Wayfinding during a wildfire evacuation

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Abstract

Purpose – Emergency evacuation plans are often developed under the assumption that evacuees will use wayfinding strategies such as taking the shortest distance route to their nearest exit. The purpose of this paper is to analyze empirical data from a wildfire evacuation analyzed to determine whether evacuees took a shortest distance route to their nearest exit and to identify any alternate wayfinding strategies that they may have used.

Design/methodology/approach – The wildfire evacuation analysis presented in this paper is the outcome of a natural experiment. A post-fire online survey was conducted, which included an interactive map interface that allowed evacuees to identify the route that they took. The survey results were integrated with several additional data sets using a GIS. Network analysis was used to compare the routes selected by evacuees to their shortest distance routes, and statistical hypothesis testing was employed to identify the wayfinding strategies that may have been used.

Findings – The network analysis revealed that 31 percent of evacuees took a shortest distance route to their nearest exit. Hypothesis testing showed that evacuees selected routes that had significantly longer distances and travel times than the shortest distance routes, and indicated that factors such as the downhill slope percentage of routes and the elevation of exits may have impacted the wayfinding process.

Research limitations/implications – This research is best regarded as a spatiotemporal snapshot of wayfinding behavior during a single wildfire evacuation, but could inspire additional research to establish more generalizable results.

Practical implications – This research may help emergency managers develop more effective wildfire evacuation plans.

Originality/value – This research presents an analysis of an original data set that contributes to the broader body of scientific knowledge on wayfinding and spatial behavior during emergency evacuations.

Keywords GIS, Wildland fire management, Routing, Networks, Evacuation, Geographic Information Science, Natural hazards planning

Paper type Case study

1. Introduction

An effective emergency evacuation plan can help people move quickly and safely out of hazardous areas. Most current approaches to emergency evacuation planning are focused on representing the physical characteristics of a road network with great accuracy, but do not fully incorporate wayfinding behavior in developing estimates of vehicular traffic flow. These planning approaches often rely on common assumptions about the wayfinding strategies that people will use to choose an evacuation route. One common assumption is that evacuees will choose the shortest distance route to their nearest exit, or egress point, away from a hazardous area (Chen *et al.*, 2014; Shekhar *et al.*, 2012; Alçada-Almeida *et al.*, 2009). In this paper, empirical data from a wildfire evacuation are analyzed to determine whether evacuees took a shortest distance route to their nearest exit and to identify any alternate wayfinding strategies that may have been used.

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The wildfire evacuation analysis presented in this paper is the outcome of a natural experiment. A post-fire online survey was deployed in an area of the wildland–urban interface near Santa Barbara, California that received a mandatory evacuation order due to a fast-moving wildfire. One of the survey questions asked respondents to map their evacuation route using an interactive mapping interface. The survey data were integrated with several additional data sets using a Geographic Information System (GIS). Network analysis was used to compare the routes selected by evacuees to the shortest network distance route from the origin of their route to both their chosen exit and their nearest exit. Statistical hypothesis testing was then employed to identify wayfinding strategies that may have been used by the evacuees.

The remainder of this paper is structured as follows: first, the relevant literature on wayfinding, wildfires, and transportation engineering for emergency evacuation planning is reviewed and seven research questions (RQ) are posed. Next, the GIS layers and survey data used for this research are presented. The methods and results of the network analysis and hypothesis testing are then presented and discussed within the context of the RQ posed above. The paper concludes with a brief discussion of pertinent limitations, as well as a synopsis of promising areas of future research.

2. Background

Wayfinding is the process of navigation using distal information not immediately available to the senses, and is involved in determining and following a route between an origin and a destination (Golledge *et al.*, 1995; Montello and Freundschuh, 2005). Determining and following a route can involve one or more wayfinding strategies that simplify the route planning process (Hirtle and Garling, 1992). Laboratory and field research has suggested some general wayfinding strategies, including shortest distance, least time and movement in the direction of the destination as well as choosing straighter routes rather than routes with many turns (Bailenson *et al.*, 1998; Bailenson *et al.*, 2000). One unique characteristic of emergency evacuations is the additional stress that evacuees may be under, but the specific role of stress in the wayfinding process is unclear (Evans *et al.,* 1984). Experiencing a certain amount of stress during an evacuation may actually allow individuals to move more quickly, but excessive stress can lead to distortions in information processing that hinder route choice (Ozel, 2001). One general wayfinding strategy under stress has been identified in a study of lost wilderness hikers, who tend to travel downhill (Koester, 2008; Doke, 2012). While modern communication and geospatial technologies have given people access to extensive information about hazards that can help them make decisions (Iwan *et al.*, 1999), human psychological responses under conditions of risk and uncertainty still play a critical role in determining the course of action that they will take (Stone, 2006; Coleman *et al.*, 2011).

Determining the routes that evacuees choose is one of the fundamental problems in evacuation planning (Yuan and Wang, 2007). Mathematical models and simulations to predict evacuation routes are often built on Wardrop's (1952) principles of route choice, which assume that all evacuees will take the shortest distance route that is available (Hobeika *et al.*, 1994; Yamada, 1996; Chen *et al.*, 2014; Shekhar *et al.*, 2012; Alçada-Almeida *et al.*, 2009) and that evacuees will always choose a less congested route if the shortest distance route becomes too congested (Chalmet *et al.*, 1982; Hobeika and Kim, 1998). Models of different wayfinding strategies have proven useful in the study of emergency evacuations (Lovas, 1998) and recent efforts use such models to demonstrate how environmental conditions may lead to more complex exit and route-choice behavior when compared with a shortest distance strategy (Veeraswamy *et al.*, 2009). Simulations have been used to evaluate the impact of different evacuation travel behaviors on the choice to evacuate, departure time choice, destination choice and route choice (Pel *et al.*, 2012), and have also explicitly incorporated behavioral factors such as cognitive intent (Joo *et al.*, 2013). In general, research in the social sciences on spatial behavior during emergency evacuations has been poorly integrated with the evacuation models and simulations (Lindell and Prater, 2007), which limits the ability of researchers to calibrate these models and validate subsequent results (Schadschneider *et al.*, 2008).

Empirical data can help researchers develop a better understanding of evacuation wayfinding behavior (Kobes *et al.*, 2010), and may help uncover systematic deviations from optimal behavior that enable more accurate emergency evacuation modeling and simulation approaches (Dash and Gladwin, 2007). Investigators have conducted interviews to compare the emergency and non-emergency egress behavior of pedestrians (Haghani and Sarvi, 2016) and administered surveys to explore how risk perception and location influence evacuee behavior during a flood evacuation (Siebeneck and Cova, 2012). A critical need exists for research on emergency evacuations from wildfires (Wolshon and Marchive, 2007; Cova *et al.*, 2013; Moritz *et al.*, 2014), but such work is significantly hampered by a general lack of empirical data on human wayfinding behavior during such events. Wildfire evacuees have been surveyed to identify factors relevant to evacuation decisions such as if and when to depart (McCaffrey *et al.*, 2015; McCaffrey *et al.*, 2018), and several previous modeling and simulation approaches have focused on the same geographic area within which our post-fire survey was conducted (Cova and Church, 1997; Church and Sexton, 2002). These studies have shown that a safe short-notice evacuation in this area may be difficult due to factors such as high ratios of population to exit capacity (Cova and Church, 1997), but do not account for variability in driver route choice or route selection.

There are several important research topics examined in this paper: Do evacuees take shortest distance routes? If not, what alternate wayfinding strategies might evacuees employ to choose a route? The selection of a route depends on the final destination; thus, the selection of exits from the study area road network is examined as well. The complete set of the seven RQ addressed in this paper is shown in Table I below. The answers to these questions provide an important addition to the body of scientific knowledge related to wayfinding and spatial movement behavior during wildfire evacuations, and can assist emergency managers in developing evacuation plans and implementing traffic management techniques.

RQ_n	Research questions (RQ)	Scientific rationale
RQ1	Did evacuees select their nearest exit?	Many emergency evacuation modeling and simulation approaches operate under the assumption that evacuees will take the shortest distance route to their nearest exit (Alçada-Almeida *et al.*, 2009; Chen *et al.*, 2014; Shekhar *et al.*, 2012)
RQ2	Did evacuees take a shortest distance route?	
RQ3	Did evacuees take routes that had shorter travel times than the shortest distance route?	Laboratory and field research has suggested some general wayfinding strategies, including least time (Bailenson *et al.*, 1998; Bailenson *et al.*, 2000)
RQ4	Did evacuees take routes that had higher speed limits than their shortest distance route?	
RQ5	Did evacuees take routes that had greater downhill slope than their shortest distance route?	Wayfinding strategies can vary significantly between individuals, but one strategy used by lost hikers who may be under panicked conditions is moving downhill (Koester, 2008; Doke, 2012)
RQ6	Did evacuees select exits that were at a lower elevation than their nearest exit?	
RQ7	Did evacuees select exits that were at greater distance from the fire than their nearest exit?	When humans are fleeing from a specific hazard that threatens their well-being, it is likely they will take a route moving them away from the hazard (Bolton *et al.*, 2007)

Note: Empirical data from a survey was used to identify the wayfinding strategies that wildfire evacuees may have used

Table I. Research questions (RQ) and scientific rationale

3. Data

On the afternoon of May 5, 2009, a wildfire began in the foothills above Santa Barbara, California. Named the Jesusita Fire after a popular hiking trail near the origin of the fire, this fire burned nearly 9,000 acres and destroyed 80 homes[1]. An estimated 35,000 people were ordered to evacuate due to the danger posed by the fire, and many others were warned that they might be ordered to evacuate on short notice[2]. A post-fire survey was conducted in October 2009 at the Mission Canyon and San Roque neighborhoods in Santa Barbara. These neighborhoods were selected because many residents evacuated on very short notice due to their proximity to the origin of the fire.

3.1 Evacuation survey

An online survey instrument was developed to assess household behavior during the Jesusita Fire for an approximately five square kilometer study area covering the Mission Canyon and San Roque neighborhoods in Santa Barbara, California, USA (Figure 1) This area was selected because of its location in the wildland–urban interface, close proximity to the origin of the fire, and road network with limited exits, egress points. Both of these neighborhoods are located in the foothills of the Santa Ynez mountains and are comprised primarily of single family homes. Two methods were used to recruit survey participants: door hangers placed on the front doorknob or fence, and an e-mail list provided by the Mission Canyon Homeowners Association. The survey was online administered online was written in English; thus, participation was limited to Anglophones with internet access and basic computer skills. There were 264 total responses to the survey.

Evacuation routes were self-reported by survey participants. Respondents were presented with an interactive map interface and asked to click each road segment that they traveled on when evacuating from the fire. This map interface was followed by a text box in

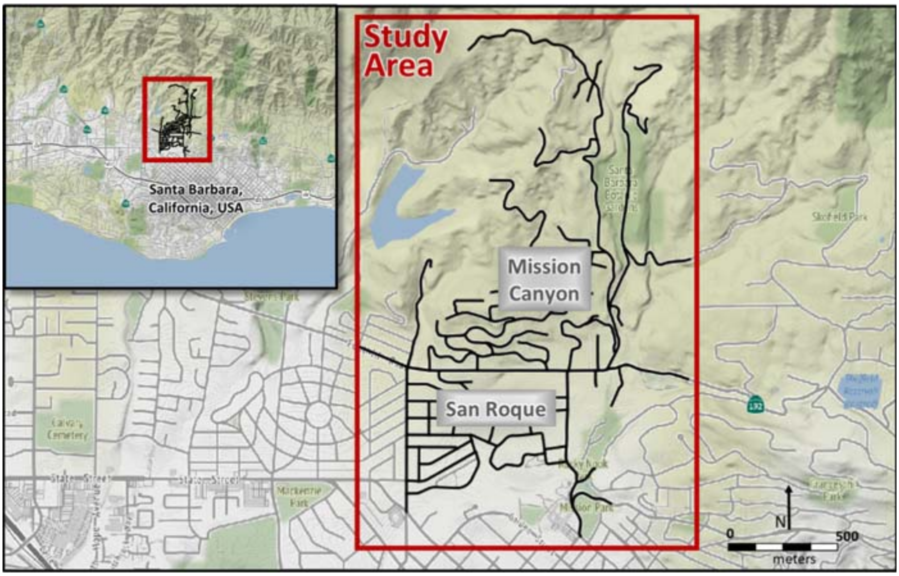


Figure 1. Jesusita Fire Study Area

Notes: The 5 km^2 study area in Santa Barbara, California, USA is indicated by the red box on the map above. This area was selected because of its location in the wildland-urban interface, close proximity to the origin of the fire and road network with limited egress points which evacuees were asked to write a turn-by-turn description of their evacuation route. In order to develop a consistent and accurate data set of evacuation routes, route validity was determined using three basic rules: the route must have an origin point within the study area; the route must follow a connected set of road segments; and the route must have an exit at the edge of the study area. Of the 264 survey respondents, 123 (46 percent) did not click on a road segment on the interactive map. Four of the routes provided by survey respondents did not have a valid origin in the study area (2 percent), 40 routes did not follow a connected set of road segments (15 percent) and 7 routes did not have an exit at the edge of the study area (3 percent). Thus, of the initial set of 264 survey responses, there were 90 valid evacuation routes that were used for the analyses presented in this paper.

3.2 GIS data

Several GIS data layers were collected that characterize the built and natural environment in the study area. Fire perimeter polygon shapefiles representing the location of the Jesusita Fire at different points in time between May 5 and 9, 2009, were obtained from the California Department of Fire and Forestry Protection. A Digital Elevation Model (DEM) covering Santa Barbara was obtained from the US Geological Survey, and a street layer shapefile was obtained from the Santa Barbara County GIS Office that included attributes such as street names, address ranges and speed limits.

4. Methods and results

4.1 Network analysis

Network analysis was used to compare the evacuation routes reported by survey respondents to shortest distance routes. For the purposes of this analysis, the graph (G) represents the roads in the study area, and each evacuation route is comprised of a set of nodes (N) connected by arcs (A). Each route has an origin node (N_O), which is the starting point for the evacuation, a destination node (N_D), which was used to exit the study area, and transshipment nodes (N_T) that the evacuee passed through. There were only three nodes used by evacuees to exit the study area. These exit nodes, or egress points, are shown in Figure 2.

The comparison of survey routes to shortest distance routes can be broken in two separate questions. First, did the evacuee choose the destination node (N_D) that had the shortest network distance from the origin node (N_O) where their route began? Second, did the evacuee choose the shortest distance route from their origin node to the destination node that they used to exit the study area network? To answer these questions, Dijkstra's (1959) algorithm was used to calculate the shortest network distance from the origin node of each evacuation route to each of the three possible destination nodes. The network analysis process and results are shown graphically in the flow chart shown in Figure 3.

Of the 90 evacuation routes collected in the online survey, 44 (49 percent) ended at the nearest exit in the study area and 46 (51 percent) ended at a more distant exit. Of the 44 evacuation routes that ended at the nearest exit, 28 were a shortest distance route. Thus, 28 of the ninety total evacuation routes (31 percent) were shortest distance routes to the nearest exit. In sum, 16 evacuees (18 percent) chose a longer distance route to their nearest exit, 24 evacuees (27 percent) chose a shortest distance route to a farther exit and 22 evacuees chose a longer distance route to a farther exit (24 percent).

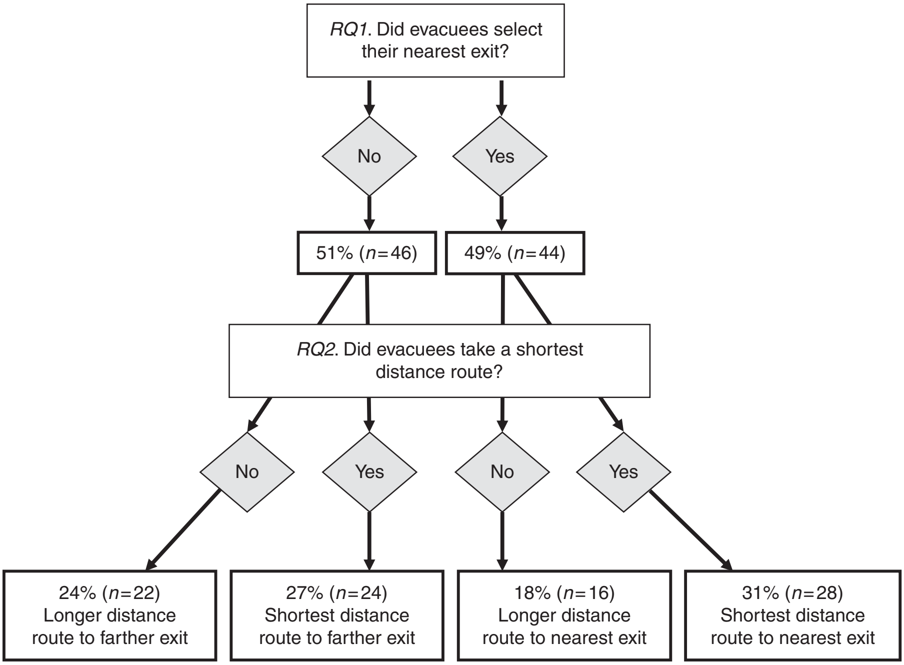
One way to further investigate evacuee wayfinding strategies is to compare two maps (Figure 4). Map 1 shows the routes taken by Jesusita Fire evacuees. The distribution of evacuees to each exit is relatively even, as is the distribution of evacuees on the roads leading into these nodes. Map 2 shows the routes that evacuees would have taken if they chose the shortest distance route to their nearest exit. The distribution of evacuees to exits is not as balanced as Map 1. Rather, exit 1 (39 percent of total evacuees) and exit 3 (47 percent) should be utilized much more than exit 2 (13 percent). The distribution of evacuees on the

Figure 2.
Study area road network in Santa Barbara, CA

Note: The dark black lines show the roads that were used by survey respondents and the squares numbered 1 through 3 show the exits, or egrees points, that they used

roads leading into these exits is not balanced either. In particular, the road leading directly south to exit 3 (Mission Canyon Road) shows much lower usage on Map 1 than would be expected if evacuees took the shortest distance route to their nearest exit (Map 2), and the road leading directly south to exit 2 (Alamar Street) shows much higher usage than would be expected if evacuees took the shortest distance route to their nearest exit (Map 2).

Examining the attributes from several GIS layers can provide some insight into the wayfinding strategies that evacuees may have used. The elevation values in the DEM GIS layer show that exit 3 is at an elevation of 92 meters (used by 30 percent of Jesusita fire evacuees) and exit 2 is at an elevation of 70 meters (used by 38 percent of evacuees) (see Figure 4, Map 1). If evacuees had chosen the shortest distance route to their nearest exit, 47 percent would have used exit 3 and only 13 percent would have used exit 2 (Figure 4, Map 2). The speed limit attribute in the shapefile of roads in the study area indicates that all exits are along a road with a speed limit of 35 mile per hour (mph). Further examination of these GIS data shows that approximately 85 percent of the total road distance in the study



Notes: Dijkstra's (Dijkstra 1959) algorithm was used to calculate the shortest network distance from the origin node of each evacuation route to each of the three possible destination nodes in the study area road network. Of the 90 evacuation routes collected in the online survey, 44 (49 percent) ended at the nearest exit in the study area and 46 (51 percent) ended at a more distant exit. In all, 28 evacuees (31 percent) took the shortest distance route to the nearest exit. A total of 16 evacuees (18 percent) chose a longer distance route to their nearest exit, 24 evacuees (27 percent) chose a shortest distance route to a farther exit and 22 evacuees chose a longer distance route to a farther exit (24 percent)

Figure 3. Network Analysis Results

area has a posted speed limit of 25 mph and 15 percent has a posted speed limit of 35 mph; thus, it is possible that evacuees choose routes that favored these higher speed limit roads. Finally, the map below of Jesusita Fire perimeter boundaries at different points in time shows that the location of the fire may have influenced evacuee wayfinding depending on the date and time of their departure (Figure 5).

4.2 Hypothesis testing

Results from the network analysis were used to further address the RQ posed in Table I. For each of the RQ related to exits, a statistical hypothesis test was used to compare the more distant destination nodes (N_D) chosen by Jesusita Fire evacuees (Groups A and B, $n = 46$) to their nearest destination nodes (N_D). Hypothesis tests were then used to compare the arcs (A) of longer routes taken by evacuees (Groups A and C, $n = 38$) to the arcs (A) of their shortest distance routes for RQ related to route choice. The variables compared to address *RQ1* through *RQ4*, *RQ6* and *RQ7* are not normally distributed thus the two-sample Wilcoxon signed-rank test was used to test for statistical significance (Hollander and Wolfe, 1973). The fifth RQ (*RQ5*) is addressed using directional data and therefore requires use of circular statistics; thus, Watson's two-sample test of homogeneity was employed (Jammalamadaka and Sengupta, 2001).

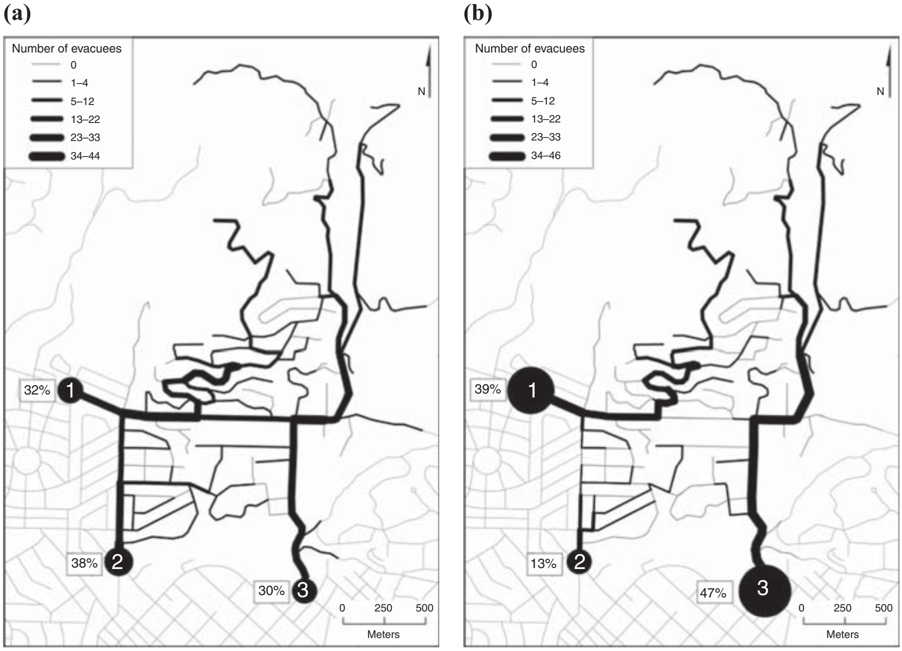


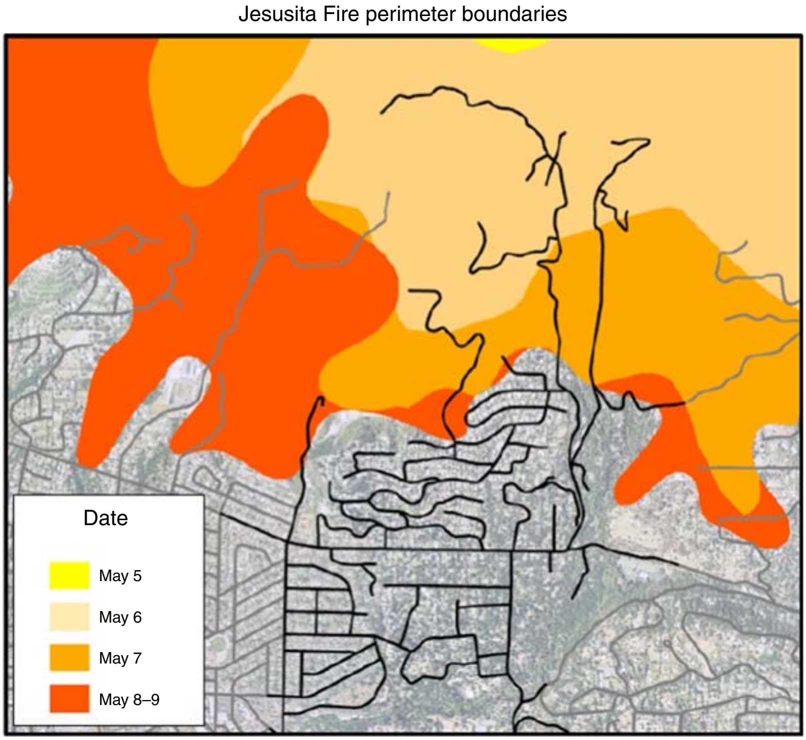
Figure 4.
Actual versus expected evacuee routes in the Jesusita Fire survey

Notes: Map 1 (a) shows the evacuation routes reported by respondents to the Jesusita Fire survey and the percentage of routes that end at each exit. Map 2 (b) shows the routes that evacuees would have taken had they chosen the shortest distance route to their nearest exit, or egress point. The distribution of evacuees to exits is not as balanced when Map 2 (a) is compared to Map 1 (b). Rather, exit 1 (39 percent of total evacuees) and exit 3 (47 percent) would be utilized much more than exit 2 (13 percent) if all evacuees had chosen the shortest route to their nearest exit

Several additional variables were created using GIS data to address these RQ. For *RQ7*, each route was matched to the most recent fire perimeter boundary at the time of evacuation, and the Euclidian distance from each destination node (N_D) to the nearest point of the fire perimeter boundary was calculated. For *RQ3*, a simple measure of travel time was calculated by multiplying the speed limit by the distance of each arc (A) and summing these values for each evacuation route and shortest distance route. The speed limit variable used to address *RQ4* was the average of the speed limit of the arcs in each route, and the downhill slope variable used to address *RQ5* was generated by averaging the slope ratio of the arcs in each route.

As stated earlier, the results of the network analysis showed that 51 percent of evacuees did not select their nearest exit (*RQ1*). Hypothesis testing was used to determine if there was a significant difference between the distance that these evacuees traveled to reach a more distant exit and the distance to their nearest exit. The longest distance difference between an evacuation route and the shortest distance route to the nearest exit was 1,480 meters, and the median distance difference was 407 meters. The Wilcoxon signed-rank test showed that there was a significant difference between the distance that evacuees traveled to reach a more distant exit and the distance to their nearest exit ($V = 1081$, p-value < 0.01). The complete results of the hypothesis testing are shown in Table II.

The network analysis also revealed that 42 percent of evacuees did not select a shortest distance route (*RQ2*). Hypothesis testing was used to determine if there was a significant



Note: Distinct colors indicate the changes in the perimeter over time, with yellow and light orange indicating the early perimeter and dark orange and red indicating the later perimeter

Figure 5. Perimeters of the burn area of the Jesusita Fire from May 5-9, 2009 relative to the study area

difference between the distance of the evacuation routes selected by these evacuees to the distance of the shortest path routes to their chosen exit. The median evacuation route was 61 meters longer than the shortest distance route between the same origin and destination nodes, and based on a Wilcoxon signed-rank test, this difference was significant ($V = 741$, p-value < 0.01).

The next set of RQ and hypothesis tests investigated the significance of several different wayfinding strategies that evacuees may have used. One possible reason for selecting a longer evacuation route is that it might have a shorter travel time based on the speed limits of the roads (*RQ3*). These hypothesis tests are done using an empty network assumption because the actual travel times during the event given traffic are not recoverable. Hypothesis testing showed that there was a significant difference in travel times between evacuation routes and shortest path routes ($V = 731$, p-value < 0.01), but the median difference in travel times for evacuation routes was 39 s longer than shortest distance routes. There was not a significant difference between the average speed limit of evacuation routes and shortest path routes ($V = 286$, p-value $= 0.14$) (*RQ4*). Another wayfinding strategy that may have been used is traveling downhill (*RQ5* and *RQ6*). The median downhill slope percentage of evacuation routes was 4.1 percent compared to 5.6 percent for shortest distance routes, and the results of the hypothesis test showed that this difference was significant ($t = 0.34$, p-value < 0.01).The median difference in elevation between the exit nodes selected by evacuees and their nearest exit nodes was 16 meters lower, and this

Table II.
Hypothesis testing results

Research questions (RQ) and hypotheses (H)	Summary statistic	Test result	Conclusion
RQ1. Did evacuees select their nearest exit? *H1*. Evacuees took routes that were longer than the length of the shortest distance route to their nearest exit H_0. There is no difference in route length	The median distance difference of routes chosen by evacuees was 407 meters longer than the length of the shortest distance route to their nearest exit	Wilcoxon signed-rank test $V = 1{,}081$ p-value < 0.01 Reject H_0	No. Evacuees selected exits that were significantly further away than their nearest exit
RQ2. Did evacuees take a shortest distance route? *H1*. Evacuees took routes that were longer than the length of the shortest distance route to their chosen exit H_0. There is no difference in route length	The median distance difference of routes chosen by evacuees was 61 meters longer than the length of the shortest distance route to their chosen exit	Wilcoxon signed-rank test $V = 741$ p-value < 0.01 Reject H_0	No. Evacuees took routes that were significantly longer distance than the shortest distance route to their chosen exit
RQ3. Did evacuees take routes that had shorter travel times than the shortest distance route? *H1*. The total travel time of the routes chosen by evacuees was shorter that the travel time of the shortest distance route to their chosen exit H_0. There is no difference in travel time	The median travel time difference of routes chosen by evacuees was 39 s longer than the travel time of the shortest distance route to their chosen exit	Wilcoxon signed-rank test $V = 731$ p-value < 0.01 Reject H_0	No. Evacuees took routes that had significantly longer travel times than the length of the shortest distance route to their chosen exit
RQ4. Did evacuees take routes that had higher speed limits than their shortest distance route? *H1*. The speed limit of the routes chosen by evacuees was higher that the speed limit of the shortest distance route to their chosen exit H_0. There is no difference in speed limits	The median speed limit difference of routes chosen by evacuees was 0.37 mph higher than the travel time of the shortest distance route to their chosen exit	Wilcoxon signed-rank test V = 286 p-value $= 0.14$ Cannot reject H_0	Inconclusive
RQ5. Did evacuees take routes that had greater downhill slope than their shortest distance route? *H1*. The downhill slope of the routes chosen by evacuees was greater than the downhill slope of the shortest distance route to their chosen exit H_0. There is no difference in downhill slope	The median downhill slope percentage of routes chosen by evacuees was 4.1 vs 5.6% for the shortest distance routes to their chosen exit	Watson's two-sample test $t = 0.34$ p-value < 0.01 Reject H_0	No. Evacuees took routes that had significantly less downhill slope than the length of the shortest distance route to their chosen exit

(*continued*)

Research questions (RQ) and hypotheses (H)	Summary statistic	Test result	Conclusion
RQ6. Did evacuees select exits that were at a lower elevation than their nearest exit? *H1*. The elevation of the exits chosen by evacuees was lower than the elevation of their nearest exit H_0. There is no difference in elevation	The median elevation difference of exits chosen by evacuees was 16 meters lower than their nearest exit	Wilcoxon signed-rank test $V = 80$ p-value < 0.01 Reject H_0	Yes. Evacuees selected exits that were at a significantly lower elevation than their nearest exit
RQ7. Did evacuees select exits that were at greater distance from the fire than their nearest exit? *H1*. The distance from the fire of the exit chosen by evacuees was greater than the distance from the fire of their nearest exit H_0. There is no difference in distance	The median distance difference of exits chosen by evacuees was 341 meters further from the fire than their nearest exit	Wilcoxon signed-rank test $V = 556.5$ p-value $= 0.87$ Cannot reject H_0	Inconclusive

Notes: These results show that Jesusita Fire evacuees chose exits that were significantly further away than their nearest exits and selected routes that were significantly longer than their shortest distance routes. They may have used wayfinding strategies such as selecting exits at lower elevations and choosing routes that had less downhill slope

Table II.

difference was significant as well ($V = 80$, p-value < 0.01). For the final RQ (*RQ7*), there was not a significant difference between the distance from the wildfire of the exits selected by evacuees and the distance from the fire of their nearest exit at the time of evacuation ($V = 556.5$, p-value $= 0.87$).

5. Discussion

This work serves as a first step in the larger goal of assisting emergency managers in developing evacuation plans and implementing traffic management techniques. In addition, the empirical evidence provided in our study is an important addition to the body of scientific knowledge related to wayfinding and spatial movement behavior during wildfire evacuations. Results from the network analysis show that less than one-third of survey respondents chose a shortest path route to their nearest exit. Examined independently, 49 percent of evacuees chose their nearest exit and 58 percent of evacuees chose a shortest distance route. These results indicate that emergency evacuation modeling approaches built on the assumption that evacuees will choose their nearest exit or take a distance route may not always be applicable for real world emergency evacuation situations.

Statistical hypothesis testing showed that evacuees might have used wayfinding strategies such as selecting lower elevation exits and less steep routes. One possible reason for selecting a lower elevation exit is that these exits connect to the major arterial streets of Santa Barbara, thus providing evacuees more routing options to their final destination. Evacuees may have also perceived lower elevation exits to be safer because they seemed further from the fire. Another wayfinding factor that warrants further discussion based on our results is the average slope of an evacuation route. Similar to the elevation of exits, the underlying behavioral assumption is that people prefer to move downhill as quickly as possible under stressful conditions (Koester, 2008; Doke, 2012). Statistical testing shows that while there is a significant difference between the slope of evacuation routes and shortest path routes, the evacuation routes were actually less downhill than the shortest paths. One possible explanation is that evacuees perceived flatter routes to be safer since they entailed less braking while traveling downhill. It is also possible that the flatter routes were on roads that were wider, straighter and/or had higher speed limits, which, in addition to potentially being perceived as safer, might be perceived as faster as well.

It is important to consider that the alternate evacuation routes in this study area might have been psychologically equivalent with respect to the wayfinding strategies. At a constant speed of 25 mph, the longest distance difference between an actual evacuation route and the shortest distance route to the nearest exit (1,480 meters) would yield a difference of just over 2 min of travel time. The median distance difference between an actual evacuation route and the shortest distance route to the nearest exit (407 meters) would yield a difference of less than 1 min, and the median distance difference of routes chosen by evacuees than the length of the shortest distance route to their chosen exit (61 meters) would yield a travel time difference of approximately 6 s. Although the differences in distance, exit elevation and downhill slope are statistically significant based on the results of the hypothesis testing, these differences may not have made a meaningful difference to evacuees.

6. Limitations and future research

There are several important limitations of this research. First, the Jesusita Fire was a single event that occurred in a part of the world that experiences multiple wildfires every year. The 90 evacuation routes collected and analyzed represent a fraction of the estimated total number of evacuees from this fire, and the survey was administered in a small, high-risk area in the greater Santa Barbara region. While the study area for this analysis was carefully chosen based on the neighborhood boundaries and characteristics of the road network, it is possible that the results could be different in a larger or smaller study area with a different number of network egress points. This study is best regarded as a spatiotemporal snapshot of wayfinding behavior during an emergency evacuation that could inspire future studies of similar events either in the same area or in other areas.

The second important consideration is the limited set of wayfinding strategies and variables that were tested. Elevation, speed limits and downhill slopes are static variables that influence wayfinding, but additional static variables such as lane width, road sinuosity and intersection controls should be considered in future studies. The travel time measurement used in this analysis implicitly assumes that evacuees travel the speed limit at all times, and does not account for the delays that might be incurred due to infrastructure elements such as stop signs or stop lights. Distance from the fire was the one dynamic variable that was evaluated; dynamic factors such as traffic congestion, queuing, smoke from the fire and directions given by police or other emergency response personnel may influence the route selection process as well.

A third consideration is the potential for sample bias. The evacuation route data used in this analysis came from an online survey that included an interactive map interface. Some survey respondents reported being confused by the map interface, and 46 percent of the 264 survey respondents did not use it. Others who did attempt to use the interactive map interface failed to submit a route that could be validated using a detailed turn-by-turn description of their evacuation route (20 percent). This 66 percent attrition rate is likely related to both spatial ability and computer skills, thus the evacuation routes analyzed in this study may biased toward individuals who are more proficient in these areas.

Wayfinding during an emergency evacuation is a complex spatiotemporal decision-making process, and thus future studies should expand upon the RQ, data, methods and geographic area used in this study. To help account for the possibility that the alternate evacuation routes in this study area might have been psychologically equivalent with respect to the wayfinding strategies, future research should examine evacuation route choice in locations where different wayfinding strategies would produce greater differences in evacuation route choices. Additional general wayfinding strategies, such as movement in the direction of the destination and choosing straighter routes (Bailenson *et al.*, 1998; Bailenson *et al.*, 2000), should be examined, and a better understanding of how excessive stress can impact route choice (Evans *et al.,* 1984; Ozel, 2001) is needed. Longitudinal studies of people living in high-risk areas before and after a hazard requiring an evacuation could provide valuable new data sets. Such studies could provide a baseline of the routes people take for everyday travel to compare against their evacuation routes, and could help determine if personal familiarity with a specific route leads to a higher likelihood of it being used for evacuation purposes (Lindell *et al.*, 2011; Wu *et al.*, 2012). Future studies should also further examine how congestion (Khattak and Khattak, 1998) and traffic incidents (Knoop *et al.*, 2010) might influence route choice and wayfinding. Big geospatial data such as a full motion video could be analyzed using automated computer vision methods to count cars going from origins to destinations during an evacuation, and could also be incorporated into a neural network or other machine learning methodology to predict traffic flows based on changes in weather conditions or other dynamic variables.

Finally, some routes taken by Jesusita fire evacuees simply defy what any researcher can reasonably predict or explain. Figure 6 shows two examples of such routes. In the first map (a), the evacuee chose a route that was 747 meters longer than the shortest distance route between the same origin and destination. This evacuee drove uphill and in the direction of the Jesusita fire, which had spread into the northern most sections of the study area at this evacuee's time of departure. One possible explanation is that this evacuee wanted to get a closer look at the fire before leaving the area. In the second map (b), the evacuee chose a route that was 1,072 meters longer than the shortest distance route. One possible

Figure 6.
Unexpected routes taken by Jesusita fire evacuees

Notes: Black lines show the actual evacuation route and thick gray lines show the shortest distance route. The circle is the route origin node. The black square is the route destination node

explanation for this choice is that the evacuee wanted to avoid a specific area of the road network due to concerns about traffic congestion or safety. The research presented in this paper represents one small step toward a better understanding of the complex emergency evacuation behaviors represented by these types of routes.

Notes

1. http://cdfdata.fire.ca.gov/incidents/incidents_details_info?incident_id=310
2. www.noozhawk.com/article/121109_jesusita_fire_investigation

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