Public Safety in the Urban–Wildland Interface: Should Fire-Prone Communities Have a Maximum Occupancy?

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Abstract: Residential development in fire-prone wildlands is a growing problem for land-use and emergency planners. In many areas housing is increasing without commensurate improvement in the primary road network. This compromises public safety, as minimum evacuation times are climbing in tandem with vegetation and structural fuels. Current evacuation codes for fire-prone communities require a minimum number of exits regardless of the number of households. This is not as sophisticated as building egress codes which link the maximum occupancy in an enclosed space with the required number, capacity, and arrangement of exits. This paper applies concepts from building codes to fire-prone areas to highlight limitations in existing community egress systems. Preliminary recommendations for improved community evacuation codes are also presented.

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Introduction

Residential development in fire-prone wildlands is a growing problem for land-use and emergency planners. Easy access to recreation, panoramic scenery, and lower property costs are enticing people to build homes in areas that would otherwise be considered wildlands. This development steadily increased in the United States from the mid 1940s, although local growth rates varied according to economic, demographic, and amenity factors (Davis 1990). At the same time, decades of fire suppression has resulted in a record abundance of fuel in and around many developments (Pyne 1997). This led the Forest Service to recently identify thousands of communities near federal lands as "at risk" to large conflagrations (U.S. Forest Service 2001).

The area where residential structures and fire-prone wildlands intermix is called the urban–wildland interface or wildland–urban interface (Cortner et al. 1990; Ewert 1993; Fried et al. 1999). In much of this area, homes are being added as the primary road network remains nearly unchanged. This is not surprising, as interface communities are often nestled in a topographic context that prohibits the construction of more than a few exiting roads. It is generally too expensive to build a road into a canyon, or onto a hillside, from every direction. Also, residents prefer less access because it reduces nonresident traffic. A common road-network addition is a culdesac that branches off an existing road to add more homes.

Incremental planning in fire-prone areas has a number of adverse impacts (e.g., wildfire effects, open space decline), but the focus in this paper is evacuation egress. "Egress" is defined as a means of exiting, and it can be viewed as accessibility out of an area in an evacuation. When a wildfire threatens a community, residents generally evacuate in a condensed time either voluntarily or by order. In past urban wildfires with short warning time, limited egress has proven to be a problem ("Charing cross bottleneck was a big killer" 1991; Office of Emergency Services 1992). Sheltering-in-place is a competitive protective action when there is not enough time to escape or a homeowner wishes to remain behind to protect property, but it is much less tested than evacuation in wildfires. However given increasing housing densities in fire-prone areas without commensurate improvements in the primary road network, the case for sheltering-in-place is gaining ground. This leads to an important question: "How many households is too many?" Or alternatively, "What is the maximum occupancy of a fire-prone community?"

Maximum occupancies are well defined and enforced in building safety, and it is common to see the maximum number of people allowed in an assembly hall posted clearly on the wall. This concept has not been applied to community development in fire-prone areas, although the broader terms of "access" and "egress" appear in contemporary codes (National Fire Protection Association 2002; International Fire Codes Institute 2003). Egress standards are currently defined in terms of minimum exit-road widths, or a minimum number of exits, without regard to how many people might rely on the exits. This is less sophisticated than building egress codes which link the maximum expected occupancy of an enclosed space with the required number, capacity, and arrangement of exits (Coté and Harrington 2003). Building egress codes have been hard earned over nearly a century of research, refinement, and loss of life (Richardson 2003).

The purpose of this paper is to apply egress concepts drawn from building fire safety to community egress in fire-prone areas. Although these concepts and codes were originally developed for

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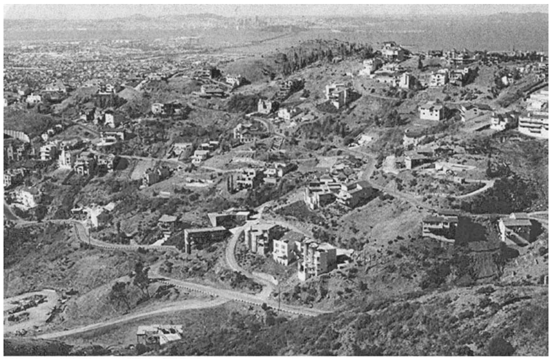
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Fig. 1. Looking west at narrow roads surrounding 1991 Oakland–Berkeley fire origin

small-scale, indoor spaces, they have potential utility in fire-prone communities. The first section reviews background on the growing urban–wildland egress problem. The next section reviews basic means-of-egress concepts defined in building codes. A method is presented to compare community egress systems based on concepts and standards from building safety that includes preliminary recommendations for new community egress codes. The paper concludes with a discussion of improvements that can be made to community egress systems.

Growing Urban–Wildland Egress Problem

Representative Communities

There are literally thousands of fire-prone communities in the West with a static road network and steadily increasing housing stock. This section briefly examines 2 representative examples. To date, the dominant focus of planners and residents in these communities has been structure protection with much less attention focused on egress issues. This may be due to the fact that property loss in wildfires is much more common than loss of life. Poor egress in interface communities is generally the result of narrow roads, irregular intersections, and few exits. In most of these areas the likelihood of an extreme fire is increasing in tandem with the vulnerability created by steadily climbing minimum evacuation times. Without fire to rejuvenate the ecological system, vegetation advances toward its fire recurrence interval as home construction adds additional fuel, residents, and vulnerability (Rodrigue 1993; Radke 1995; Cohen 2000; Cutter 2003).

Buckingham, Oakland, Calif.
Fig. 1 shows the neighborhood at the origin of the 1991 Oakland–Berkeley Fire 4 years after the fire. Without vegetation to obscure the view, it is clear that the road network is a maze of narrow streets. The photo was taken during the initial rebuilding process when hazard abatement procedures were being considered. At the time of the fire there were 337 homes in this neighborhood with four exits. The fire blocked the two primary exits in its first 1/2 h (Tunnel Road east and west), leaving the remaining residents two narrow, uphill exits. Most of these residents chose to leave on Charing Cross Road, a 13 ft wide afterthought that was not designed to handle this volume. Many of the fatalities (Fig. 2) were residents caught in or near their cars at the end of a traffic queue when the fire passed.

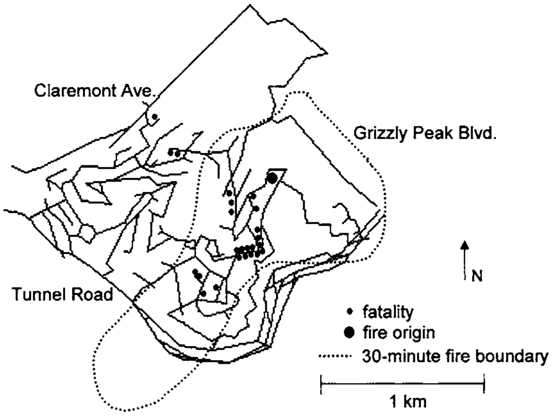

Fig. 2. Fatalities, fire origin, and approximate 30 min fire boundary in 1991 Oakland–Berkeley fire

Mission Canyon, Santa Barbara, Calif.
Mission Canyon is a community just northwest of downtown Santa Barbara, Calif. that is adjacent to a chaparral ecosystem. The basic road network geometry was established in the 1930s and has changed little since (Fig. 3). In 1938 there were four households in the upper canyon using two exits (shown in white), but by 1990 there were more than 400 households relying on the same two exits. All households north the two exits (above) must use one of these two exits to leave, but households south of these exits (below) have more exiting options. The area was originally grasslands, but today it contains a significant amount of flammable, non-native vegetation (e.g., Eucalyptus) intermixed with wood structures. Prior evacuation studies have concluded that


(Date: 1938)

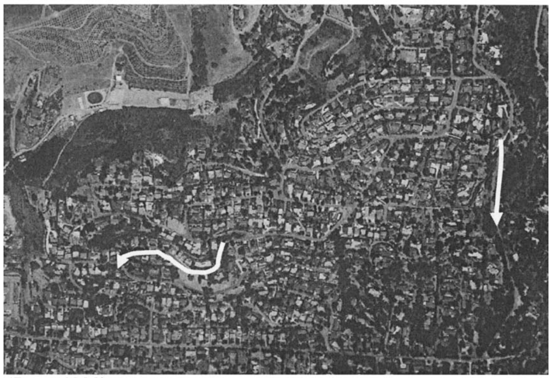
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Fig. 3. Mission Canyon in 1938 (4 homes, 2 exits in white) and 1990 (400+homes, same 2 exits in white)

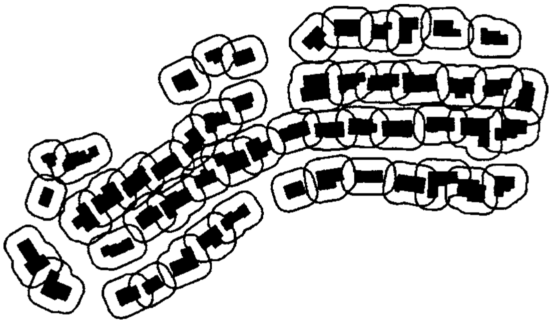

Fig. 4. Overlapping home ignition zones in fire-prone neighborhood (30 ft defensible-space buffer)

clearing upper Mission Canyon in the event of a wildfire would be relatively difficult (Cova and Church 1997; Law 1997; Church and Sexton 2002).

Protective Actions in Wildfires

Protective actions in a wildfire differ from a building fire in that sheltering-in-place in a structure, water body or safe zone (e.g., parking lot or golf course) is possible. This distinction is important because it means that evacuating a community may not be the best protective action in some cases (Krusel and Petris 1992). However, these cases can be difficult to assess during an event. Given more than enough time to evacuate, this is generally the best option for protecting life. If there is little to no time to evacuate, sheltering-in-place is likely the best option because evacuees risk being overcome by the fire in transit with much less protection than offered by a shelter. In the middle lies a gray area where evacuating may be the best option. As strongly as many experts feel about this issue (Wilson and Ferguson 1984; Decker 1995; Packman 1995; Oaks 2000), the uncertainty associated with a scenario can be too great to definitively state the best protective action. It depends on the quality of a shelter, road network geometry, fire intensity, wind speed and direction, visibility, travel demand, water availability and many other factors that are difficult to assess and synthesize under pressure.

A key hurdle in advising people to shelter-in-place in their homes is that not all structures are defensible. A defensible structure offers its occupants sufficient protection to withstand a passing wildfire. This is embodied in the concept of a "home ignition zone," or the area immediately surrounding a structure where ignition is feasible (Cohen 2000). Structures are not defensible if their ignition zones contain substantial fuel, adjacent ignition zones overlap, or both. If ignition zones overlap, then creating a defensible space would require homeowners to clear their neighbors' vegetation (Fig. 4). In other words, the wood structures in this figure are not defensible and an ignition chain reaction is possible. In cases where structures are sufficiently spaced, vegetation and other fuel within the home ignition zone can also render a structure indefensible. This is common because residents in these areas generally embrace trees and the amenities they provide. In dense, residential areas with wood structures, overlapping ignition zones and few viable shelters or safe zones, providing residents with sufficient egress is a critical issue.

Building Egress Codes

Early History

The concept of a maximum occupancy originated in an area of study called "means of egress." A means-of-egress is defined as, "… a continuous and unobstructed way of travel from any point in a building or structure to a public way consisting of three distinct parts: the exit access, exit, and exit discharge (Coté and Harrington 2003, p. 99)." Means-of-egress studies and associated codes incorporate all aspects of evacuating a building from stairway capacities and known crowd behavior under varying density to the proper illumination of exit signs. In setting standards for an enclosed space, an analyst can either examine the number, capacity, and arrangement of exits and calculate a maximum occupancy or, alternatively, examine the expected maximum occupancy and construct the required minimum egress. In either case, state-of-the-art egress standards and methods link occupancy to the number, capacity, and arrangement of exits.

Building egress standards can be traced to an occupancy–density study conducted by Rudolph Miller around 1910 in Manhattan (Nelson 2003). Miller's objective was to tabulate the density of workers per floor in 500 workshops and factories. This resulted in a wide range of densities from 19 to 500 ft^2 per person with the average for all floors at 107 ft^2 per person. In 1913 the National Fire Protection Association established the "Committee on Safety to Life" to study egress and formulate standards with a particular focus on advancing the principle of apportioning means-of-egress to the number of occupants in a building. One of the first egress standards was set by the New York Department of Labor in 1914 which limited the occupancy on each floor to 14 persons for every 22 in. of stair width. In 1935 the National Bureau of Standards published, "Design and construction of building exits," an important work in the history of building egress codes. One finding was that egress codes varied widely in regards to how many exits are needed, where they should be, and their required characteristics. Five different methods were discovered for determining required exits widths, and the report concluded with a new method that required stairwells have sufficient capacity to handle an evacuation of the most populated floor, the current method used in North American codes (Nelson 2003).

Modern Building Egress Codes

Contemporary methods for calculating a maximum occupancy for a building, floor, or meeting room are simple, but the number of possible building space uses and exit types is extensive (Coté and Harrington 2003). For example, the 2003 Life Safety Code© includes detailed exit-capacity adjustments (in persons) for stairways based on the presence, size and positioning of handrails, as well as ramp-capacity adjustments that incorporate ascending or descending slope (National Fire Protection Association 2003). In general, occupant load and building geometry determine the required number, location, and capacity of exits. An important aspect of a means-of-egress is that, "it is only as good as its most constricting component." Furthermore, a good design principle for an egress system is balance among exits because one or more might be lost in a fire.

A central concept in determining building egress is that of an occupant load factor. Occupant load factors are upper limits on density that vary with the use of the space. In other words, the nature of the use of a space determines its allowable density. For example, a "residential apartment building use" is allowed a gross

Table 1. Occupant Load Factors from Life Safety Code®[a]

Use	m^2 per person	ft^2 per person
Assembly use		
Concentrated, without fixed seating	0.65 net	7 net
Less concentrated, without fixed seating	1.4 net	15 net
Educational use		
Classrooms	1.9 net	20 net
Shops, laboratories, vocational rooms	4.6 net	50 net
Day Care use	3.3 net	35 net
Residential use		
Hotels and dorms	18.6 gross	200 gross
Apartment buildings	18.6 gross	200 gross
Industrial use		
General and high hazard	9.3 gross	100 gross

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Table 2. Capacity Factors from Life Safety Code®[a]

	Stairwells (width per person)		Level components and ramps (width per person)	
Area	(mm)	(in.)	(mm)	(in.)
Board and care	10	0.4	5	0.2
Board and care, sprinklered	7.6	0.3	5	0.2
Health care, nonsprinklered	15	0.6	13	0.5
High hazard contents	18	0.7	10	0.4
All others	7.6	0.3	5	0.2

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density of 200 ft^2 per person while a "concentrated assembly (without fixed seating) use" allows a much higher net density of 7 ft^2 per person (Table 1). "Net" density refers to rooms, and "gross" density refers to floors or an entire building. Defining the maximum density for an indoor space based on its use is valuable because it bypasses the need to conduct an empirical occupancy study for every building. Occupant load factors derived from the table are then used in conjunction with the area of a meeting room or floor to design the means-of-egress system and also to trigger provisions like the need for a sprinkler system.

The required number, capacity, and arrangement of exits are determined using the occupancy load, the use of the space, and simple geometric rules. The required number of exits for each story is determined with a step function based on the use of the space and the occupancy load. Stories with less than 500 occupants require a minimum of two exits, those with between 500 and 1,000 require at least three exits, and more than 1,000 occupants requires at least four. A capacity-factor table specifies the minimum width for stairways and horizontal exits based on the use of the space. Most indoor activities require stairwells to have 0.3 in. of width for each person on the floor with the greatest number of occupants, but areas with hazardous contents require 0.7 in. per person, a much greater capacity (Table 2).

The linear relationship between the maximum number of occupants and exit widths was originally proposed by Pauls (1974) and widely adopted in North America. For example, a stairwell 44 in. wide has a capacity of (44 in./0.3 in. per person) = 147 persons for most floor uses (Table 2). If the occupancy of the floor is expected to exceed 147, then the stairwell capacity is insufficient and the maximum occupancy must be lowered or the stairwell egress capacity must be increased. The arrangement of the exits is determined using a simple geometric rule called the "one-half diagonal rule" that states that two exits shall not be located closer than one half the length of the maximum diagonal dimension of the area served (Fig. 5). This requires exits to be sufficiently remote so as to prevent a fire from blocking more than one. For example, if the maximum diagonal distance across a room with two exits is 60 ft., then the exits must be at least 30 ft. apart. Finally, an arbitrary distance cutoff is used to ensure that no building occupant is too far from an exit.

Community Egress Codes

Despite the tremendous fire hazard in many interface communities, few studies have been done on residential densities in fire-prone areas (Theobald 2001; Schmidt et al. 2002; Cova et al. 2004). There is certainly nothing as complete as Nelson's (2003) longitudinal study of Washington D.C. federal building occupancy densities from 1927 to 1969. Second, there are no road-capacity studies for fire-prone communities on par with Pauls' (1974) extensive research on doorway and stairwell capacities. Roads in interface communities can be very narrow, intersect at odd angles, and vary in width. The capacity of this type of road network in dense smoke is difficult to quantify but would likely be very low. Third, existing egress codes for fire-prone communities are very general and do not provide the elegant methods for comparing and testing egress systems found in the building safety codes. The following codes serve as representative examples of contemporary community egress codes (National Fire Protection Association 2002):

1. 5.1.2 Roads shall be designed and constructed to allow evacuation simultaneously with emergency response vehicles.
2. 5.1.3 Roads shall be not less than 6.1 m (20 ft) of unobstructed width with a 4.1 m (13.5 ft) vertical clearance.

While the intent of the codes is clear, they do not link the occupant load with the required minimum number, capacity, and arrangement of exits. Current codes also tend to overlook the furthest distance a household is from its closest exit as well as vulnerability owed to dense fuel along the exits. In general, standards for interface community access focus more on maintaining fire-fighter ingress than resident egress (International Fire Code Institute 2003). Given that it is easy to find growing interface communities with miles of tangled narrow roads, many residents, and few exits, improved egress codes are a growing need.

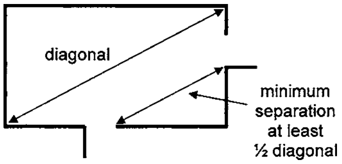


Fig. 5. One-half diagonal rule in building egress codes ensures that exits are sufficiently remote from one another

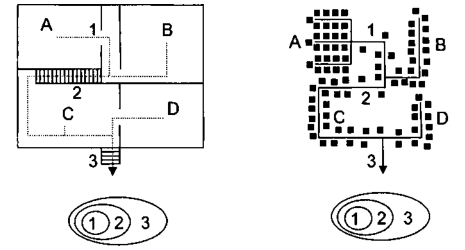
Differences in Community and Building Means-of-Egress Systems

Although there are many similarities between building and community egress systems, there are also significant differences. First, notification systems vary across communities (Sorensen 2000), whereas warning is generally issued with a siren, flashing lights, and a public address system in a building. For this reason, warning is nearly instantaneous and uniform in modern buildings, where it can take minutes to hours to warn all residents in a community, depending on the area, population density, and notification modes (e.g., reverse 911 or door to door). This has egress implications because the most constraining component in a community's egress system may simply be information, a vital yet scarce resource in most emergencies (Alexander 2002). However, slow notification can have benefits (if it is not too slow), as it can dampen household departure rates which reduces the likelihood of a traffic jam from a sudden burst of travel demand in a wildfire. Sudden bursts of travel demand are rare in evacuations but can lead to extreme stress when egress is constricted (Quarantelli et al. 1980; Chertkoff and Kushigian 1999), as in the case of the 1991 Oakland Fire.

Emergency manager behavior, population mobility, and human response are also important elements of an egress system. Emergency manager behavior is important because an incident commander generally decides who should evacuate and when they should leave (Lindell and Perry 1992). Mobility in a community context refers to the proportion of available drivers and vehicles in a population, whereas building evacuees are generally on foot or in a wheelchair. A glaring example of this constricting factor exists in many developing countries where mobility can be so low as to render regional evacuation infeasible (e.g., cyclones in Bangladesh). However, mobility can also cause problems if a highly mobile population leaves in a condensed amount of time and overloads an egress system.

Human response is also important, and evacuee behavior can be very different in wildfires than buildings. In building fires, occupants generally proceed directly out of the building or facility given sufficient egress, knowledge of the floor plan, and clear directions. In wildfires, there are family members, pets, horses, and livestock to evacuate, property to protect, and sheltering-in-place is always an option. These factors can dampen sudden spikes in egress demand but are more often a drawback in clearing an area quickly. In a building evacuation, the "walk, don't run" rule is used to dampen demand spikes and to reduce the likelihood of panic. Unfortunately, there are very few studies on wildfire evacuation behavior, but analogies can be drawn to evacuation behavior in other hazards that have been studied in greater depth (Perry 1985; Mileti and Sorensen 1990; Zelinsky and Kosinski 1991; Vogt and Sorensen 1992; Drabek 1996; Dow and Cutter 2002).

Perhaps the most obvious difference between building and community egress systems is the engineered components. Buildings have stairways, elevators, escalators, ramps, doors, handrails, and hallways, where communities have driveways, roads, intersections, stop signs, and traffic signals. Although these differences are significant, general concepts drawn from building codes may have value in a community context. One approach is to modify and extend building egress codes to achieve codes of comparable quality for communities.



Building evacuation plan with nested, constricting components

(a)

Community evacuation plan with nested, constricting components

(b)

Fig. 6. Comparing nested, constricting components in building egress system with similar ones in community

What is a Community "Exit"?

An initial geographic problem in designing codes for communities might be deemed "the community exit problem." In a building context, exits have a component referred to as the discharge that leads people to a public way outside the building. In other words, safety is defined as "outside" the room or building. Inside and outside are ambiguous concepts in a community context and difficult to specify. If a predefined emergency planning zone (EPZ) is centered on a known hazard like a nuclear power plant or chemical stockpile site (Sorensen et al. 1992), then safety can be defined as outside the EPZ. In wildfires the zone to evacuate is defined on-the-fly at the time of the event and may expand in any direction as the fire progresses. For this reason, setting egress codes in advance that relate occupancy load to exit capacities requires searching the set of all potential evacuation zones.

An insight drawn from building studies can aid in addressing this problem. As noted, "A means of egress is only as good as its most constricting component." In a road-network context, this is referred to as a "bottleneck." A bottleneck can be used to define the inside and outside of a community, as traversing one is similar to clearing an exit discharge in a building (Cova and Church 1997). In other words, once a vehicle has successfully traversed a bottleneck, it is no longer a constraint on travel. This means that the community exit problem can be viewed as a search for potential roadway bottlenecks. In a sense, this is the approach adopted by interface codes that require at least two exits, as this precipitates a search for communities with only one exit, a potential bottleneck.

One problem with requiring that communities have more than one exit is that a bottleneck can still exist. In short, more than one exit does not ensure that an egress system is sufficient. It depends on the number of occupants, the arrangement and capacity of the exits, and the concentration of travel demand in space and time. Adding to this problem, bottlenecks can be nested in communities as they can in buildings. Fig. 6 compares nested constricting components in a building egress system with similar constricting components in a community context. Neighborhood A is nested within bottlenecks 1, 2, and 3. A building's outer wall is the point at which nested constraining components terminate, but in a community context, components nest from a street segment to a neighborhood, city, region, and so on. This can be addressed by terminating the search for egress bottlenecks when the area constrained is larger than that likely to be evacuated in a wildfire.

Table 3. Proposed Load Factors for Interface Communities

Use	Road length per household (m)	Road length per vehicle (m)
Residential[a]		
Low wildfire hazard	12.5	6.3
Moderate wildfire hazard	16.7	8.3
High+ wildfire hazard	20.0	10.0
Residential and tourism[b]		
Low wildfire hazard	12.5	4.2
Moderate wildfire hazard	16.7	5.6
High+ wildfire hazard	20.0	6.7

[a] 2 vehicles per household.

[b] 3 vehicles per household.

Table 5. Proposed Capacity Factors for Interface Communities

Use	Minimum total exit capacity (vph per household)	Minimum evacuation time (h)
Residential[a]		
Low wildfire hazard	1	2
Medium wildfire hazard	2	1
High+wildfire hazard	4	0.5
Residential and tourism[b]		
Low wildfire hazard	1.5	2
Medium wildfire hazard	3	1
High+wildfire hazard	6	0.5

[a] 2 vehicles per household.

[b] 3 vehicles per household.

Improving Community Egress Codes

Methods

The focus in a community context is therefore on identifying constricting components in a means-of-egress system. Furthermore, to achieve a comprehensive code and associated methods, the most constricting component should be defined in terms of the expected maximum occupancy as well as the number, capacity, and arrangement of exits. This is accomplished in a building context with look-up tables and simple geometric rules like the one-half-diagonal rule. In this section, preliminary analogues for interface communities are proposed. Agreed-upon community egress tables and codes will take significant cooperation among planners, and this represents a more formidable hurdle in terms of code development and compliance than the technical concepts discussed here (Burby et al. 1998).

Tables 3–5 represent community look-up tables for residential loading factors and the minimum number and capacity of exits. Table 3 depicts preliminary recommendations for community-based load factors expressed in road length per household, where communities with a greater fire hazard are required to have a lower density. In other words, as fire hazard increases the maximum allowable household density along roads should decline (Fig. 7). This is analogous to building codes which require a lower occupant density for buildings that contain hazardous materials (Table 1). To avoid delimiting a community's boundary, which is very subjective, "density" was defined as the average length of road (e.g., street centerline) per household in kilometers. This can be viewed as the average number of driveways per unit length of road. This calculation requires two easily acquired inputs that can be objectively measured: the number of households and total road length in the community.

Table 4 represents the minimum number of exits required for a community, which is a step function of the number of households. Allowing communities with only one exit to have up to 50 households avoids classifying all culdesacs as noncompliant with a two-exit minimum code. Table 5 represents the required minimum (total) exit capacity expressed in vehicles per hour (vph) per household. This is analogous to the linear relationship between persons and stairwell width in North American building egress codes (Table 2). The basis for the minimum required vph per household is a desired minimum evacuation time. For example, if a community has a high fire hazard (or greater), then the minimum evacuation time should be at most 30 min (0.5 h). Assuming two registered drivers per household, this requires that the exits have a minimum capacity of 4 vph per household. So a community with 100 households would need a total exit capacity of at least 400 vph to allow the estimated 200 vehicles to leave in 1/2 h (200 vehicles/0.5 h=400 vph). This coarse approach to estimating minimum evacuation time can be better tested for a given community with a traffic simulation model (Cova and Johnson 2002).

Table 4. Proposed Minimum-Exits Table for Interface Communities

Number of households	Minimum number of exiting roads	Maximum households per exit
1–50	1	50
51–300	2	150
301–600	3	200
601+	4	

In most fire-prone communities, the "use" of the space is residential, but in larger communities there may be businesses, schools, churches, community centers, and tourist attractions (e.g., lakes, botanical gardens, hiking trails). Facilities and attractions above and beyond residences are important because community occupancy may vary significantly when tourists and tran-

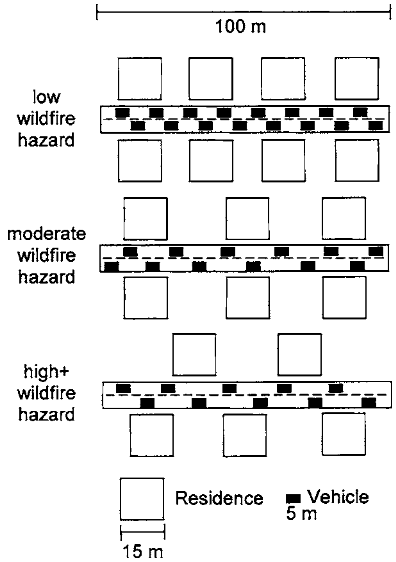


Fig. 7. Visual depiction of loading factor table for "residential use" assuming average of 2 registered drivers per home

sients are drawn (Drabek 1996). Furthermore, transient knowledge of the environment (e.g., evacuation routes) can be very poor. A community with a high degree of transients is analogous to an "assembly use" in building egress codes because occupants are generally unfamiliar with their environment. Table 5 requires a minimum capacity of 6 vph per household for high fire-hazard communities with tourism. So a community with 100 households and tourists would need a total exit capacity of at least 600 vph to allow the estimated 300 vehicles to leave in 1/2 h (300 vehicles/0.5 h=600 vph). The assumed mean number of vehicles per household can be adjusted, but standards should be set using the maximum probable occupancy in an area rather than the residents (and thus vehicles) recorded by the census.

Using Tables 3–5 in conjunction with a diagonal rule, a maximum-distance threshold and an exit-vulnerability rule, it is relatively straightforward to develop preliminary codes and compare community egress systems. For example:

1. Occupant load factor (density). The density of homes along the roads in any fire-prone community or portion thereof should not exceed that specified in Table 3.
2. Number of exits. The number of means-of-egress from any fire-prone community or portion thereof shall meet the minimum specified in Table 4.
3. Exit capacity. The total egress capacity from a fire-prone community or portion thereof shall meet the factors specified in Table 5.
4. Exit arrangement. The closest distance between any two points along any of the *n* exits from a fire-prone community must be at least $1/n$ the maximum diagonal distance across the community. The maximum diagonal of a community is defined as the greatest Euclidean distance between any two households that rely on the same exit set, and the minimum distance between exits is defined as the shortest Euclidean distance between any two points along two exiting roads.
5. Maximum exit distance. No household in a fire-prone community shall be further than 3 km by road from its closest exit. The maximum exit distance for a community is defined as the household with the greatest shortest-path distance on the road network to an exit discharge in the most constraining bottleneck set (i.e., the end of one of the exiting roads from the community).
6. Exit vulnerability (distance to fuel). Exits in a fire-prone community shall have a 30 ft buffer on each side that is clear of fuel.

An important aspect of this approach is that each recommended code is an independent test. This means that a community can meet or fail any subset of the codes. For example, a community might meet the density and minimum-number-of-exits codes but fall short of the exit-capacity code. The advantage of independent tests is that distinct limitations in a community's egress system can be highlighted separately. Fig. 8 depicts the proposed characteristics measured for Mission Canyon.

Table 5 provides the important link between expected maximum occupancy and required minimum exit capacity. An interesting aspect of this table is that it can be applied in reverse to calculate a community's maximum occupancy. For example, if a high-fire-hazard residential community (i.e., minimum evacuation time no greater than 30 min) has a total exit capacity of 1,000 vph in the most constraining bottleneck set, then from Table 5 the maximum occupancy would be (1,000 vph/4 vph *per household*)=250 households.

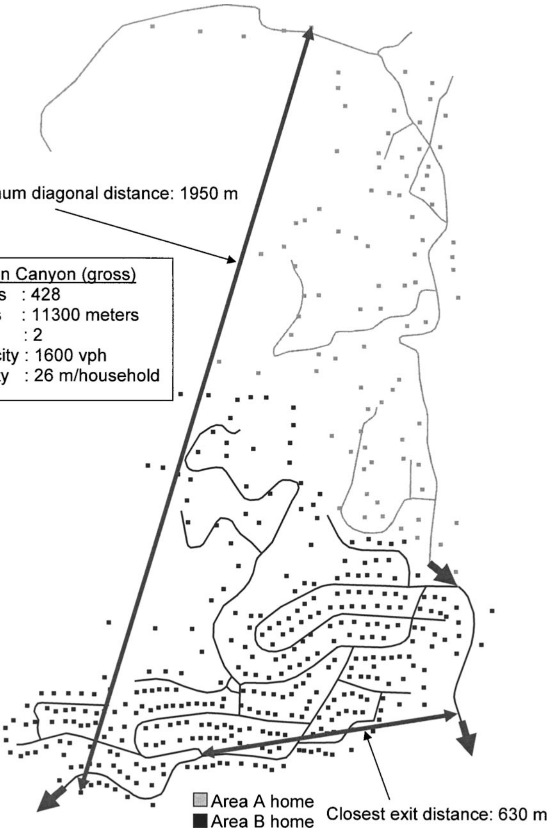


Fig. 8. Example (gross) egress calculations for Mission Canyon

Comparing Interface Communities

This section applies the proposed method to sample interface communities with high wildfire hazard, relatively low egress, and residential land use. A community with residential land use simplifies the estimation of occupant load by eliminating commercial, educational, and tourism activities. The inside (and outside) of each community is defined by the most constraining road-network bottleneck set. For example, if a community's most constraining bottleneck set is two exits, the calculations are for the households that would need to traverse one of these exits in an evacuation.

Perhaps the most involved calculation is for road capacity. This was crudely estimated using Eq. 8-3 in the *1997 highway capacity manual* (Transportation Research Board 1997):

$$\mathrm{SF}i = 2{,}800(v/c)_i f_d f_w f_g f_{\mathrm{HV}} \tag{1}$$

This equation states that a road's service flow rate (SF_i) in vehicles per hour (vph) is the product of the volume-to-capacity ratio for level-of-service i $(v/c)_i$ and a set of adjustment factors for directional traffic distribution f_d, lane and shoulder width f_w, grade f_g, and the presence of heavy vehicles f_{HV}. A narrow, mountainous road operating at level-of-service E (0.78) (maximum capacity) is assumed (for this analysis) with 100% of the traffic in one direction (0.71) on a 9 ft wide lane and 2 ft shoulder (0.70) heading downhill (1) with the possible 3% presence of large recreational vehicles (0.75) for an estimate of capacity per exit in clear visibility conditions with moderate demand rates of 814 vph (rounded to 800). In communities with uphill exits, wider roads or no recreational vehicles, this can be adjusted. Concentrated demand could greatly degrade this flow rate to level of service *F* where capacity can no longer be reliably estimated. Also, it should be noted that this number is very optimistic be-

Table 6. Data for Comparing Interface Community Egress Systems

Community	Homes	Exits	Road length (m)	Density (m per home)	Exit capacity (vph)	Max. diam. (m)	Exit separ. (m)	Max. dist. (m)	Exit fuel buffer
Buckingham[a]	337	4	5,293	16	3,200	1,040	85	430	No
Emigration Oaks	250	2	11,820	47	1,600	3,212	1,589	2,550	No
Summit Park	446	2	18,960	43	1,600	2,230	395	4,700	No
Mission Canyon	428	2	11,300	26	1,600	1,950	630	2,300	No
Area A (net)	60	1	4,576	76	800	1,520	NA[b]	1,750	No
Area B (net)	368	3	6,724	18	2,400	1,250	630	1,900	No

[a] 1991 data.

[b] Not applicable.

cause it does not consider driveways along a road or other merge points that may create flow turbulence.

Table 6 shows the raw data for the communities in the comparison which all have "high+" wildfire hazard during the fire season. Community fire hazard was grossly assigned based on the predominant vegetation and residential construction type. A community of wood structures intermixed with a combination of highly flammable vegetation (e.g., Gambel Oak or Eucalyptus) was assigned a "high+" wildfire hazard. Table 7 is derived from Table 6 and the recommended codes presented in the prior section by determining which aspects of each community are "compliant" (C) or "noncompliant" (N).

An interesting result of this comparison is that the neighborhood at the origin of the 1991 Oakland–Berkeley fire is compliant for three of the six egress tests. The number and total capacity of the exits, as well as the furthest distance from any home to its nearest exit were reasonable. The problem appears to have been the relatively high residential density, the close proximity of exits 1 and 3 (Fig. 9), and the tremendous amount of fuel along the exits. The neighborhood had been built to urban density with only 16 m of road per household (i.e., street centerline length), the most densely developed neighborhood in the comparison (Table 6). This means that in 1991 the neighborhood had a driveway, on average, every 16 m. This is very dense development for an area with extremely high fire hazard. The arrangement of the exits was also not ideal, as exits 1 and 3 were closer than 1/4 the maximum diagonal distance between the furthest two households relying on the exits. In 1991, exits 1 and 2 were blocked by the fire in its first 1/2 h, and most of the remaining residents chose exit 3 (Charing Cross Road). However, from the point of view of a wildfire, exits 1 and 3 are too close to one another to be considered genuinely separate means-of-egress, so a fire that blocks exit 1 is almost certain to block exit 3 which is just uphill, and this is what happened in 1991. Finally, there was a substantial amount of fuel along the exits, and this is what led exits 1 and 2 to be blocked by the fire so early in the event. However, all told, if this neighborhood had less than four exits the number of fatalities would likely have been much higher.

In regards to the other neighborhoods in comparison, it is easy to identify canyon and hillside neighborhoods in the West with relatively poor egress systems to varying degrees. Emigration Oaks is a neighborhood just East of Salt Lake City, Utah that has a reasonably good egress system, but it is an elongated community and the two exits are less than 1/2 its maximum diagonal distance (Cova and Johnson 2002). This resulted in the community being noncompliant in regards to exit arrangement. The community also has a substantial amount of highly flammable Gambel Oak lining the exit-road shoulders. Summit Park is a community on the Wasatch Mountain ridgeline between Salt Lake City and Park City. This neighborhood did very poorly, as it currently has 446 homes relying on two proximal exits that are lined with conifers. Mission Canyon in Santa Barbara, Calif. also scored poorly for the same reasons. To provide one example of "net" egress calculations for a community, Mission Canyon is divided into areas A (upper canyon) and B (lower canyon). Area A is not compliant in regards to the number of exits because it has 60 homes and only one exit, where Area B is too dense and does not

Table 7. Comparing Interface Communities Against Egress Standards[a]

Community	Density	Number of exits	Exit capacity	Exit arrange	Maximum exit distance	Exit fuel buffer
Buckingham, Oakland, Calif.[b]	N	C	C	N	C	N
Emigration Oaks, Utah	C	C	C	N	C	N
Summit Park, Utah	C	C	N	N	N	N
Mission Canyon, Calif.	C	N	N	N	N	N
Area A (net)	C	N	N	N	N	N
Area B (net)	N	C	N	C	N	N

[a] C=compliant, N=noncompliant.

[b] 1991 data.

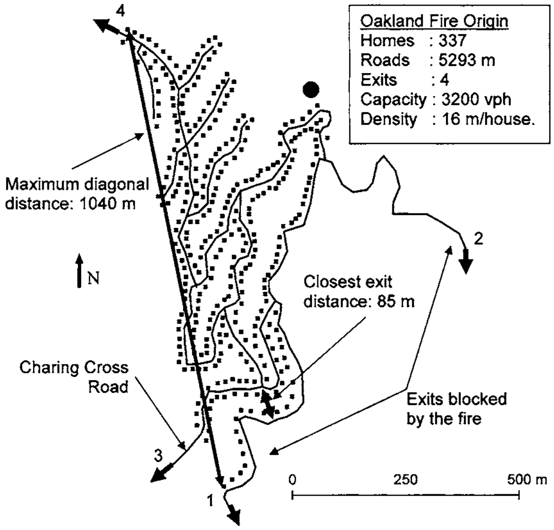


Fig. 9. Neighborhood at origin of Oakland–Berkeley fire in 1991

have sufficient exit capacity to serve its households. The main point with Tables 6 and 7 is simply that it is easy to identify neighborhoods with equal or greater fire hazard than the 1991 Oakland–Berkeley fire case and a more constrained egress system.

Urban and Emergency Planning Implications

The primary implication of developing a method comparable to building egress codes is that it is easy to identify fire-prone communities with relatively poor egress. The focus for urban and emergency planners should then turn to implementing new codes and improving egress systems. The proposed codes in the prior section can serve as a starting point and would need to be adjusted (or expanded) to work for a given locality. Also, despite the obvious limitations of the egress systems in the prior section, there are many actions that communities can take to improve their overall system (Plevel 1997). If a community has relatively poor egress, there are both demand-side and supply-side improvements (or adjustments) that can be implemented with varying cost (Burton et al. 1993). The focus in demand-side adjustments is reducing the concentration of vehicles in an evacuation in space and time to alleviate the need for egress capacity (e.g., supply). Example demand-side options include limiting the construction of new homes or businesses, limiting renters, constructing wildfire shelters, and identifying internal safe zones. Another demand-side adjustment is to require that structures be defensible so that residents can shelter-in-place. If a community can demonstrate that enough structures are defensible or there is sufficient public wildfire shelter or safe areas provided within the community, then the loading and capacity calculations could be adjusted to recognize that all not all residents will need to evacuate in a wildfire. This means that the following statement might be appended to each of the prior preliminary recommended codes:

"… unless a sufficient number and capacity of defensible structures, public shelters, or safe areas exist in the community for residents to shelter-in-place during a wildfire."

Supply-side adjustments to improve a community's egress system are also an option. This includes detailed evacuation route planning (i.e., Who will go where?) as well as reversing lanes and restricting turns at intersections to improve exit capacities (Wolshon 2001; Cova and Johnson 2003). Communities should also maintain their egress system. On-street parking restrictions can prevent low-capacity roads from becoming even lower, and clearing vegetation and other fuel along evacuation routes can minimize the loss of important exits during a wildfire. In cases where the egress system is severely substandard, widening roads or building new roads may be needed if more households are to be added.

Conclusion

Residential development in fire-prone areas is continuing without commensurate improvements to community-based transportation egress systems. This is only a small part of a much larger policy problem in fire-prone areas (Busenberg 2004), but it is an important one in protecting life. The codes presented in this paper would need to be integrated into a community's comprehensive hazard mitigation plan (Burby et al. 2000; Prater and Lindell 2000). However, the methods presented in this paper should help an analyst or planner in comparing community egress systems and possibly formulating codes. This may lead to improved community egress codes comparable to the higher-quality ones already in place for buildings. Limiting residential construction in low-egress, fire-prone areas with a "maximum occupancy" is not currently practiced but may be needed in some communities. If very few homes in a low-egress community are defensible and there is no safe zone or other public shelter, then limiting occupancy is one approach to maintaining public safety.

Economic pressure is strongly toward developing fire-prone communities to a density beyond which the egress system can safely handle in an urgent wildfire evacuation. The beneficiaries of new home development include new residents, developers, construction companies, and property tax collectors among many others. The parties that stand to lose include the residents who may perish in a wildfire, insurance companies, and the emergency managers challenged with the increasingly difficult task of protecting life and property in these rapidly growing areas. Thus, for political and economic reasons the methods presented in this paper may only find application in evacuation planning and comparing community egress systems. In the longer term, it is up to engineers and planners to ensure public safety in the urban–wildland interface by providing sufficient egress (or shelter) and educating residents on protective actions.

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