The Wildfire Evacuation Dilemma -- How Not To Become Lahaina

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Abstract

According to public records obtained from the Caltrans Division of Research, Innovation and System Information[1], Nevada does not "currently use or have plans to use modeling tools and other practices to evaluate potential emergency wildfire evacuation routes when designing road improvements for highways in areas with high fire potential." Neither the Nevada Department of Transportation (NDOT) nor Tahoe Regional Planning Agency (TRPA) have conducted a detailed analysis of traffic congestion issues associated with the evacuation of the City of South Lake Tahoe, Stateline casinos, and residents and visitors along the Tahoe East Shore, should a substantial wildfire breakout in the Lake Tahoe Basin. This paper reports the conclusions of a traffic flow analysis conducted by the Tahoe East Shore Alliance Tech Team that clearly shows the massive loss of life that would occur if a Caldor-like wildfire were to devastate the South and East shores of Lake Tahoe. It also shows a consistency with the real-world conditions leading to the massive loss of life in Paradise, CA[2] and Lahaina, Maui, HI[3], when wildfires broke out in these evacuation-constrained communities.

In an effort to understand the magnitude of the evacuation problem along the South and East Shores of Lake Tahoe, we developed several traffic flow macrosimulation models, ranging from very optimistic to very conservative. Even in the most optimistic case, we conclude that the condition of the national forest, existing fire management policies, staging of emergency equipment, evacuation timelines, and traffic flow conditions prevalent at the time of the Caldor wildfire are insufficient to prevent a disaster similar to Paradise and Lahaina. We further conclude that reducing the number of available egress lanes from three to two as a result of a "road diet" would reduce the lives that could be saved by approximately 25%, reflecting experience with the road diet in Paradise, CA.

Actions that can (and should) be taken by government authorities to improve the survival rate include:

- Improve Forest Management Policies and Practices in the Lake Tahoe Basin to lessen the risk and severity of wildfires.
- Reduce time between wildfire detection and evacuation order.
- Reduce wildfire spread rate through additional personnel and enhanced firefighting infrastructure.
- Increase (not decrease) road capacity within the US 50 East Shore corridor, i.e., no road diet!

Problem Statement

According to the Tahoe Fund[4], "[The] year-round resident population [in the Tahoe Basin] is 40,000. Total population can reach 300,000 on peak days. About 15 million people visit Lake Tahoe each year." Should a wildfire break out at the West end of the US Hwy 50 corridor, for example near the Lake Lucille (5.7 miles west of Meyers, CA) a significant number of these residents, visitors, and vacationers would need to evacuate the region, traveling East along US 50 as the "main route out of town"[5], with a substantially smaller number egressing along Kingsbury Grade (SR207). Simultaneously, one lane of US 50 and one lane of Kingsbury Grade would need to be kept open allowing for ingress of firefighting equipment, earth-moving equipment (e.g., bull dozers), command & control vehicles, and emergency vehicles.

The US 50 East Shore Corridor is a 4-lane mountain highway from Spooner Summit to Stateline, with occasional turn, acceleration, and deceleration lanes; multiple curb breaks for the residential communities; and six intersections controlled by traffic lights. The speed limit ranges from 25 mph near the Stateline casinos to 50 mph between Glenbrook and Spooner Summit. The predominant speed limit is 45 mph, but yellow caution signs reduce the posted speed at horizontal curves in several locations.

Evacuation Scenario

For the purpose of evaluation, we presume that a wildfire flares up near Lake Lucille, 5.7 miles due west of Meyers, CA. Both US 50 and SR89 are assumed blocked to westbound traffic and SR89 north of "the Y" and the capacity-constrained northbound SR89 is used only for the evacuation of D. L. Bliss State Park, Eagle Falls (Vikingsholm), Fallen Leaf Lake, Taylor Creek, Tallac historic site, Valhalla, and Camp Richardson. We assume that the SR28 intersection at Spooner Summit remains in the free-flow zone and is not a factor in any evacuation scenario, despite the proposed SR28 - US 50 roundabout in the NDOT Corridor Management Plan[6]. We further assume that Kingsbury Grade is used only for evacuation of the residential areas that have direct access to it. These assumptions constrain the number of people that must evacuate eastbound along US 50 over Spooner Summit.

In addition to these assumptions, we set the following conditions to simplify the analysis: (1) all evacuating vehicles entering from the South Shore (South Lake Tahoe, Meyers, and unincorporated areas to the West) are available at the Stateline boarder when needed to optimize traffic flow; (2) all local evacuating vehicles within a segment enter at a single point at the downstream end of the segment; (3) all vehicles within a segment are consumed when the wildfire reaches the downstream end; (4) no vehicles have special status regarding evacuation priority; and (5) no behavioral or decision making attributes are assigned to the drivers. The last condition ensures that the traffic flow will resemble a fluid dynamics macrosimulation rather than an agent-based microsimulation.

Once the presumed Lake Lucille wildfire is detected, we assume that the 4 total lanes of US 50 will be reassigned under emergency order to allow 3 lanes for evacuation egress, with one lane reserved for inbound firefighting and support vehicle ingress. For the purpose of this analysis, the East Shore Corridor of US 50 is divided into segments characterized by the number of lanes, lane width, and posted speed limit. Each is identified by a list of road characteristics that remain constant within each scenario.

Road Segment Characteristics

As shown in Table 1, the numbered road segments are the same as those identified in the by Nevada Department of Transportation[6], however, several are further subdivided by letter where road characteristics change, and one (Segment 7*) is added to represent the entirety of South Lake Tahoe. In all cases, we assume intersections are controlled to optimize evacuation conditions and would not present an independent bottleneck to egress. The initial number of local vehicles seeking to enter the segment through one or more major entry points (vehicle queue) is estimated in Appendix A, based on summer peak-season resident and vacationer statistics.

Table 1. Road Segment Characteristics

Road Segment Characteristics		Units		Road Segments (in direction of travel)									
			Segment 7*	Segment 6	Segment 5B	Segment 5A	Segment 4B	Segment 4A	Segment 3	Segment 2C	Segment 2B	Segment 2A	Segment 1
Segment Description			South Lake Tahoe	Stateline Ave. to Kingsbury Grade	Kingsbury Grade to Elks Point Rd.	Elks Point Road to Round Hill Pines	Round Hill Pines to South of Zephyr Cove	Zephyr Cove to Skyland	Skyland to North of Cave Rock	North of Cave Rock to South of Logan Shoals	Along Logan Shoals	North of Logan Shoals to South of Glenbrook	South of Glenbrook to Spooner
Scenario 1: Present Configuration	Number of Evacuation Lanes		3	3	3	3	3	3	3	3	3	3	3
	Number of Ingress Lanes		1	1	1	1	1	1	1	1	1	1	1
	Lane Width	ft	12	12	12	12	12	12	12	12	12	12	12
	Lowest Posted Speed Limit	mph	25	25	35	45	45	45	45	45	45	45	50
	Speed Limit at Curves	mph	--	--	--	--	30 & 35	35	30	35	--	--	--
	Maximum Operating Speed	mph	38	38	48	55	43	48	43	48	55	55	60
	Speed at Capacity	mph	19	19	24	27.5	21.5	24	21.5	24	27.5	27.5	30
	Number of Bins			5	7	4	10	7	12	5	5	3	16
	Assumed Operating Speed	miles	19	19.44	23.81	24.31	20.83	21.83	20.83	25.00	30.56	27.78	28.65
	FF Traffic Flow Capacity	vph	4870	4870	4246	3880	4543	4246	4543	4246	3880	3880	3650
	Max Local Flow Capacity	vph	6131	0	541	541	541	541	811	270	270	541	0
	Jam Density	vpm		500.9	356.7	319.2	436.1	389.1	436.1	339.7	253.9	279.3	254.8
Road Length		miles		0.7	1.2	0.7	1.5	1.1	1.8	0.9	1.1	0.6	3.3
Number of Entry Points			1	0	2	2	2	2	3	1	1	2	0
Initial Number of Local Vehicles Seeking to Enter Segment (Queue)			48400	0	570	851	1222	819	753	43	137	109	549
Local Vehicle Entry Speed		mph	19	5	5	5	5	5	5	5	5	5	5
Local Vehicle Entry Delay		hours	0.0037	0.0037	0.0037	0.0037	0.0037	0.0037	0.0037	0.0037	0.0037	0.0037	0.0037
Time Interval		hours	0.0072	0.0072	0.0072	0.0072	0.0072	0.0072	0.0072	0.0072	0.0072	0.0072	0.0072
Distance to Wildfire Origin		miles	11.5	12.2	13.4	14.1	15.6	16.7	18.5	19.4	20.5	21.1	24.4

The distance from wildfire origin for each segment is the straight-line distance from Lake Lucille origin to state-line plus the length of the current segment and all upstream segments. This puts the datum for determining the cumulative number of exiting vehicles and vehicle attrition at the downstream end of each segment.

For the Caldor wildfire, the order to evacuate Grizzly Flats and Pollock Pines (where the fire started) was delayed 24 hours after the rapid spread phase began. For the traffic flow models described in the next section, we used a range of values for the delay in issuing the evacuation order: 24, 12, and 9 hours. The latter two assume an improvement in State and local decision-making policy regarding emergency response.

Traffic Flow Models

Three traffic flow models were developed to bound the problem posed by the evacuation of the residents and guests from the South and East Shores of Lake Tahoe.

1. Optimal Flow Rate

The most optimistic model assumes the optimal traffic flow rate for a 3-lane evacuation corridor, based on the second-order capacity flow *vs.* speed relationship from Dougherty[7]. This sets the flow rate throughout the corridor at a constant 2060 vehicles per hour per lane (vphpl) or 6180 vehicles per hour (vph). The corresponding constant speed at this optimal flow rate is 16 miles per hour (again according to Dougherty), and the traffic density is 386.25 vehicles per mile (vpm). We use the "delay in issuing evacuation order," the fire-front progression in Appendix B, and this optimal flow rate to calculate the vehicle attrition and lives lost as the fire front catches up with the evacuating vehicles in the corridor.

2. Flow Rate based on Caldor Evacuation Transit Time

The second model uses the transit time observed for the Caldor wildfire evacuation to calculate the average flow rate. According to SFGATE[8] regarding the Caldor wildfire evacuation:

> "It was a tense few moments I think for our citizens in south Lake Tahoe today," South Lake Tahoe Police Chief David Stevenson said. "Three and a half hours of being stuck on Highway 50. I'm so appreciative that our citizens listened to the warning and the order and evacuated the city. Their response was fantastic, and we appreciate them. I'm glad to know they are safe."

Given that approximately 3.5 hours may be needed to traverse the 12.9-mile East Shore corridor, the average vehicle speed would be 3.69 mph.

" 'Jam density' refers to extreme traffic density when traffic flow stops completely, usually in the range of 185–250 vehicles per mile per lane[9,10]." We assume an average density that is half of the most optimistic jam density of 250 vpmpl, which equates to 375 vpm for the three egress lanes. We may expect the actual vehicle density to be less than this number at Lake Tahoe, due to the number of large SUVs, pickup trucks, and recreational vehicles typically seen there.

The average traffic flow rate is the traffic density times the average vehicle speed or 1290.9 vph. We use this flow rate to determine the vehicle attrition and lives lost, as before.

We also scaled the flow rate down, assuming two egress lanes, as would be the case if the NDOT CMP "road diet" were implemented.

3. TESsim Traffic Flow Macrosimulation

Appendix C describes the methodology used to build our TESsim traffic-flow macrosimulation model. This model reasonably represents variable flow rates, speeds, and densities that would occur in a real wildfire evacuation. In particular, it captures the compressibility of the traffic flow in a congested evacuation condition leading to wave-like flow dynamics. Several state variables are used to characterize the evacuation process as a function of time, and these variables are advanced with time using equations-of-state, described more fully in the appendix. Vehicle attrition is then calculated as the fire front advances through the traffic column. The "conveyor-belt" approach used to approximate vehicle speed and traffic density variations produces attrition results that are considered pessimistic (and may be overly pessimistic), suggesting the need for a higher-fidelity evacuation traffic-flow microsimulation.

Simulated Wildfire Evacuation Results

Table 2 compares the vehicle attrition and lives lost for each of the traffic flow models described above. Assuming the same 24-hour delay in issuing an evacuation order experienced during the Caldor wildfire, approximately 90% of all evacuating vehicles and their occupants would be lost under best-case conditions. The attrition is reduced substantially given a 12-hour delay, and more so given a 9-hour delay. Yet these attrition numbers are still very disturbing, indicating the need for improved forestry management and more effective fire-containment emergency response to slow the wildfire spread rate.

Table 2. Vehicle attrition and Lives Lost in Presumed Lake Lucille Wildfire

Case	Transit Time (hrs)	Vehicle Speed (mph)	Vehicle Density (vpm)	Average Flow Rate (vph)	Delay in Issuing Evacuation Order (hr)					
					24		12		9	
					Vehicle Attrition	Lives Lost	Vehicle Attrition	Lives Lost	Vehicle Attrition	Lives Lost
Optimal Flow Rate (3 lane)	0.81	16.00	386.3	6180.00	47,045	117,613	0	0	0	0
Clador Transit Time (3 lane) half jam density	3.50	3.69	350.3	1290.92	48,117	120,292	32,626	81,565	28,753	71,883
TESsim (3 lane)		all variable		130.60			48,198	120,496		
Zero Attrition Threshold (24 hr delay)	0.02	630.32	350.25	220770.00	0	0				
Zero Attrition Threshold (12 hr delay)	1.14	11.31	350.25	3960.90			0	0		
Zero Attrition Threshold (9 hr delay)	1.42	9.08	350.25	3180.10					0	0

The last three lines in Table 2 show average flow rate and corresponding transit time, vehicle speed, and vehicle density required to achieve zero attrition (no fatalities). Given the Caldor 24-hour delay in issuing an evacuation order, the fire front would have nearly reached the Stateline border by the time the formal evacuation began; and the required vehicle speed to bring the entire population to safety would be that of a Mach 0.85 jet aircraft -- totally unrealistic. The only numbers even approaching reality are for the 9-hour delay case.

Table 3 compares the vehicles and lives that would be saved for three egress lanes (existing US 50 configuration) and two egress lanes (CMP "road diet"). As shown, with two evacuation lanes, the number of lives saved decreases by approximately 25% under the same transit time and vehicle speed conditions. The clear conclusion from this analysis is that a road diet would significantly increase fatalities and makes absolutely no sense for the US 50 East Shore corridor.

Table 3. Vehicles and Lives Saved: Existing US 50 *vs.* Proposed CMP

Case	Transit Time (hrs)	Vehicle Speed (mph)	Vehicle Density (vpm)	Average Flow Rate (vph)	Delay in Issuing Evacuation Order (hr)					
					24		12		9	
					Vehicles Saved	Lives Saved	Vehicles Saved	Lives Saved	Vehicles Saved	Lives Saved
Clador Transit Time (3 lane) half jam density	3.50	3.69	350.3	1290.92	5,336	13,340	20,827	52,068	24,700	61,750
Caldor Transit Time (2 lane) half jam density	3.50	3.69	233.5	860.61	5,242	13,104	15,569	38,923	18,151	45,377

APPENDIX A: VEHICLE QUEUE CALCULATIONS

This appendix calculates the summer high-season population of residents, their visitors, and vacationers for the City of South Lake Tahoe (including the Stateline Casinos) and the residential communities plus resorts along the East Shore between Stateline Ave. and Spooner Summit.

South Lake Tahoe Vehicles

The year-round resident population within the Lake Tahoe Basin in 2019 was 53,668[11]. The summer high-season population for residents, their visitors, and vacationers is estimated to be 300,000[4].

The year-round resident population for the City of South Lake Tahoe, CA in 2023 is 21,636[12]. We estimate that the summer high-season population for residents, their visitors, and vacationers in just South Lake Tahoe is in direct proportion to the year-round resident population, which is estimated to be 121,000 persons, including the Stateline casinos. We believe this to be reasonable given that there are a proportional number of casinos and hotels in the CalNeva and Incline Village areas along the North Shore.

According to Wikipedia[13], there are 0.803 vehicles per capita in Nevada. The per capita number for visitors and tourists in a destination resort would be less for several reasons: public transportation from airports and other transportation hubs, one car per visiting family, carpooling by out-of-area workers, etc. We thereby estimate a smaller number, say 0.4 vehicles per capita in South Lake Tahoe. This equates to 48,400 vehicles that would need to be evacuated during a wildfire.

Tahoe East Shore Vehicles

The number of vehicles that would need to be evacuated within each segment of the East Shore corridor comprises vehicles of local residents and visitors, vacation home renters, campers, local resort vacationers, and daily non-lodging tourists.

We estimate the number of local resident vehicles from the number of parcels recorded in Douglas County. Since not all parcels are developed, we include a parcel overcount factor taken from the ratio of developed parcels to the number of recorded parcels in the Glenbrook community (0.88). We assume that the average number of vehicles per living unit for the low-density parcels is the 2017 national average of 1.88[14], and that the high-density parcels have half that number of vehicles per living unit. We further assume that the number of vehicles added by residential visitors and upper-tier vacation home rental occupants is relatively small and can be ignored.

The number of campers and other vehicles at local resorts is limited by the number of camping sites and parking spaces. Similarly, the number of vacationer vehicles will be limited to a large extent by the number of legal parking spaces, once on-road parking is eliminated along the corridor. These numbers have all been determined by counting the number of spaces in satellite imagery.

Table A1 provides an estimate of the number of vehicles within each segment requiring evacuation, and this data is used in the traffic-flow models as the initial number in the vehicle queue.

Table A1. Vehicles Requiring Evacuation per Segment

Characteristic	Total	Segment 1 North of Glenbrook to Spooner	Segment 2A North of Logan Shoals to North of Glenbrook	Segment 2B Along Logan Shoals	Segment 2C North of Cave Rock to South of Logan Shoals	Segment 3 Skyland to North of Cave Rock	Segment 4A Zephyr Cove to Skyland (incl. Skyland)	Segment 4B Round Hill Pines to South of Zephyr Cove	Segment 5A Elks Point Rd. to Round Hill Pines (Incl. Elks Pt. Rd.)	Segment 5B Kingsbury Grade to Elks Point Rd.	Segment 6 Stateline Ave. to Kingsbury Grade
Number of Parcels	2950	0	398	83	26	427	238	724	440	614	0
Low Desnity	2187	0	398	83	26	422	238	602	343	75	0
High Density	763	0	0	0	0	5	0	122	97	539	0
Cars per Household											
Low Desnity	1.88	1.88	1.88	1.88	1.88	1.88	1.88	1.88	1.88	1.88	1.88
High Density	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94
Parcel Overcount Factor	0.880	0.880	0.880	0.880	0.880	0.880	0.880	0.880	0.880	0.880	0.880
Residential Vehicles	**4247**	**0**	**658**	**137**	**43**	**702**	**394**	**1096**	**647**	**570**	**0**
Camp Sites	**204**	**0**	**0**	**0**	**0**	**0**	**150**	**0**	**54**	**0**	**0**
Nevada Beach	54								54		
Zephyr Cove	150						150				
Resort Parking	**602**	**0**	**0**	**0**	**0**	**51**	**275**	**126**	**150**	**0**	**0**
Nevada Beach	150								150		
Round Hill Pines	126							126			
Zephyr Cove	275						275				
Cave Rock Boat Ramp	51					51					
Total Vehicles in Queue	**5053**	**0**	**658**	**137**	**43**	**753**	**819**	**1222**	**851**	**570**	**0**
Equivalent Entry Points		**0**	**2**	**1**	**1**	**2**	**1**	**3**	**2**	**2**	**0**

APPENDIX B: WILDFIRE SPREAD RATE CALCULATIONS

Wildfire Spread Distance

The extent of the 2021 Caldor wildfire on Oct 6, 2021, was mapped using NASA Scientific Visualization Studio imagery[15]. Figure B1 shows the results of this visualization and identifies the origin, near Grizzly Flats. The wind direction is predominately Southwest, which is the same as the average wind direction in the Lake Tahoe Basin, and the elongated shape of the wildfire follows the shape of the valley.

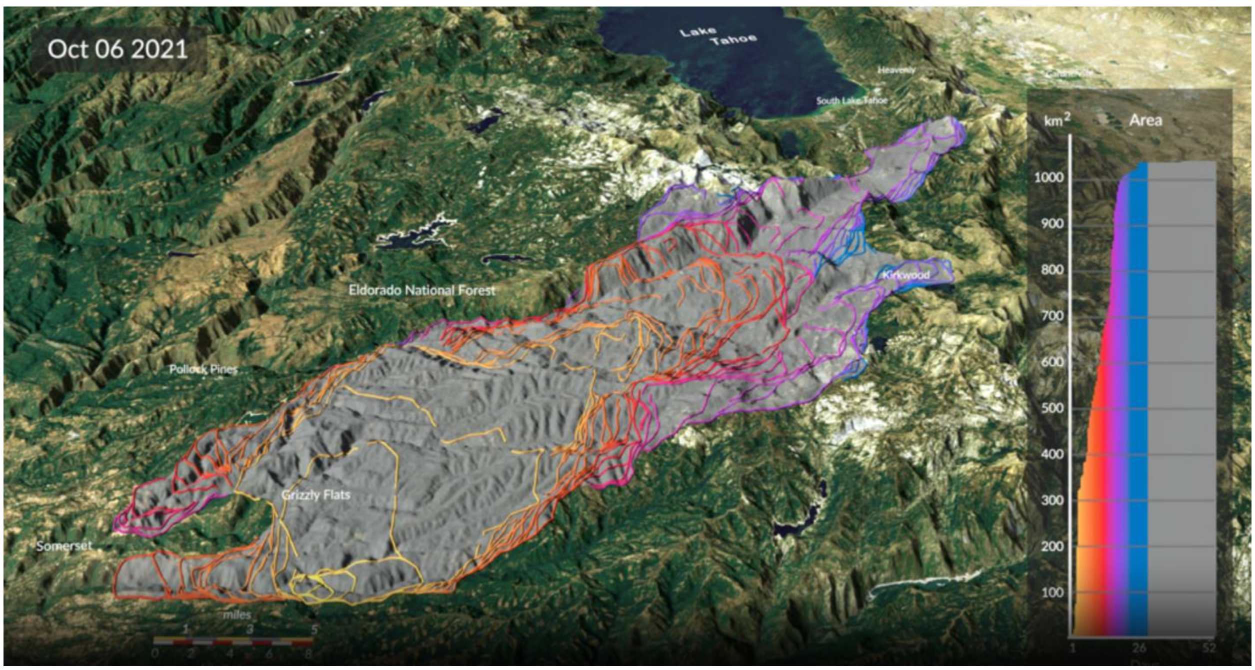

Figure B1. Caldor Fire Spread Rate

Table 2 shows the area burned each day of the Caldor Fire[16]. The fire was started on August 14, 2021, and an evacuation order for Pollock Pines and Grizzly Flats was issued August 17, 2021, at which time the fire had already consumed to 2,261 acres. The following day saw a rapid growth in burned area to 22,919 acres. From August 18 to Sept 1, the fire grew to 207,931 acres. The shape of the fire front was approximately elliptical with an eccentricity of 0.947 and radiated with one of the foci remaining at the fire's origin near Grizzly Flats. In this approximation, the fire front progressed linearly from Aug 16 to 18 at a rate of 0.324 mph and linear thereafter at 0.047 mph.

We can reasonably assume that a postulated Lake Lucille wildfire, which could threaten the South and East Shore communities of Lake Tahoe , would have a similar spread rate and direction. We further assume that a mandatory evacuation order is announced within the first day the fire is detected, specifically 12 hours after the fire has spread 2,250 acres. This represents an improvement over the Caldor response time, but certainly within the capability of

CalFires and the respective government authorities. We also assume that US 50 and its intersections are reconfigured for emergency evacuation when the announcement is made.

Table B1. Caldor Fire Spread Rate

Date	Time from Start (t)	Containment	Actual Area Burned		Actual Fire Front Distance (X')	Fire Front Linear Model (X)	
	hr	%	acres	km^2	km	km	miles
16-Aug	0	0	2,261	9.150	5.875	5.875	3.651
17-Aug	24	0	22,919	92.75	18.705	18.393	11.429
18-Aug	48	0	62,588	253.28	30.911	30.911	19.207
19-Aug	72	0	68,630	277.74	32.369	32.728	20.336
20-Aug	96	0	71,845	290.75	33.118	34.544	21.465
21-Aug	120	0	90,107	364.65	37.089	36.360	22.593
22-Aug	144	5	104,309	422.12	39.905	38.177	23.722
23-Aug	168	9	114,166	462.01	41.748	39.993	24.851
24-Aug	192	11	122,980	497.68	43.330	41.810	25.979
25-Aug	216	12	126,566	512.19	43.957	43.626	27.108
26-Aug	240	12	139,510	564.58	46.150	45.443	28.237
27-Aug	264	19	145,463	588.67	47.124	47.259	29.365
28-Aug	288	19	152,545	617.33	48.258	49.076	30.494
29-Aug	312	13	168,387	681.44	50.702	50.892	31.623
30-Aug	336	15	186,568	755.01	53.369	52.709	32.752
31-Aug	360	19	199,632	807.88	55.206	54.525	33.880
1-Sep	384	23	207,931	841.47	56.341	56.341	35.009
2-Sep	408			841.47	56.341		
3-Sep	432			841.47	56.341		
4-Sep	456			841.47	56.341		
5-Sep	480	44	215,400	871.69	57.344		
6-Sep	504	44	216,358	875.57	57.472		
7-Sep	528			875.57	57.472		
8-Sep	552	50	217,859	881.64	57.671		
9-Sep	576			881.64	57.671		
10-Sep	600	53	218,459	884.07	57.750		
11-Sep	624			884.07	57.750		
12-Sep	648	65	219,267	887.34	57.857		
13-Sep	672			887.34	57.857		
14-Sep	696	69	219,267	887.34	57.857		

APPENDIX C: TESsim Model

In an effort to understand the traffic flow dynamics for rapid evacuation should a major wildfire directly threaten the City of South Lake Tahoe and the surrounding communities, the Tahoe East Shore Alliance developed a low-fidelity traffic-flow macrosimulation model, "TESsim. The model presumes the breakout of a fast-expanding wildfire, similar to the Caldor wildfire, with origin near Lake Lucille, which is located 5.7 miles East of Meyers, CA. The population to be evacuated and the spread rate of the fire are described in Appendices A and B, respectively. The model is built on Microsoft Excel as a platform and, as such, lacks the fidelity that an agent-based microsimulation[17], such as Vissim or TransModeler.

The results obtained from TESsim are considered pessimistic, as the jam conditions tend to be amplified, extending corridor transit times. Therefore, the results obtained for a particular set of fire mitigation, emergency response time, and UD 50 East Shore Corridor capacity, while useful in identifying the macro problem, cannot accurately predict evacuation times and casualties. Moreover, TESsim should NOT be used to contrast different road configurations, as that approach would only reveal the model's idiosyncrasies (e.g., jam conditions, local queueing delays, capacity *vs.* speed relationship) rather than provide accurate comparative results.

The breadth and depth of the Excel spreadsheet used in TESsim to calculate vehicle attrition rates are too large to represent in this paper, and the reader is encouraged to request a copy. The TESsim spreadsheet is open source and can be made available upon formal request through TESA. The following section describes the general methodology used to build TESsim.

TESsim Modeling Methodology

The state variables for each road segment are updated in time using equations-of-state, which include Greenshields traffic flow equations[18] and a continuity equation. A time interval, dt, is chosen such that the state variables will not change appreciably from one time point to the next. A reasonable time interval is found to be the minimum time it takes a vehicle traveling at flow capacity speed to traverse one third the length of any segment (Segment 5A being the limiting case), which is approximately 26 sec (0.0073 hrs). This ensures that there will be at least three bins per segment.

$$dT = Db_Z/(3 * vC_Z), \quad Z \text{ such that } dT \text{ is minimized}$$

The TESsim macrosimulation is run as part of a Microsoft Excel spreadsheet, with segment characteristics and state variables listed across the horizontal axis, and time points incremented along the vertical axis, which also reports progression of the wildfire and calculates vehicle attrition.

A macrosimulation of this sort could be based on various flow models (fluid dynamics, macro-particles, etc.), each providing similar results. Our use of an Excel spreadsheet best lends itself to a conveyor-belt flow model, as shown in Figure C1, where vehicles are grouped into bins that run along an imaginary conveyor belt moving at a fixed velocity, v_Z. The number of evacuating vehicles in a given bin is determined by flow parameters from the upstream segment. When a bin reaches the downstream end of the segment belt, vehicles from a segment-specific queue of local vehicles (seeking evacuation) are added to those in the last bin and transferred to a bin at the upstream end of the downstream segment within the current time segment, t. If a downstream traffic jam occurs, the model allows traversing vehicles to be added to the local queue. While not representative of actual flow, this partially compensates for the fixed speed of the conveyor (a modeling artifact), essentially enabling compressibility (traffic density increase). The downside of this model is that propagation delays are not accurately represented. This issue is diminished somewhat as the selected time interval, dt, is reduced.

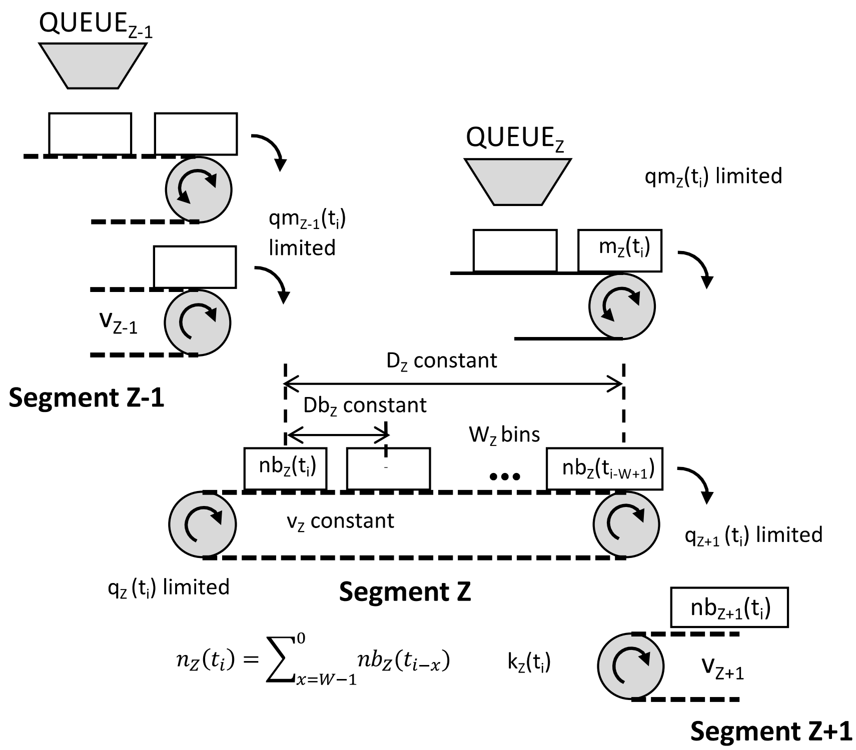

Figure C1. Road Segment Traffic Flow Conveyor-Belt Model

The 85-percentile operating speed within the 35-mph portion of Segment 5 was reported by Wood Rogers[19] as 48 mph. As such, we assume a maximum operating speed that is 13 mph over lowest posted limit (or speed limit at horizontal curves) in segments where the posted limit is less than 45 mph. Section 3.1 of the *NDOT Road Design Guide*[20] states: "For all other routes [other than rural freeways], the design speed shall be set at 10 mph over the posted speed." We shall adopt this philosophy and set maximum operating speed at design speed (10 mph above the posted speed limit) for segments where the posted limit is 45 mph or greater. This is in accordance with observed behavior within the US 50 corridor and considered appropriate for evacuation.

According to Greenshields[18], average vehicle speed at traffic flow capacity, vC, is half the free-flow speed (i.e., maximum operating speed), v_f. This is the assumed operating speed within each segment and is equivalent to the constant conveyor speed.

$$vC_Z = v_f/2$$

For the conveyor-belt flow model to converge, it is important that the number of bins, W_Z, within each segment be an integer. To accommodate this, average vehicle speed is adjusted downward accordingly.

$$v_Z \leq vC_Z \; such\ that\ W_Z\ is\ the\ next\ larger\ integer\ value$$

State Variables

State variables are ascribed to each road segment, Z, and are updated by TESsim at each time point (identified as t_i, where i represents the present time increment). These are listed below in the order they are calculated within TESsim.

- distance from fire front (miles), $B_Z(t_i)$
- vehicles per bin entering from upstream segment (vehicles), $nb_Z(t_i)$
- vehicles entering from segment queue (vehicles), $m_Z(t_i)$
- traffic flow rate at upstream end of segment (vehicles per mile), $q_Z(t_i)$
- total number of vehicles within segment (vehicles), $n_Z(t_i)$
- traffic density within segment (vehicles per mile), $k_Z(t_i)$
- number of local vehicles remaining within segment queue (vehicles), $mr_Z(t_i)$
- cumulative number of vehicles having exited the segment (vehicles), $p_Z(t_i)$
- new vehicle attrition from segment due to fire (vehicles), $F_Z(t_i)$

Equations-of-State

Equations-of-state are used to advance the state variables within a given segment, Z, from the previous time interval, t_{i-1}, to the present time interval, t_i. Equations-of-state and other formula used in TESsim are listed below in order of calculation.

(1) For each new time point, the distance from the fire front to the downstream end of each segment, $B_Z(t_i)$, is calculated; where BY_Z is the distance of the segment from Lake Lucille origin, and $A(t_i)$ is the distance the fire front has progressed at time t_i from Appendix B.

$$B_Z(t_i) = BY_Z - A(t_i)$$

(2) The initial traffic flow rate for each segment is the capacity flow rate, qC_Z, at the free-flow vehicle speed, vM_Z. Traffic flow capacity is the maximum number of vehicles that can pass a particular point along a single or multi-lane roadway. Table C1 compares various models for single-lane free-flow traffic capacity, including both first- and second-order equations. These are plotted in Figure C2.

Table C1. Free-Flow Traffic Capacity Models

Source	Description	Traffic Capacity Model
NHCRP[17]	1st order	for v < 70 mph, q = 2200 + 10*(v-50)
		for v > 70 mph, q = 2400
Johnson[7]	1st order	q = 5280*v/(15 + 0.5*v)
Johnson[7]	2nd order	q = 5280*v/(15 + v^2/15)
Johannesson[7]	1st order	q = 5280*v/(25 + 2.2*v)
Dougherty[7]	2nd order	q = 5280*v/(15 + 0.056*v^2 + 0.73*v)

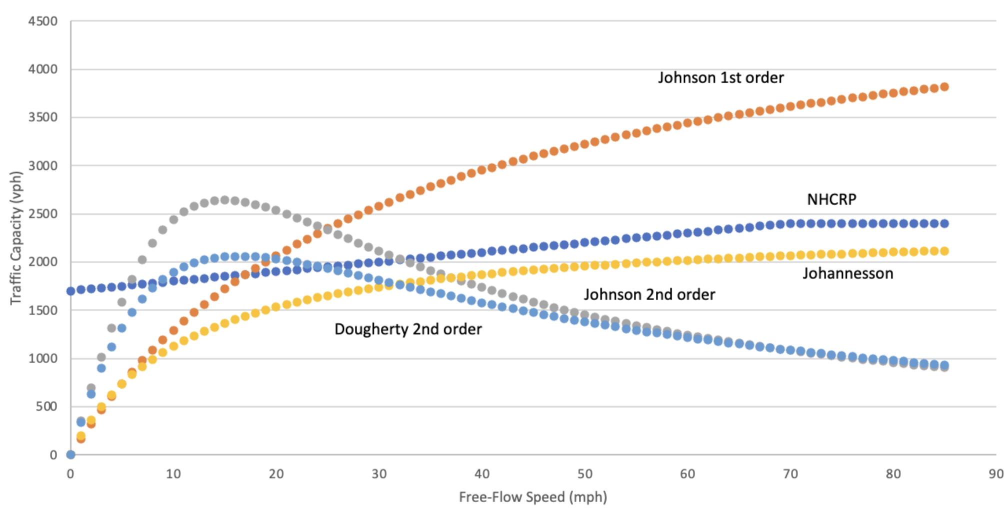

Figure C2. Traffic Flow Traffic Capacity *vs.* Average Operating Speed

We chose the second-order equation according to Dougherty[7] as a reasonable compromise within the range of vehicle speeds-of-interest, where speed is in miles per hour. Note, however, that none of these models consider additional factors, such as road condition, road width, sight distance, horizontal curvature, vertical curvature, and superelevation.

$$qC(single\ lane) = \frac{5280\ v}{15 + 0.056\ (v)^2 + 0.73\ v}$$

As shown in Figure 2 for the Dougherty second-order model, there is a maximum traffic flow capacity, qC, of 2060 vehicles per mile, corresponding to an average operating speed of 16 mph. The shape of this curve is determined by an average driver's perception of reaction time and stopping distance. Note that flow capacity at speeds below the optimum is severely curtailed, and this condition should be avoided. However, flow capacity at speeds above optimum is much less diminished, so operating in the region to the right of the peak is acceptable, but excessive speeds should be avoided.

We make a simplifying assumption that during an evacuation, egressing vehicles will largely stay within their lane, so that multi-lane capacity can be calculated as the single-lane capacity times the number of lanes, L_Z, without adjusting for passing and other conditions. As the model progresses in time, flow rate for each segment is determined from the flow characteristics of downstream segments.

$$qC\ (multi\ lane)\ =\ L_Z\, qC(single\ lane)$$

(4) The number of vehicles (per bin) that can flow into the downstream segment, $nb_Z(t_i)$, is the product of downstream flow rate from the previous time point, $q_{Z+1}(t_{i-1})$, and time interval, dt.

$$nb_Z(t_i) = q_{Z+1}(t_{i-1})dt$$

(5) A continuity equation is then used to calculate the number of local vehicles that can be added within each segment, $m_Z(t_i)$. This can be a negative number, and flow rates within the upstream sections are adjusted in future times to achieve positive flow out of the queues.

$$m_Z(t_i) = nb_{Z+1}(t_i) - nb_Z(t_{i-W+1})$$

(6) The average time it takes for a local vehicle to enter the roadway, tL, was measured at 10:00 AM on Oct 12, 2023, to be 13.49 sec or 0.0037 hrs. Under actual evacuation conditions, maximum flow rate from a single entry point, qL_Z, would be the reciprocal of tL.

$$qL_Z = 1/tL$$

The maximum number of local vehicles that can enter in a time interval, $mM_Z(t_i)$, would be maximum flow rate times the time interval.

$$mM_z(t_i) = qL_Z dt$$

$$m_Z(t_i) \leq mM_z(t_i)$$

However, because we are modeling segment compressibility by adding congested vehicles to the local vehicle queue, we do not limit local queue flow rate in TESsim. This feature may overestimate the evacuation rate of local residents, but it does not significantly affect overall evacuation metrics.

(7) Continuity also demands that the total number of vehicles remaining within the local queue, $mr_Z(t_i)$, is the total from the last time point, $mr_Z(t_{i-1})$, minus vehicles currently leaving the queue, $m_Z(t_i)$.

$$mr_Z(t_i) = mr_Z(t_{i-1}) - m_Z(t_i)$$

(8) The traffic flow rate, $q_Z(t_i)$, is set initially at the capacity flow rate, $q_Z(t_i)$, and maintained at capacity unless a downstream traffic jam occurs, as discussed below.

(9) The total number of vehicles traversing the segment, $n_Z(t_i)$, is then calculated, which is the total across all bins within the segment. Since there are W bins per segment, the total is:

$$n_Z(t_i) = \sum_{x=W-1}^{0} nb_Z(t_{i-x})$$

where: $W \sim D_Z/(v_Z \mathrm{dt})$

(10) The traffic density for each segment, $k_Z(t_i)$, is the number of vehicles traversing the segment divided by segment length.

$$k_Z(t_i) = n_Z(t_i)/D_Z$$

(11) Jam density, k_j, is the average number of vehicles per mile that the roadway can handle during a traffic jam, when the velocity reaches standstill. According to Greenshields[18], the jam density is twice the density at capacity, while other traffic models extend jam density.

$$k_j = 2\; qC_Z v_Z$$

A traffic jam is detected in the TESsim model when the number of vehicles entering from the local queue goes negative (i.e., vehicles begin to stack up in the local queue). When this happens, traffic flow rate is adjusted downward in all upstream segments until the jam has cleared, at which point flow rate is returned to capacity.

(12) The cumulative number of vehicles that have exited the segment, $p_Z(t_i)$, is then calculated as the vehicles exited in the previous time point, $p_Z(t_{i-1})$, plus the new vehicles that exit the segment, $n_Z(t_i)$. Vehicles artificially introduced into the pipeline to begin the simulation are subtracted from the attrition numbers.

$$p_Z(t_i) = p_Z(t_{i-1}) + n_Z(t_i)$$

(13) When the calculated distance from the fire front to the downstream end of the segment at the present time point, $B_Z(t_i)$, goes negative; the fire front has consumed the segment and all vehicles within the segment are considered lost. At that point, new vehicle attrition, $F_Z(t_i)$, is the number of vehicles originally in the local queue, mr_Z, plus the number of vehicles presently traversing the segment, $n_Z(t_i)$.

$$if\ B_Z(t_i) < 0,\quad then\ F_Z(t_i) = mr_Z - n_Z(t_i),\ \ else\ F_Z(t_i) = 0$$

(14) The cumulative number of vehicles that have been lost at the current time point, is then calculated.

$$FT(t_i) = FT_Z(t_{i-1}) \sum_{1}^{all\ Z} F_Z(t_i)$$

The macrosimulation is allowed to run until all vehicles in South Lake Tahoe and the East Shore communities, not consumed by wildfire, have exited the final segment.

Formulae used in the macrosimulation are listed in Tables C3 through C5 for initial parameters, segment characteristics, and equations-of-state, respectively.

Table C3. TESsim Initial Parameters

Initial Parameters		Condition	Formula
Interval Time (hr)	dt	Minimum across all segments	dt = INT(10,000*D_Z/(3*vC_Z))/10000
State Line to Fire Origin (miles)	BY		Appendix A
Initial Spread intercept (miles)	A1		
Initial Spread Rate (mph)	S1		
Final Spread Intercept (miles)	A2		
Final Spread Rate (mph)	S2		
Crossover time (hrs)	tY		
Local Vehicle Delay per Entry Point (hr)	tL		Empirical Measurement 13.492 sec = 0.0037 hrs
Flow Rate Decrement near Jam (%)	QD		Trial and eror to minimize queue backup

Table C4. TESsim Segment Characteristics

Segment Characteristics		Condition	Formula
Segment Label	Z		
Road Length (miles)	D		From Google Maps
Number of Evacuation Lanes	L		Present Configuration and CMP Reconfiguration
Lane Width (ft)	U		
Posted Speed Limit	vP		Existing limits
Maximum Operating Speed (mph) same as Free Flow Speed	vMA	vP<45 mph	vMA_Z = vP + 13 mph
		else	vMA_Z = vP + 10 mph
	vM	U<12 ft	vM_Z = vP
		else	vM_Z = vMA_Z
Speed at Capacity (mph)	vC		vC_Z = vM_Z/2
Bin Length (miles)	Db		Db_Z = D_Z(minimum)/3
Number of Bins per Segment	W		input largest W such that v_Z < vC_Z
Assumed Operating Speed	v		v_Z = D_Z/(W_Z*dt)
Free Flow Traffic Capacity (vph)	qC		qC_Z = 5280*L*vM_Z/[15 + 0.056*vM_Z^2 + 0.73*vM_Z]
Jam Density (vpm)	kj		kj_Z = 2*qC_Z*v_Z
Initial Number of Local Vehicles	mrY		Appendix B
Number of Entry Points	Y		
Max Local Flow Capacity (vph), all entry points	qL		qL_Z = Y/tL
Max Local Vehicles Entering	mM		mM_Z = qL_Z*dt
Distance from Fire Origin (miles)	BY		From Google Maps

Table C5. TESsim Equations-of-State

Equations-of-State				
State Variables		**Condition**		**Formula**
Fire Front Leading Edge Distance (miles) -- all segments	A	t<tY	high slope portion	A=A1 + S1*t
		else	low slope portion	A=A2 + S2*t
Distance from Fire Front (miles)	B_Z	none		B_Z=BY-A
Vehicles per Bin	nb_Z	$B_{Z-1}>0$	upstream not in fire	$nb_Z(i)=q_{Z+1}(i-1)dt$
		else	fire reached upstream	$nb_Z(i)=0$
Local Vehicles Entering	m_Z	$B_Z>0$	seg not in fire	$m_Z=nb_{Z+1}(i)-nb_Z(i-W+1)$ can be negative
		else	fire reached seg	$m_Z=0$
Local Vehicles Remaining	mrA_Z	$mr_Z(i-1) - m_Z(i)>0$	vehicles still in queue	$mrA_Z=mr_Z(i-1) - m_Z(i)$
		else	no local venicles left	$mrA_Z=0$
	mr_Z	$B_Z>0$	seg not in fire	$mr_Z=mrA_Z$
		else	fire reached seg	$mr_Z=0$
Traffic Flow Rate (veh/hr)	JF	$m_Z<0$	downstream pileup Z+1	$JF_Z=1$
		else	no downstream pileup	$JF_Z=0$
	q_Z	$\sum_{z=Z+1}^{max\ Z} JF_Z(i) > 0$	pileup any downstream segment	$q_Z(t_i) = (0.01)(QD)nb_Z(t_i)/\left[\sum_{z=Z+1}^{max\ Z} JF_Z(t_i)\right]$
		else	pileup at Z+1	$q_z(i) = nb_{Z+1}(i)/dt$
Number Vehicles Traversing	n_Z	none		$n_Z(t_i) = \sum_{x=W-1}^{0} nb_Z(t_{i-x})$
Traffic Density (veh/mi)	k_Z	$B_Z>0$	seg not in fire	$k_Z=n_Z(i)/D_Z$
		else	fire reached seg	$k_Z=k_Z(i-1)$
Cumulative Vehicles Exited	p_Z	$B_Z>0$	seg not in fire	$p_Z=p_Z(i-1) +nb_{Z+1}(i)$
		else	fire reached seg	$p_Z=p_Z(i-1)$
New Vehicle Attrition	FA_Z	$B_Z>0$	seg not in fire	$FA_Z=0$
		else	fire reached seg	$FA_Z=mr_Z+n_Z$
	F_Z	FAZ>FAZ(i-1)	future time	$F_Z=FA_Z$
		else	fire just reached seg	$F_Z=0$
Cumulative Vehicle Attrition	FT	none		$FT(t_i) = FT_Z(t_{i-1})\sum_{1}^{all\ Z} F_Z(t_i)$

Simulation Results and Conclusions

Table C6 records the results of the TESsim analysis for The Lake Lucille wildfire scenario. The average number of vehicles per capita in South Lake Tahoe is estimated in Appendix A as 0.4. The number of persons per vehicle used in the fatality calculations must therefore be 2.5 for consistency. Given the vehicle attrition data resulting from the TESsim wildfire evacuation simulation, we conclude that for the presumed Lake Lucille wildfire under the stated evacuation conditions, 120,496 lives of the original 133,633 residents and vacationers would be lost. A fatality rate exceeding 90 percent. A truly devastating result!

Table C6. Vehicles and Lives Lost in Tahoe Basin Given Postulated Wildfire

Scenario	Segment	Time Fire Front Reached Segment	New Vehicle Attrition	Cumulative Vehicle Attrition	New Fatalities	Cumulative Fatalities
Present Configuration	**7***	24.2	47813.47	47813.47	119533.66	119533.66
	6	26.4	0.19	47813.65	0.47	119534.13
	5B	30.1	1.07	47814.72	2.67	119536.81
	5A	32.2	367.53	48182.26	918.84	120455.64
	4B	36.9	3.76	48186.02	9.40	120465.04
	4A	40.3	5.10	48191.12	12.75	120477.80
	3	45.8	7.10	48198.22	17.75	120495.54
	2C	52.1	0.05	48198.27	0.14	120495.68
	2B	75.5	0.38	48198.65	0.94	120496.62
	2A	88.2	0.09	48198.74	0.23	120496.85
	1	158.4	0.00	48198.74	0.00	120496.85
Total to be Evacuated				**53453**		**133633**
Percent Atrtrition / Fatalities						**90.2**

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