Forest Science, Vol. 35, No. 3, pp. 870–877.
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Expert Opinion Estimation of Fireline Production Rates

Jeremy S. Fried and J. Keith Gilless

ABSTRACT. An expert opinion survey of wildland firefighters (engine captains, handcrew bosses, and dozer operators) was used to obtain estimates of fireline production rates for use in stochastic simulations of initial attack on wildland fires. The survey design was inspired by the probabilistic PERT/CPM technique of expressing the time required to complete a given activity as a beta distribution. This design proved intelligible to firefighters, cost-effective, and caused minimal disruption of normal firefighting activities. The survey produced useable information quickly. Comparisons of the results with production rates reported in prior studies indicate that the latter are quite optimistic. Production rates appear to be strongly influenced by variations in topography and vegetation that could not be easily categorized on a statewide basis. Other researchers may find this estimation technique to be of value for quantifying a stochastic production process, especially one not readily amenable to direct measurement.

ADDITIONAL KEY WORDS. Initial attack, stochastic simulation, fire protection, survey methods, probabilistic PERT/CPM, wildfire.

STATE AND FEDERAL WILDLAND FIRE PROTECTION ORGANIZATIONS are experiencing unprecedented pressure to justify their expenditures and methods of operation. This has motivated the development of several simulation models of wildfire control efforts (Bratten et al. 1981, Mills and Bratten 1982, USDA Forest Service 1985, Fried and Gilless 1988a). These models share a reliance on assumptions regarding the rates at which bulldozers, fire engines, and handcrews produce fireline.

The fire literature contains dozens of fireline production rate studies for different firefighting resources (Wilson 1980, Haven et al. 1982, Phillips et al. 1988). The rates reported in these studies depend on crew size, fuel type, percent slope, and whether line construction moves up or downhill. The rates vary widely among studies: differences of 500% are not uncommon for what appear to be the same type of firefighting resources operating under the same conditions. Even allowing for inconsistencies in experimental design, this degree of variability clearly indicates that fireline production is most appropriately simulated with stochastic methods.

Unfortunately, prior studies usually report only tables of rates by fuel and resource type, typically with many cells empty. The rates in these tables are usually interpreted as averages, despite the fact that they are often based on a single observation per cell. Not surprisingly, basic distributional parameters (e.g., variance) are seldom reported, and can rarely be inferred from comparisons across studies. The lack of replication that characterizes these studies is at least partially the result of insurmountable logistical problems in deploying observers. Nonfirefighters can rarely be deployed quickly enough, and incident commanders are understandably reluctant to forego the services of a qualified firefighter at the site of an ongoing fire. Aerial observation is limited by its expense, visibility problems, and the difficulty of precisely measuring fireline lengths from the air. Some researchers have attempted to circumvent these problems by measuring fireline production during preparations for prescribed burning, or in the absence of ongoing (or even anticipated) fire activity. The representativeness of measurements thus obtained is questionable.

Capturing the variability in fireline production rates is essential to improve the

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Reprinted from the *Forest Science* Vol. 35, No. 3, September 1989.

initial attack simulation model used by the California Department of Forestry and Fire Protection (Fried et al. 1987, Fried and Gilless 1988b). In light of the deficiencies in the literature outlined above, an expert opinion survey seemed best suited for quantifying this variability. We hoped to tap the accumulated experience of a large number of wildland firefighters who make implicit assessments of fireline productivity on a daily basis when deciding how to attack wildland fires. We surveyed fire captains (fire engines), fire crew supervisors (handcrews), and heavy fire equipment operators (bulldozers) for their assessments of condition-specific fireline productivity for the types of firefighting resources that they command. The survey design, inspired by the probabilistic PERT/CPM technique of expressing the time required to complete a given activity as a beta distribution (Moder et al. 1983), proved both intelligible to the firefighters and cost-effective to implement. Other researchers considering an expert opinion approach to quantify the stochastic properties of a production process may find this design to be of considerable value.

SURVEY METHOD

BASIC ASSUMPTIONS

Discussions with firefighters suggested that a small number of "control conditions" characterized by fuel type, topography, habitation density, and a few other critical factors (e.g., road density, arrival time of supporting resources, and the presence of fences, lava dikes, or rocky soils) can be used to account for much of the variability in fireline production rates. Within these control conditions, firefighters cannot identify the individual factors responsible for the residual variation in production rates; however, they can estimate both likely production rates and the variability to be expected about those rates for a given control condition.

A pilot study unexpectedly revealed that firefighters rarely think in terms of production rates, but *are* comfortable estimating the time required to build a section of fireline. Consequently, we designed our survey to elicit estimates of the *time* required to build a specified length of fireline for a given control condition, avoiding direct estimation of rates. Specifically, firefighters were asked to estimate best possible ($T_{\min}$), most likely (T_{mode}), and worst possible times ($T_{\max}$)—defined as the time achieved when everything goes perfectly with fresh, motivated personnel, the time one would expect to see most of the time, and the time required on a day when everything seems to go wrong. Survey participants were also asked to estimate a time that would be exceeded on no more than 10% of the fires in a control condition, i.e., a time that would be greater than required on 90% of these fires (T_{90}). This estimate, as explained below, provides a check on the traditional PERT/CPM assumption of a standard deviation equal to one sixth of the range from best to worst time estimates (Moder et al. 1983).

PREPARATION FOR THE SURVEY

To obtain production rate estimates that adequately reflected locally important factors, our survey was administered at the ranger unit level. Each of the California Department of Forestry and Fire Protection's (CDF) ranger units covers from one to three counties (1,500 to 50,000 square km). Four to ten control conditions were sufficient to represent the range of firefighting situations encountered on a typical ranger unit. A representative field site (RFS) for each control condition was identified prior to administration of the survey. At each RFS, an eight-foot scaling stake was photographed from all four cardinal directions to document topography and vegetation. Photographs were taken using either a wide angle or normal lens from a distance sufficient to capture the entire stake. A close-up photograph, centered on the bottom 2 ft of the scaling stake, documented the configuration of ground fuels (e.g., duff and leaf litter). All photographs were taken using Kodak Plus-X (black and white) film and printed in 5 × 7″ format. (Color film was not used because of low ambient light at some RFSs, and to minimize the effect of the seasonal state of vegetation on estimates of production times. Firefighters seem to perceive less fire threat when shown color pictures of spring-green grass or succulent chaparral, and have difficulty envisioning the potential range of fire conditions.) Slope, aspect, distance, and direction to a relocatable point were noted on the site description form, along with the presence of any special considerations (e.g., rocky soils or fences) not immediately obvious from the photographs.

For most ranger units, three fire captains, three heavy fire equipment operators, and three fire crew supervisors were selected to participate in the survey. On ranger units where USDA Forest Service resources play a cooperative role on state responsibility wildlands, three USFS fire captains and/or fire crew supervisors were also selected. Where possible, only individuals with considerable experience fighting fires on the range unit were selected.

SURVEY ADMINISTRATION

First, survey participants were taken into the field to visit sites similar to the most important RFSs to ensure that they had a clear, consistent understanding of the control conditions and survey process. A site fitting the description of "least complicated" control condition was usually assessed first. A survey administrator would measure out a distance over which fireline production would be essentially constant, 500 ft for brush and coniferous timber areas and 1320 ft for grass and oak woodland. On a simplified version of the survey form, participants were asked to first estimate T_{mode}, the time required to complete a length of line of that distance, most of the time (i.e., the most likely time). Next, they were asked how long it would take to build the same length of line under optimal conditions (T_{min}) with fresh but experienced personnel, low fire intensity, and no hose breaks (i.e., the best case time). The worst case time, T_{max}, was then estimated assuming the most pessimistic conditions reasonably imaginable—a high intensity fire, frequent hose bursts, and inexperienced and exhausted firefighters. The case of failing to produce any fireline was explicitly eliminated from consideration. Finally, participants were asked to estimate T_{90}, a time to complete the fireline such that they would expect to do better (faster) than on 90 fires out of 100 and exceed (i.e., go slower) on 10 out of 100 fires (i.e., the ninetieth percentile time).

After writing down their independent estimates, participants were asked to share their answers aloud. When there was substantial variation among estimates for the same firefighting resource, participants were asked to explain the reasoning behind their estimates. This often revealed that different individuals were considering different scenarios, especially for the "worst case." The prevalence of agreement in estimates made without collaboration surprised most participants and substantially increased their confidence in the validity of their responses.

This process was repeated at one or two more field sites characteristic of other control conditions. At each site, one survey administrator would walk out the distance appropriate to the fuel to help the participants fix in their minds the lengths of line for which they would be estimating fireline production times. The final survey dataset did not contain the estimates made at these training stops. They were elicited as a practice exercise only, and occasionally reflected collaboration between participants or were elicited at sites not truly representative of any control condition.

The next phase of the survey was administered at another set of field sites similar to the RFSs. At each of these field sites, the photos and site descriptions for all RFSs with the same fuels as a field site were displayed on poster boards. The participants were asked to complete a survey form for each control condition. They were asked to work independently, were given freedom to move about among site descriptions, and were allowed as much time as they needed to complete all survey forms.

This survey has been administered at eight CDF range units to date, and another thirteen are scheduled. By collecting data from each ranger unit, we expect to obtain production rate estimates that reflect both locally important phenomena and the ranger unit's own unique approach to initial attack, thereby enhancing the validity of CFES simulations.

DATA ANALYSIS

PARAMETER ESTIMATION

Survey estimates of the four critical fireline production times (T_{min}, T_{mode}, T_{90}, and T_{max}) were used to estimate parameters for probability density functions of the time required to complete a given length of fireline for each control condition. In keeping with standard PERT/CPM practice, these density functions were assumed to have a beta form:

$$f(x) = \frac{\Gamma(\alpha + \beta)}{\Gamma(\alpha)\Gamma(\beta)} [x^{(\alpha-1)}(1 - x)^{(\beta-1)}]$$

The α and β parameters of the beta distribution were first estimated assuming a standard deviation of one-sixth of the range from best to worst time (after rescaling times to the interval between 0 and 1). The implied distribution was integrated numerically between T_{min} and T_{90} to test the validity of the accepted practice of calculating the standard deviation as one-sixth of a distribution's range. If the area between these two estimates was not equal to 0.9, the standard deviation factor was incremented or decremented as appropriate, and the integration repeated until either the integral equaled 0.9 or the parameters of the beta distribution were no longer defined. An ANOVA of the calculated factors revealed no significant effects from vegetation or firefighting resource but some effect from ranger unit. The distribution of these factors from all surveys combined suggested no reason not to use its overall mean (7.22) from all surveys combined for the derivation of operational beta distributions for all resources and fuel types statewide, allowing estimation of T_{90} to be dropped from future surveys. The distribution of the standard deviation factor was itself reasonably approximated by the beta distribution, but could also be summarized by its mode (6.99) or median (6.69).

RESULTS

As expected, most of the estimated distributions of the time required to build a given length of fireline were either symmetric or skewed left, with T_{mode} closer to T_{min} than T_{max}. In terms of the implicit beta distributions, this meant that α parameters were consistently smaller than the corresponding β parameters. For all control condition/resource combinations, there was some variation among individuals' estimates of T_{min}, T_{mode}, and T_{max}, with T_{max} being the most variable—not surprising given the range in firefighters' "worst" experiences. A beta curve generated from the means of the individual estimates of T_{min}, T_{mode}, and T_{max} for a given control condition/resource combination usually captured the central tendency of the individual beta curves nicely (Figure 1).

Discussions with firefighters revealed that they perceive significant differences in initial attack methods among comparable firefighting resources operated by different agencies. For example, CDF engine crews deploy simple progressive hoselays in which line is principally built at the nozzel end, while their USFS counterparts depend on lateral hoses connected at 100-ft intervals to construct fireline. This difference in strategy appeared to more than offset the numerical advantage of five-person USFS engine crews to three-person CDF crews, since the latter had faster production rates.

Expected values of fireline production *rates* for different situations and resources were calculated from the parameters of the corresponding beta distributions (Table 1). Differences observed in the expected values among ranger units for control conditions with similar slopes and vegetation point to the importance of local factors like rocky soils or fences, although some of this variation appears to be related to differences in initial attack methods among units within the CDF. Expected values derived from prior studies appear to fall either within or *considerably* above the range defined by the survey estimates. Because the published rates are based upon only a few field observations, often taken under ideal conditions, we believe the survey estimates will prove far more robust as descriptors of the mean production rates.

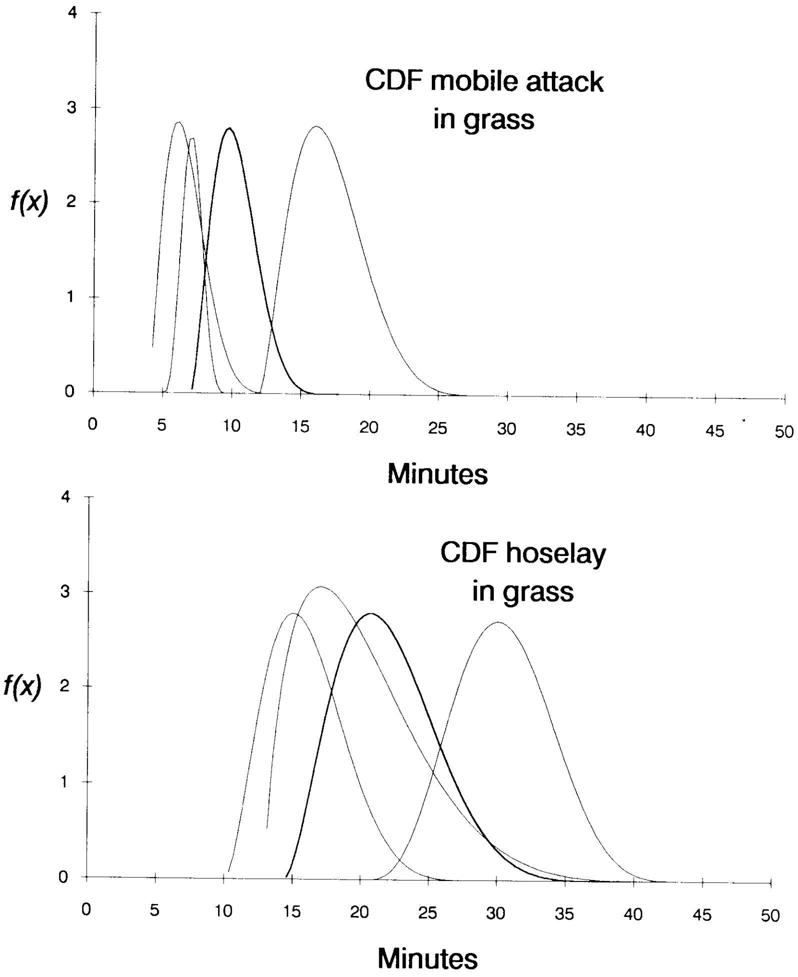

FIGURE 1. Beta distributions of the time required to build 1325 ft of fireline by hoselay and mobile attack in grass fuels on the Madera Mariposa Ranger Unit by CDF three-person engine crews. Distributions derived from an individual's time estimates are drawn as thin lines; distributions derived from the averages of individual estimates are shown as a thick line.

While all of the published rates appear optimistic, those for handcrews and bulldozers seem wildly so. The optimism reflected in the published rates is understated by a simple comparison between the means and survey derived expected values in Table 1. The former are supposedly rates sustainable over a 12-hour period, while the survey reflects firefighters' assessment of a rate sustainable in initial attack, a period of 1 or 2 hours. The published rates seem to incorporate none of the unlucky events that can and do influence real production rates, and thus provide a less than satisfactory basis for simulation of initial attack.

DISCUSSION

An expert opinion survey proved to be a robust, cost effective, and expedient way to gather quantitative information on fireline production rates, an essential element of any stochastic simulation of initial attack on wildland fires. By tapping the collective experience and knowledge of scores of firefighting professionals, the estimated distributions are implicitly based on literally thousands of fires—orders of magnitude more than could be observed directly. With clear, consistent instructions, most

TABLE 1. Expected values of fireline production rates for different firefighting resources for control conditions with similar slopes and vegetation by CDF ranger unit (chains/hr).

Firefighting resource and tactic	Vegetation	Percent slope	Ranger Unit							Rates in prior studies
			BDU	CZU	MMU	MVU	SCU	SLU	SNU	
Engine-mobile	Grass	0–20	32	99	80	—	33	101	47	70
	Grass	20–40	—	—	43	—	—	94	—	—
	Grass	>40	—	—	—	70	—	—	—	—
	Sagebrush	0–20	32	—	—	—	—	—	—	73
Engine-hoselay	Grass	0–20	14	41	37	—	19	—	17	42
	Grass	20–40	—	—	36	—	—	27	—	—
	Grass	>40	12	—	—	47	7	—	—	34
	Brush	0–20	—	14	11	—	—	—	—	36
	Brush	20–40	—	—	—	—	10	—	9	—
	Brush	>40	10	17	9	18	—	17	—	42
	Timber	0–20	—	—	—	—	7	24	—	—
	Timber	>40	—	—	11	—	—	—	—	—
Dozer	Grass	0–20	66	—	65	—	64	187	25	119
	Grass	20–40	—	—	35	—	—	85	—	105
	Grass	>40	56	—	—	27	14	—	—	74
	Brush	0–20	—	—	17	—	—	—	—	58
	Brush	20–40	—	—	—	5	18	—	9	49
	Brush	>40	11	—	9	12	—	13	—	27
	Timber	0–20	—	—	—	—	16	9	—	100
	Timber	>40	—	—	—	5	—	—	—	55
Handcrew	Grass	0–20	12	—	—	—	19	18	12	70
	Grass	20–40	—	—	—	—	—	12	—	—
	Grass	>40	12	—	—	9	5	—	—	—
	Brush	0–20	—	3	1	—	—	—	—	12
	Brush	20–40	—	—	—	—	5	—	8	—
	Brush	>40	5	2	1	6	—	4	—	—
	Timber	0–20	—	—	—	—	7	7	—	82
	Timber	>40	—	—	—	5	—	—	—	—

Notes: Grass, brush, sagebrush, and timber denote vegetation characteristic of NFDRS fuel models A and L, B and F, T, and G and U respectively. BDU, CZU, MMU, MVU, SCU, SLU, and SNU denote the San Bernardino, Santa Cruz, Madera Mariposa, San Diego, Santa Clara, San Luis Obispo, and Sonoma CDF ranger units, respectively. "Prior studies" production rates are from Haven et al. (1982), Phillips et al. (1988), and Wilson (1980).

firefighters had little trouble responding to the questions posed in the survey. The prevalence of agreement among estimates made without collaboration at the RFSs at the beginning of the survey reinforced the confidence of the participants, the credibility they attached to their estimates, and their enthusiasm for the process. Judging by the outcome of a validation exercise in which the survey was administered in conjunction with direct measurement of fireline production rates on several vegetation management planned burns of grass and brush in Riverside County, CA, this confidence seems justified.

Because the survey is being conducted throughout the state at the local level, one could safely say that each of the CDF's 10,000 employees will know at least one firefighter who participated in the survey. This is important, because removing any mystery as to the origin of the production rates greatly increases the probability of their general acceptance in the CDF. In fact, survey data collected in such a fashion must be taken seriously by any fire control organization, since to disavow or consign them to oblivion as "a set of measurements that didn't work out" would cast aspersions on the expertise of its brightest and most experienced firefighters.

The survey's simplicity has several advantages. Once it has been successfully administered one or two times for an organization, the bulk of the unanticipated problems will have been uncovered, minimizing the need for researcher participation in the remaining surveys. Properly trained agency representatives can administer additional surveys independently, preferably in two-person teams.

The nondestructive nature of the survey approach confers distinct advantages over direct measurement of fireline production. It has no visual impact, degrades no airsheds, and poses no risks to people, equipment, or nontarget vegetation or improvements. It does not require firefighters to overcome their aversion to modifying prescribed burns to accommodate researchers, especially when this *might* involve some element of increased risk. The validity of the estimates thus obtained is not called into question by measurement in a noninitial attack context. The survey is also considerably less expensive and time consuming to carry out than any program of replicated field measurements, especially in remote administrative units. It need not negatively affect an organization's ability to carry out its primary responsibilities, since the survey participants remain available to respond to emergencies. Since salaried firefighters are employed year-round, they can be assigned to the survey process at essentially no cost during periods of low fire activity. However, making use of this time does require some scheduling flexibility on the part of researchers and survey administrators.

Administration of the survey at a local level is critical, since fireline production rates are significantly affected by "fuzzy" factors. Control conditions that seem to be identical on the basis of a written description can be quite dissimilar with respect to fireline construction. Variation among units in what is considered to be standard practice, even within protection organizations, may be more important than generally acknowledged. The observed differences in production rates among organizations highlight the importance of surveying all relevant protection organizations.

The expert opinion approach is particularly well suited to quantifying the stochastic nature of production rates. This "four-estimate" approach (T_{min}, T_{mode}, T_{90}, and T_{max}) is also well suited to quantifying the central tendencies of production rates (e.g., mean, mode). The consistency in our results leaves no doubt that production rate distributions are skewed to the right (toward faster rates). We recommend calculating mean production times as the expected values of the implied beta distributions

$$E(T) = \alpha/(\alpha + \beta),$$

since reliance on the tradition PERT/CPM approximation of the mean as

$$(T_{\text{min}} + 4 * T_{\text{mode}} + T_{\text{max}})/6$$

produces assessments of $E(T)$ that do not reflect skewness. Researchers and fire professionals should keep this skewness in mind when interpreting field measurement studies, especially in light of the limited replications on which they are typically based. At the very least, a normal distribution for production rates cannot be assumed.

A field-site venue for soliciting estimates based on photographs of the control conditions of interest proved far less problematic than conducting this part of the survey in an office environment, or at each RFS. With a physical example of the fuel type, a measured distance in front of them, and photos and descriptions of all control conditions with the same fuel type handy, survey participants were much better equipped to consider the range of sites represented by the control conditions. Any undesirable influence of factors specific to a particular site (e.g., fences, gullies, or cut-banks that impede the onset of initial attack) was also considerably reduced. The field environment also appeared to enhance their confidence in their estimates by reducing the level of abstraction from that inherent in a "photographs in the office" approach.

It should be noted that estimation of T_{90} was regarded as the most difficult part of the survey by most participants. However, the finding of an average standard deviation factor that differed significantly from the standard PERT/CPM assumption of six suggests that the more astute survey participants should always be polled to obtain T_{90} estimates. The results will almost certainly be a better description of the variance of the estimated distributions. Undoubtedly, this factor will depend on the system for which estimates are sought, with larger values likely in systems characterized by more randomness or less knowledge.

The numerical results obtained from this survey effort are noteworthy in several respects beyond the novelty of the way in which they were obtained. First, they capture the stochastic properties of fireline construction. Second, they indicate that the limited data available from field measurements are quite optimistic. Third, the variation in responses observed for control conditions characterized by the same NFDRS fuel models (Deeming et al. 1977) and slope class suggest that production rates are affected at least as much by local conditions and vegetation characteristics not reflected in the NFDRS models. Finally, they shed some light on engines' fireline production rates, a subject heretofore virtually ignored in the fire literature despite its importance in some parts of the world.

Firefighting professionals were capable of responding intelligently to a survey of this sort because they possess a substantial base of informal knowledge about the phenomenon of interest. This application of the four-estimate approach has great potential for describing complex phenomena in other areas for which knowledgeable individuals can be identified. Analysts simulating wildlife populations, for example, could poll wildlife biologists to estimate the impact of some management action on population levels.

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