protection than a structure during a wildfire. Therefore, a scenario where evacuees sit in dense traffic for longer periods increases aggregate wildfire exposure. Although it might take longer to evacuate the entire neighborhood with a slightly slower departure rate, evacuees would be able to drive out in roughly the same time they would be accustomed to under normal conditions. This reduces exposure at the same time that it helps alleviate panic, which is very rare in evacuations, but can occur in cases of limited egress (Quarantelli, 1980)—a significant concern in this neighborhood.

Disaggregate evacuation modeling and mapping at the household level has not been explored in regional evacuation research. One of the main benefits of this level of geographic detail is that an analyst can examine evacuation scenarios, as well as the effects of various evacuation improvement strategies, in a spatial light (for example, construction of a second access road). By mapping the results of repeated evacuation simulations at the household level, we were able to map the relative evacuation vulnerability of households within a neighborhood under various 'what if?' scenarios. This allows questions to be posed about who might be trapped in a bottleneck during an urgent evacuation rather than simply the locations of the bottlenecks in an area to be evacuated. Although the network in our case study is topologically simple, the method could be applied to a more complex network that may exhibit nonlinear effects in evacuation travel times because of intersection spillovers and queues that restrict turns.

The statistical simulation approach to evaluating neighborhood evacuation characteristics is novel and has a number of strengths. Simulating vehicle use and departure timing distributions across a range of evacuation scenarios leads to more general results than striving to characterize an exact distribution of residents, vehicle ownership, and preparation time for a specific point in time. Neighborhoods change over many years, and it is more important to get a general sense of the outcome of a range of scenarios than to predict with any accuracy the outcome of one. It is also less expensive to perform statistical simulations of the dominant characteristics that affect an evacuation than to collect data on individual households within a neighborhood. Furthermore, statistical simulation protects privacy, a significant issue at the most detailed level of analysis.

One of the main advantages of using off-the-shelf microsimulation software is leveraging visualization capabilities that would not otherwise be accessible except to software engineers. The static dot maps in figures 6 to 9 reveal the variation in household evacuation times within an area, but dynamic visualization is more effective in conveying what traffic, in an evacuation scenario, might look like. Paramics™ and many other contemporary microsimulators have very sophisticated visualization capabilities. This can be invaluable in getting emergency managers, urban planners, and residents to acknowledge potential evacuation problems and to consider increasing the amount of community-based emergency planning.

The main limitation of the proposed method of using off-the-shelf microsimulation software is the inability to control fundamental aspects of the simulation model including the route-choice, car-following, and lane-changing models. Some vendors sell access to these models via source code, for a much higher price, but we opted to use the 'canned' version for this initial research project to keep the costs within reach for homeowners' associations, local emergency planners, and transportation consultants. Another alternative is to mount a software development campaign, but this creates a significant barrier-to-entry in getting microsimulation tools used by the parties who need this technology the most.

Microsimulation is very valuable but has its limitations. It is important to note that there are many levels of validation required that are especially out of reach for evacuation researchers. For example, there are no available data to aid in calibrating a car-following model during an emergency evacuation. The models used in this research were calibrated using data from driving behavior under normal conditions. The actual car-following behavior of evacuees in a fire might be very different. Also, this behavior would vary depending on the urgency of the evacuation and many other factors. One approach to this issue would be to test the sensitivity of the results in an evacuation study by recalibrating the component models in a microsimulator. If the aggregate results of many simulations were not very sensitive to changes or recalibration of the underlying car-following, lane-changing, and route-choice models, the results would gain better acceptance in emergency planning. If the results are very sensitive to these models and their parameters, then the problem becomes one of gathering relevant data on route-choice, car-following, and lane-changing behavior during emergency evacuations. This challenge is complicated by the fact that this behavior would vary by hazard type, urgency, evacuation scale, and many other factors.

6 Conclusion

We have presented a preliminary method for using an off-the-shelf microscopic traffic simulator to design and test evacuation plans for neighborhoods in fire-prone wildlands. A central goal was to develop a methodology that takes advantage of the tremendous value of simulation in evacuation planning without mounting a large-scale software engineering campaign. Microsimulation is the finest level of geographic detail in transportation modeling and thus represents the most appropriate and telling level at which to simulate neighborhood-scale evacuations. The strategy of using a commercial simulation system requires a custom evacuation-scenario generator, so the approach is not completely off-the-shelf.

Rapid urbanization in historically fire-prone regions is precipitating the need for more sophisticated approaches to emergency planning. Many of these areas were not originally designed to support the dense developments that are emerging. Residents need to increase their awareness; they should consider simple questions such as how an evacuation order will be issued and what contingency plans can be put in place. Twenty-five years of evacuation research for other hazards and recent computational advances can help improve the amount of evacuation planning in fire-prone areas.

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