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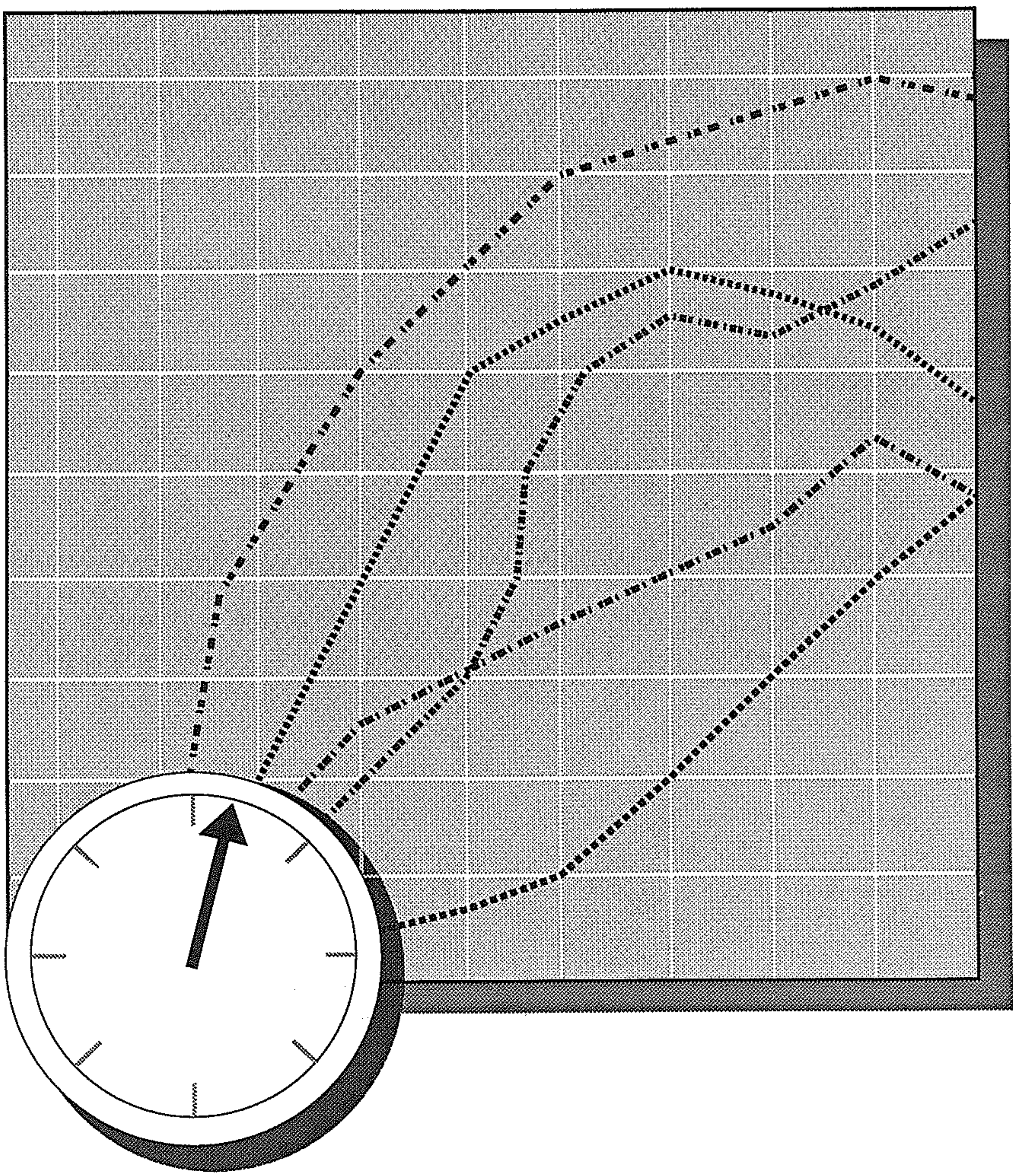
A Fire Management Simulation Model Using Stochastic Arrival Times

Eric L. Smith



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Fire management simulation models are used to predict the impact of changes in the fire management program on fire outcomes. As with all models, the goal is to abstract reality without seriously distorting relationships between variables of interest. One important variable of fire organization performance is the length of time it takes to get suppression units to the fire. Because the location of the fires cannot be predicted and because suppression units are not always available at a particular base location, the types of units sent and their arrival times vary. This aspect of fire modeling, which is especially important in representing simultaneous fires and in choosing base locations, has not previously been examined.

To express the variability of types of units and their arrival times, a stochastic dispatch model was designed and tested. Data concerning the types of units dispatched and their arrival times were obtained for the northern Rocky Mountain Forest Service study area from the computerized file of the Individual Fire Reports (form FS 5100-29). A dispatching model that used Monte Carlo techniques to select the types and arrival times of each unit type was constructed. This model was used to simulate the initial attack process for the Fire Economics Evaluation System (FEES) in an economic efficiency study for northern Rocky Mountain fire programs.

A sensitivity analysis was done on the simulation results at various levels of arrival times and fire spread rates. Results were expressed according to the proportion of fires exceeding 30 and 100 acres (12 and 40 ha). Fire management simulations limit their fire containment models in a similar way, regarding fires exceeding a set size as "escaped fires." In cases of slow arrival times or rapid fire spread, the use of a 30-acre boundary for performance measurement masked differences in results between some levels of arrival times. This was because final fire sizes for different arrival time performance levels were all over 30 acres, but varied widely above that size. Because of the way escaped fire sizes and costs are calculated, a low escape size can bias the results to underestimate superior performance for organizations with faster arrival times.

The results using arrival time distributions were compared with results using a simpler approach of a single, average arrival time for each kind of unit. The results for the distributions showed a steady increase in the proportion of escaped fires across a range of fire spread rates. The results using an average time tended to jump from no fires escaping—or almost none—to all or most fires escaping. Where large variations exist in arrival times, the use of averages may yield inaccurate results and lead to misallocations in fire management resources.

INTRODUCTION

To design more efficient wildland fire suppression programs, simulation models have been developed and applied to fire planning. These include Air Tanker Productivity Computer Simulation Model (AIRPRO) (Simard and Young 1978), Fire Operational Characteristics Using Simulation (FOCUS) (Bratten and others 1981), Fire Economics Evaluation System (FEES) (Mills and Bratten 1982), and National Fire Management Analysis System (NFMAS) (U.S. Dep. Agric., Forest Serv. 1983). These models were designed to test the efficiency of different fire suppression programs when applied to fires in a given management situation. The Initial Action Assessment Model developed as part of NFMAS (U.S. Dep. Agric., Forest Serv. 1983) is currently being used by almost every State and National Forest. Since total annual fire program expenditures of the agencies involved are about $400 million, even small improvements in their efficiency can amount to significant savings.

The general approach of these models is representing the fire suppression organization as a list of available units (engines, hand crews, aircraft) having certain performance characteristics. Each unit has a fireline-building productivity rate for different types of fuel classes and a travel time relative to each fire location. To calculate economic tradeoffs, the costs of using the various types of units are considered.

The fire situations on which suppression programs are tested are represented by fire size at discovery, burning intensity, and spread rate. Fires are assumed to be elliptical; their growth and size are calculated by their shape and rate of spread. Fires are simulated with a geometric containment model until they reach a size where such models cannot be considered reliable. The interaction of the spreading fire and the line building efforts of the suppression force involves a geometrical containment algorithm (Bratten 1978) along with certain constraints on force usage (such as the lack of effectiveness of different types of units at higher fire intensities).

Fire management models have calculated suppression unit arrival time as the travel time between base and fire. A "get-away" time is added to take into consideration the time between dispatch and when the vehicle or aircraft actually leaves. Several factors add variability to the actual unit performance. All crews that are eventually sent to a fire are not dispatched at the time of detection. If the units at the nearest base are already at another fire or otherwise unavailable, then the assumed arrival time will underestimate actual times. This may be especially important when several fires are burning simultaneously. Another delaying factor is unexpected misfortunes in transit to the fire. Flat tires or other equipment malfunctions, vehicle accidents, and travel to the wrong site are examples. Anecdotes of fire managers suggest that it is not unusual for these unpredictable events to cause the failure of initial attack forces to contain fires at small sizes. In other cases, units such as hand crews are not waiting at a base to be dispatched, but are in the field and discover the fire themselves or are dispatched from their field locations by radio. By not considering arrival time variation as a source of initial attack failure, wrong conclusions may be drawn as to how to change initial attack force levels or dispatch procedures to improve their efficiency.

The productivity rates for different types of units under various conditions, and how productivity affects fire outcomes, have been covered by a number of field and modeling studies (Barney 1983, Haven and others 1982, Schmidt and Rinehart 1982, Smith 1986, Storey 1969). The relationship of travel time to fire outcome, and its representation in simulation models, has not received similar consideration. To represent the broad range of situations for which the FEES model was designed, it was necessary to analyze these relationships. They can also be important when modeling the management of simultaneous fires and for deciding where to base units and what types of units to acquire and use.

This paper examines the relationship between the time it takes a suppression unit to arrive at a fire after it is reported (arrival time) and other fire simulation components. First, it presents a stochastic approach to simulating dispatches that takes into consideration arrival time and dispatching variations. Second, it presents an analysis of the model reaction to changes in arrival times and fire spread rates. The effect of using average arrival time, as has been done in the past, rather than arrival time distributions, is included in this analysis.

STOCHASTIC DISPATCH MODEL

Interaction of Arrival Times and Fire Spread Model

Simulation models abstract fire suppression conditions into specific mathematical relationships. Examining these relationships allows one to understand the way the model will react to changes in inputs. The simplest dispatching case is when all units arrive simultaneously at a spreading fire and the fireline is being built next to the fire's edge (direct attack). Given the shape (length-to-width-ratio) of a spreading elliptical fire, the contained fire size is dependent only on the size at the time of the unit's arrival and the rate-of-spread to rate-of-line-construction ratio (Bratten 1978). Under these conditions, the area burned by a fire will be a multiple of its size when the suppression force arrived. The additional amount of line to be constructed due to travel time is proportional to the spread rate. The cost of later arrival times in this simple case is the increased line construction cost plus the additional damages incurred.

When units arrive at different times at the same fire, the relationship of burning conditions and suppression action in determining final size becomes exceedingly complex. It is necessary to simulate the containment geometry to estimate the final size and containment time. The simulation analysis presented below shows model behavior at a series of fire spread rates. This information about the interaction of dispatching and fire spread is not available in a structured form when these models are run for administrative units, because results are aggregated across fire situations.

Two modeling approaches have been proposed to represent the types of fires faced by a wildland suppression organization. One is the site-specific approach, such as used in NFMAS. "Representative fire locations" are used to represent the places and conditions where fires are likely to occur. These are actual locations and their predicted fire management characteristics. Suppression force arrival times are estimated using distances and travel speeds from locations where forces are normally based.

A second approach, which is situation-specific, is used in FEES. It uses factors determining fire behavior conditions, such as fuel type and slope class, to define hypothetical situations. The advantage is that the results could be applied to several locations on different management units having the same characteristics. Since similarity of management situations, including arrival times, is not a criterion for classification in this approach, arrival times within classes could vary widely due to suppression force size and road density and quality.

When using the site-specific approach, the placement and number of representative fire locations should adequately represent the range of possible dispatch and arrival demands. In practice, only a few actual situations are used, and the time it takes to arrive at the range of locations represented by the modeled site varies. In the situation-specific approach, a great range of possible situations can be generated. However, without actual fire locations, the situation-specific approach cannot rely on known travel distances to estimate arrival times. To provide the dispatch information for the FEES model, a procedure which expressed the dispatch variability was needed. A dispatch model, described below, was developed to meet this need. The model uses the containment algorithm from FOCUS and two components: constructions of dispatch distributions and the stochastic dispatch procedure.

Dispatch Distributions

The dispatch model described here does not try to mimic the decisions of a dispatcher. Instead, it assumes that the conditions faced by a suppression organization, including force levels, fire behavior, fire locations, and number of simultaneous fires, will produce a distribution of responses. The model uses aggregate description of these responses, not predictions of individual cases. This approach allows the use of historical records to describe the responses of past organizations without trying to recreate the conditions under which these decisions were made.

Although arrival times are the major focus of this study, the types of units dispatched cannot be ignored, since different types of units will have different line building capabilities and costs. Similar types of fires may have different types of units dispatched to them, depending on unpredictable factors such as how many other fires the organization is involved in at the same time. A stochastic process for determining types of units sent is included in the model and data described below. Information from computerized records of the Forest Service Individual Fire Report (form FS 5100-29) for a northern Rocky Mountain study area were sorted and examined. The information concerned suppression forces and their arrival times including the following:

- Time of first arrival
- Type of unit used for first arrival
- Crew or equipment size in first arrival
- Time of second arrival
- Type of unit used for second arrival
- Total number of firefighters used on the fire

There are some problems with this data set. One is errors in reporting and recording the data. Other inconsistencies were evident, such as the sum of the number of persons in first and second arrivals being greater than the reported "total number on fire." Also, no information is given or can be inferred concerning the arrival time of the third and later units. However, the information recorded provides a nearly complete sample representing a wide range of conditions.

The task of the dispatch procedure is to represent the dispatching actions in response to the fire management situations. The major features are variable types of dispatch, variable arrival times, and the change in arrival times relative to numbers of units available. The computerized data set was used to create distributions of the following variables:

- Type of unit used for first arrival
- Time of first arrival by type
- Type of unit used for second arrival, given type of first arrival
- Time between first arrival and second arrival, referred to here as "second arrival time."

The arrival times were placed into three quartile classes and classes which included the 76th to 90th percentile and the 91st to 100th percentile (the slowest 10 percent). The means of times falling in the class were used to represent the class. The population of fires were stratified in various ways to check for differences in arrival times and unit types. Of the stratified

Table 1—*Probability of first suppression arrival type, by fire cause*

Unit type	Fire cause	
	Lightning	Person
Dozer	0.00	0.00
Engine	.09	.29
Handcrew	.50	.62
Airtanker	.03	.01
Smokejumper	.15	.03
Helitack	.23	.05

Table 2—*Probabilities of second suppression arrival type by first arrival type and fire cause*

Second arrival type and fire cause	First arrival type					
	Dozer	Engine	Hand Crew	Airtanker	Smokejumper	Helitack
Dozer						
Lightning	0.000	0.029	0.011	0.000	0.000	0.000
Person	.042	.019	.024	.000	.000	.000
Engine						
Lightning	.500	.400	.201	.063	.097	.167
Person	.484	.508	.439	.197	.091	.312
Handcrew						
Lightning	.500	.457	.684	.406	.516	.247
Person	.368	.413	.456	.417	.455	.218
Airtanker						
Lightning	.000	.029	.032	.031	.097	.077
Person	.063	.026	.031	.083	.182	.092
Smokejumper						
Lightning	.000	.029	.027	.219	.161	.065
Person	.011	.009	.014	.167	.091	.063
Helitack						
Lightning	.000	.056	.044	.281	.129	.441
Person	.032	.025	.034	.166	.181	.313

distributions created, only when separated into person- and lightning-caused fires were large differences apparent in arrival times and types of units. The lightning-caused fires had longer arrival times and used a higher proportion of airborne suppression units (smokejumpers, helitack, airtankers). This is reasonable, since person-caused fires are more likely to be along roads or in relatively accessible locations. This stratification was used in creating the dispatch responses. The differences in the types of arrivals and their arrival times for lightning and person-caused fires can be seen in their distributions *(tables 1-3).*

Dispatching Procedure

For each simulated fire, a type of unit and its arrival time are randomly selected from the appropriate distributions shown in *tables 1-3*. For first and second arrivals, the dispatches are chosen directly from the appropriate distributions. For example, if the first arrival on a lightning-caused fire is an engine, the probability that the second arrival type will be a handcrew is 0.457. When three or more arrivals are necessary, the type of arrival is chosen from the second arrival distribution, using the previous arrival type as the "first" arrival. This assumes a Markov-like relationship among types of units chosen. No information is available from the Individual Fire Reports on types of units or their arrival times after the second.

The arrival time of the third unit is arbitrarily set to be one half of the time for that type of unit from the second arrival time distribution (shown in *table 3*). The appropriate time is again cut in half for the fourth and subsequent arrivals (one fourth the *table 3* values for the fourth arrival, one eighth for the fifth arrival, and so on). Such an arrival sequence is plausible, but since records of actual arrival times are not kept, its accuracy can not be tested. This approach permits at least a relative comparison of alternative organizations. The dispatch procedure described was assumed to represent the performance of a hypothetical organization based on the average number of units of various types per million acres protected for northern Rocky Mountain National Forests during 1970-1980.

Table 3—*Arrival times for northern Rocky Mountain National Forests, by unit type and fire cause*

Unit type and fire cause	Percentile class 0-25	26-50	51-75	76-90	91-100	Mean
			First arrival *Minutes*			
Dozers						
Lightning	1	13	28	98	394	62
Person	0	6	18	44	177	29
Engine						
Lightning	19	43	72	120	278	79
Person	3	15	33	66	162	39
Handcrew						
Lightning	17	56	112	197	432	119
Person	0	4	23	71	207	39
Helitack						
Lightning	20	44	77	151	415	98
Person	11	26	48	91	230	58
Smokejumper						
Lightning	29	61	99	167	409	110
Person	24	52	88	156	327	97
Airtanker						
Lightning	21	42	63	97	227	68
Person	22	39	58	80	165	58
			Second arrival *Minutes after first arrival*			
Dozers						
Lightning	10	31	71	154	408	87
Person	9	26	71	235	639	117
Engine						
Lightning	10	30	66	119	263	69
Person	8	18	36	69	197	45
Handcrew						
Lightning	18	51	95	176	439	105
Person	10	26	51	106	314	65
Helitack						
Lightning	15	35	70	152	493	102
Person	10	26	41	73	376	65
Smokejumper						
Lightning	12	33	73	156	469	99
Person	7	18	36	68	179	93
Airtanker						
Lightning	10	26	47	84	268	56
Person	7	18	36	66	179	43

Effects of Program Level on Arrival Times

The purpose of fire management simulation models is to test the effects of changes in the number and types of suppression units on fire suppression effectiveness. A major difficulty in using a non-site-specific approach is that it provides no direct basis for deriving estimates of what units could be used and when they would arrive under different programs. Under the site-specific models, the geographic relationships are known and, disregarding the uncertainties in factors other than travel distance, the changes in travel times to various locations can be estimated when specific units are added or subtracted.

To create arrival time distributions for alternative programs in this dispatch model, a circular service area is assumed for each unit, with arrival times proportional to the radius of the circle. For program alternatives, the number of units of some inputs changes. The arrival times are changed in proportion to the change in the average distance each unit will have to travel. For example, if the number of airtankers in the program goes from one to two, the new arrival times decrease by about 30 percent. That is,

the arrival time for the alternative case =

$$\text{arrival time base}*\left(\frac{\text{no. units in base case}}{\text{no. units in alternative case}}\right)**.5$$

For example, when the number of units increases from 1 to 2, the new arrival time is to be calculated by multiplying the base time by $(1/2)^{0.5}$. This is approximately 0.7, a 30 percent decrease in the arrival time. The times for all five first arrival percentiles *(table 3)* are changed by this same proportion, as well as the second arrival and subsequent arrivals.

The dispatch model described above was used in the FEES model in an economic efficiency study of northern Rocky Mountain fire management programs (Mills and Bratten 1986). The dispatch arrival time and dispatch type assumptions were used to generate dispatch sequences and model fire containment for a variety of suppression program sizes and mixes of suppression unit types.

SENSITIVITY ANALYSIS

A few key inputs in current simulation models determine fire size results. A fire with specific characteristics always has the same simulated outcome if the organization always has the same response characteristics. When different responses are possible, such as with the use of arrival time and unit type distributions, then the fires may have different size outcomes.

Computer analyses were designed to calculate the effects of arrival times, rates of spread, and types of units dispatched on simulated final fire size. Responses of the model were generated at different rates of spread for variations of arrival time distributions. A subset of these responses were compared with the results when average (point estimates) arrival times were used rather than distributions.

Methods

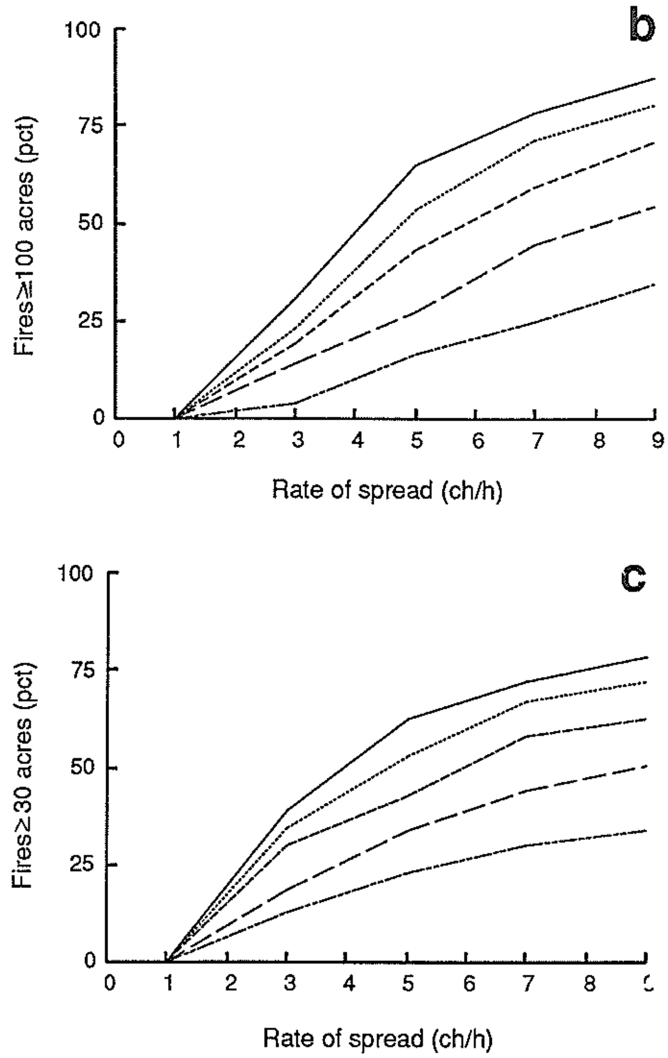
The analyses tested the reaction of the outcomes to changes in the rate of fire spread and arrival time distributions. The situation tested used productivity rates for fireline construction by suppression units that are appropriate for Northern Forest Fire Laboratory Fuel Model 10, timber litter and understory, where resistance to control is high and productivities relatively low (Smith 1986). Runs were made for forward rates of fire spread at 1, 3, 5, 7 and 9 chains per hour (20, 60, 100, 140, and 180 m/h) for a 2:1 elliptically shaped fire. Five hundred iterations were performed at each rate of spread, with each iteration randomly choosing from distributions of the arrival times and of the type of units dispatched. Averages for simulation results had been determined to be stable for 500 iterations. The same sequences of dispatches were chosen at each rate of spread. Lightning- and person-caused fires were compared separately, since they have different arrival times and suppression unit type distributions.

In most wildland situations, the major suppression costs and resource damages are caused by a few large fires. The geometric containment algorithms used in fire simulation models are generally not reliable for large fires, because assumptions about fire behavior and organizational response are likely to be violated. This has been handled in simulation models by establishing an "escaped fire" size. When a simulated fire grows beyond this size, its final size and cost is based on previous fire history for that area. In this analysis, the proportion of simulated fires exceeding an escaped fire size was used as the measure of fire organization performance. Escape sizes of 30 and 100 acres (12 and 40 ha) were used here. The appropriate size for a particular study depends on how large a fire can be handled by the organization being analyzed and on the similarity of local burning conditions.

Results and Discussion

Arrival Time Distributions

Figures 1a-1d display the behavior of the dispatch simulation model using arrival time distributions at five levels of performance. The arrival time performance is expressed as percentage change from the historical base arrival times



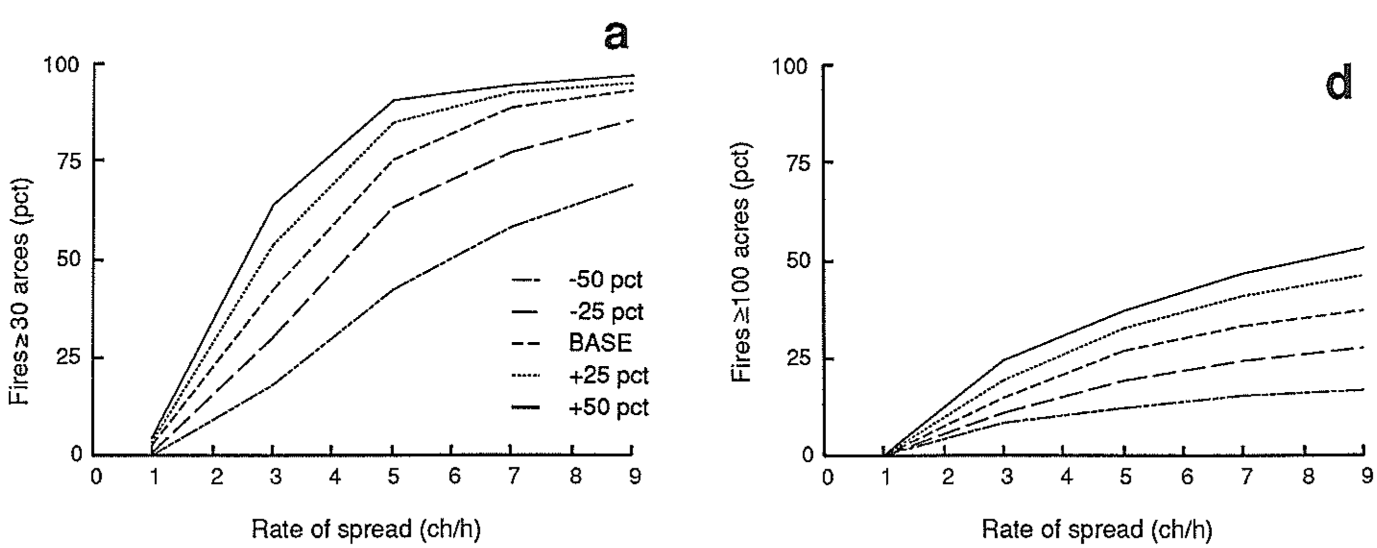


Figure 1—Percentage of (*a*) lightning-caused fires 30 acres or larger, (*b*) lightning-caused fires 100 acres or larger, (*c*) person-caused fires 30 acres or larger, (*d*) person-caused fires 100 acres or larger, determined using the initial attack simulation model, Fuel Model 10 productivity levels, and arrival time distributions, by rate of spread and arrival time levels.

shown in *table 3.* The fire outcomes are measured by the percentage of the simulated fires that exceed two areas: 30 acres *(figs. 1a and 1c),* and 100 acres *(figs. 1b and 1d). Figures 1a and 1b* apply to lightning-caused fires, and *figures 1c and 1d* to person-caused fires. From this set of results, the importance of changes in key variables can be judged, as well as the range over which the variables are sensitive.

For fires spreading at 1 chain per hour, the model indicated no fires larger than 100 acres, and very few situations where they exceeded 30 acres. At 3 to 9 chains per hour, large differences existed in the number of fires that escaped. Within this range, a 50 percent decrease in arrival time resulted in roughly a 50 percent decrease in escapes. A 50 percent longer arrival time resulted in increases of more than 50 percent at lower spread rates for some situations, to only small increases at higher spread rates, where most fires escaped.

More large fires were created using lightning-caused dispatch types and time distributions than using the person-caused distributions. This was true whether measured at the 30-acre or the 100-acre escape size. This is not to say that a higher proportion of actual lightning-caused fires will reach larger sizes than person-caused fires, even within this fuel model, since the rate-of-spread distributions differ. Weather factors influence the rate of spread, and lightning-caused fires are often accompanied by rain.

Large differences resulted between the "escape" size being set at 30 acres and at 100 acres *(figs. 1a and 1b).* At a 30-acre cutoff, smaller differences in final size were detected between historic arrival times ("base") and increased times (+25 pct and +50 pct) than between historic times and decreased times. Using too low of an upper boundary could result in the inability of the model to distinguish differences in results for different arrival time levels. At 9 chains per hour and greater, it appeared that a 50 percent increase in arrival times resulted in only a few percent more large fires. When the 100-acre cutoff was used, the additional modeling showed that even though almost all modeled fires spreading 9 chains per hour exceeded 30 acres at the base arrival time or with longer times, far fewer of these fires exceeded 100 acres. The difference between the base level and the +50 percent level grew to 16 percent more fires exceeding the escape size with 50 percent longer arrival times. With the person-caused fires *(figs. 1c and 1d),* which have quicker arrival times, the "bunching up" effect was not apparent because the proportion of escapes did not reach the 100 percent range. The same effect occurs at a higher rate of spread.

In models such as FEES and NFMAS, the cost and damage from "escaped" fires are not based on whether they were close to being contained at the set escape size. The projected size of an escaped fire in these models is based on the distribution of fire sizes of previous years. For the study area, the average size of a fire that exceeds 100 acres is about 1600 acres (650 ha). This analysis shows that by putting an escape boundary on modeled fires, the difference between slower and quicker arrivals (smaller and larger force levels) can be underestimated, and thus the cost efficiency of larger force levels can also be underestimated. NFMAS lets the user set the escape size at 1000 acres (400 ha) or less. FEES results (Mills and Bratten 1986) were based on a 100-acre escape. The NFMAS guideline for setting this size is based on how big a fire the management unit can manage locally, while the FEES size was based on expected sizes of homogeneous fuel conditions. While these are both important considerations, the danger of underestimating differences in program levels by using a low size limit apparently should also be considered.

The results suggest that the way fire spread rates are represented may also affect model results. For both NFMAS and FEES, a few spread rates are modeled for each fire situation and a weighted average result is calculated based on the spread rate distributions. Since the response curves shown in *figures 1a-1d* are not linear, which spread rates are modeled may affect aggregate results. This effect varies, depending on the arrival situation being modeled. Additional analysis could show how results for a particular fire behavior situation would respond to changes in the number and placement of fire spread rates.

Comparison of Distributions and Averages

There are two aspects of the potential differences between arrival time averages and distributions. One aspect is the difference between averages and distributions at the same arrival time performance level. If an average value gives the same results as the distribution, little is to be gained by adding complexity to the model by using distributions. Since the averages and distributions are from the same data, other things being equal, the results using the distributions presumably are more accurate. The other aspect of this analysis is whether the changes in levels (such as a 25 pct increase in arrival times) affect the results differently for the averages and distributions. In both the FEES and NFMAS models, the distributions of spread rates are calibrated so the base scenario yields results that agree with past history. The differences between average and distribution inputs at the base level may not be apparent because the calibration procedure causes results to be similar to historical results. However, the differences between levels still exist and determine the ultimate results of what is the most efficient fire program level.

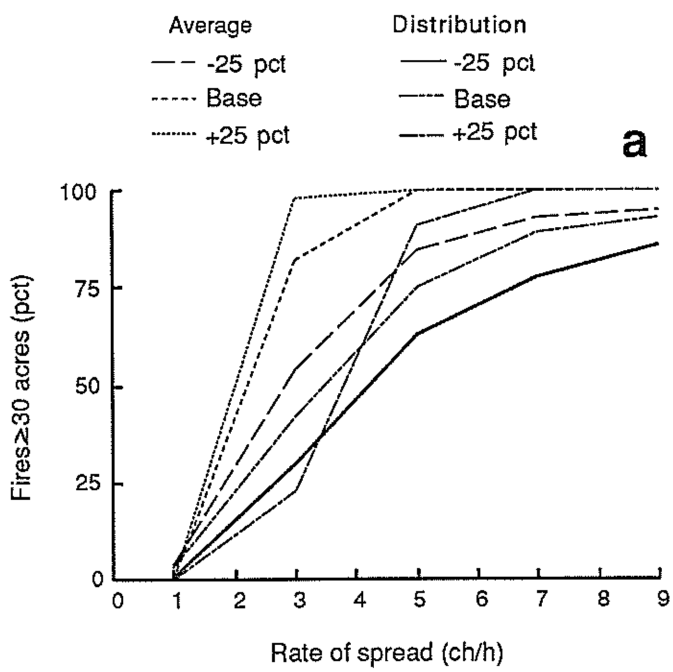
Results of arrival time distributions at three arrival time levels (+25 pct, the base level, and -25 pct) were compared with a single average value of each of these three levels *(figs. 2a-d).* Three of the distributions exhibited similar behavior *(figs. 2a-c).* At lower spread rates, the distribution and point estimates produced similar outcomes. However, the escape percentage of simulations using average data increased abruptly, whereas the simulations using distributions increased more gradually. In the case of person-caused fires with simulated outcomes over 100 acres *(fig. 2d),* this behavior started at a spread rate of 9 chains per hour.

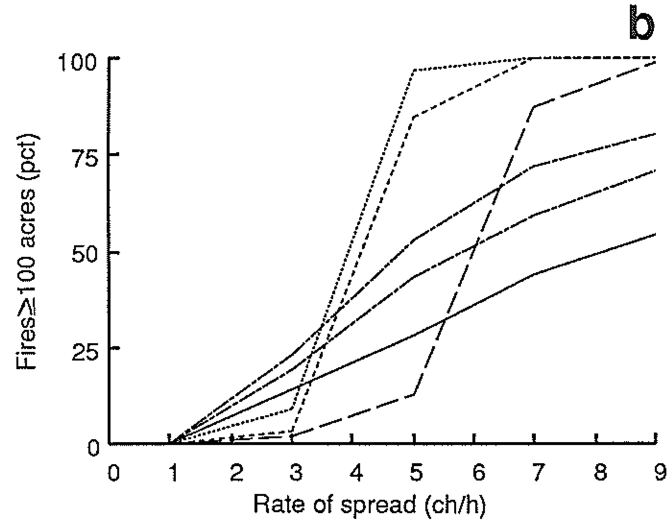
The abrupt change for the average time cases was caused by eliminating the variability contained in the arrival time distributions. In a totally deterministic model with no arrival time or dispatch variability, the simulated fires at a particular rate of spread all would have the same final size. Therefore, the outcomes would be zero percent over the size limit below a critical rate of spread, and 100 percent above that rate of spread.

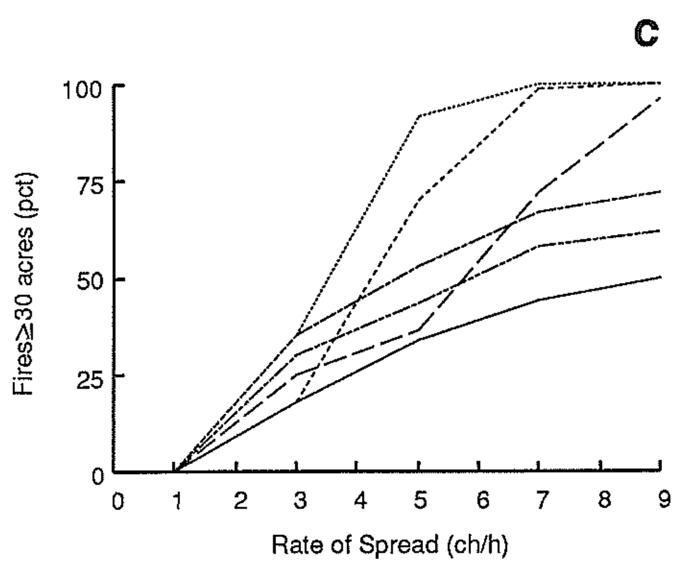
For the 30-acre escape boundary *(figs. 2a and 2c),* the averages predicted a higher escape level than did the corresponding distribution through most of the spread rates. For the 100-acre boundary *(figs. 2b and 2d),* escape percentages for average times tended to be lower than results using distributions for slower spread rates and higher for faster rates of spread. According to the Individual Fire Report data set used, about 23 percent of the spreading fires were spreading faster than 3 chains per hour when discovered. Above 3 chains per hour the results of using averages and distributions differed considerably.

The "bunching up" of the results near the 100 percent escape point, discussed in the previous section, was much more pronounced with the use of average arrival times than with arrival time distributions. Person-caused fires modeled to 100 acres *(fig. 2d)* were exceptions, because the rapid arrival times for person-caused fires resulted in fewer fires over 100 acres at 9 chains per hour and below. This bunching effect means that the use of average arrival times gives results that are overly sensitive to arrival time-fire size interactions in a narrow range of spread rates and insensitive in faster spreading fires.

The partial elimination of variability by using average arrival times produced behavior similar to the deterministic all-or-none case. The variation left in the model is caused by variation in the types and order of units dispatched to the fire. This variation is absent from previous models, as with the







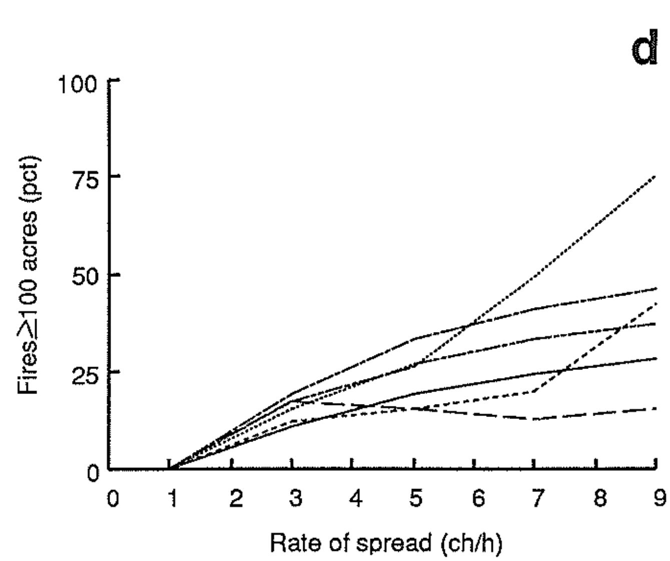


Figure 2—Percentage of (*a*) lightning-caused fires 30 acres or larger, (*b*) lightning-caused fires 100 acres or larger, (*c*) person-caused fires 30 acres or larger, (*d*) person-caused fires 100 acres or larger, determined using the initial attack simulation model, Fuel Model 10 productivity levels, and arrival time distributions and averages, by rate of spread and arrival time level.

variation in arrival times. *Figure 2* indicates the percentage of cases that were influenced by the variability caused by this dispatch sequence. For instance, for the -25 percent case for the average times in lightning-caused fires modeled to 30 acres *(fig. 2a),* the proportion of escapes was 23 percent with a 3 chain per hour spread and 91 percent with a 5 chain per hour spread. Using a single typical dispatch sequence would probably yield no fires over 30 acres at 3 chains per hour, but all fires would be over 30 acres at 5 chains per hour. If so, the variability in dispatch sequences would change the outcome in 23 percent (3 chains per hour) and 9 percent (100 minus 91) (5 chains per hour) of the fires, under these conditions. In the NFMAS process, there is some variability in dispatches because each representative fire location has separate dispatch possibilities at each fire intensity level. Given a fire site and fire intensity, the same dispatch sequence and arrival times are used in each case.

The three arrival time levels give a good indication of how the model behaves when the number of units available changes, since the model changes arrival times to adjust for numbers of units. The differences between levels for the simulations using arrival time distributions remained fairly constant. The difference in the levels using average time simulations, due to the abrupt changes in percentage of escaped fires were much more extreme in portions of the normal range of spread rates. In one example *(fig. 2b),* a change of average arrival times from the base to -25 percent resulted in a 72 percent increase in fires over 100 acres for a 5 chain per hour spread rate. The same change using arrival time distributions was a 15 percent increase. This discrepancy could lead to different conclusions about the consequences of changing the number of initial attack units or the response to fires with predicted spread rates in this range.

The overall impact of average arrival time versus distributions for the results of lightning-caused fires exceeding 100 acres *(fig. 2b)* was calculated with a weighted average, using the distribution of reported spread rates for the study area. Increases in escapes beyond 9 chains per hour were linearly extrapolated to 100 percent. The use of average times resulted in higher escape rates by 8 percent for the -25 percent level, 19 percent for the base level, and 13 percent for the +25 percent level. A small increase in the number of escaped fires can have a large financial impact, since fires over 100 acres make up about 1 percent of all fires but account for about 50 percent of all suppression costs.

The ability of fire planning simulation models to discriminate among alternative management programs depends on their precision and accuracy. The inputs used in these models are a mix of judgment and empirically derived estimates; therefore, it is not possible to specify a statistically based confidence interval or other quantifiable measure of precision for overall model results. The level of detail included in the models and the need for modeling improvements are other matters of judgment. The role of arrival times in determining fire size outcomes reported here provides a basis for such judgments. Similar studies of fire management model behavior include those by Salazar and Bradshaw (1984), Mees (1985), and Smith (1986). Ideally, studies should include testing the sensitivity of inputs and model components in the context of the entire model, so that management impacts can be measured. Because of the expense of operating these models, such studies are impractical, and partial analysis such as reported here must be employed.

SUMMARY AND CONCLUSIONS

Variation in arrival times can be an important element in simulating the outcomes of sample fire situations. The use of non-site-specific fire situations does not permit the relative physical locations of fires and suppression resources to be used in calculating effects of changes in suppression programs on arrival times. Site-specific representative fires represent fires in a range of locations, and actual suppression responses vary, depending on suppression unit availability and location.

The advantage of using empirically based arrival time distributions is that a wide range of unexpected situations that have actually occurred are included as model input. Other approaches have included only a single, most likely, response to each situation. Because of the variability of dispatch conditions in a situation-specific model such as FEES, an empirical distribution is necessary. For a site-specific model such as NFMAS, this approach could be adopted to consider simultaneous fires and other variability that could be expected in response time.

Sensitivity analysis on the major variables in the dispatch simulation showed the effects of changes in arrival time levels, fire spread rates, and escape size limits. The longer arrival times for lightning-caused fires resulted in a higher number of escaped fires. Because so many fires exceeded the 30-acre escaped fire limit for the lightning-caused fires, the differences in results for arrival time levels were apparent only for the 100-acre limit. Use of too low of an escape size limit could mask performance differences and underestimate the impact of improved, shorter, arrival times. This effect should be considered when escape size limits are set.

Comparison of simulated results based on an average arrival time with those from an empirical distribution showed differences at spread rates above 1 chain per hour. A weighted average escape rate based on the distribution of reported fire spread rates was consistently higher when average times were used in an example case. Results of using average times showed few or no escapes until a critical spread rate was reached, where the percentage of fires escaping rose abruptly. Average time results were also more affected by the escape size limit used. These differences show that the reduced information available from average times has the potential to affect model accuracy and possibly the choices between management alternatives. A similar analysis should be done for a site-specific model to determine if arrival time variability can also affect results.

The combinations of arrival times and fire spread rates displayed complex responses. There is a need for an examination of how much fire spread rate data is needed in these models. Current models use a limited number of spread rates, which are subject to calibration distortions. Which spread rates are chosen to be modeled and how results are aggregated may affect the accuracy of results.

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A stochastic dispatch approach for use in fire management simulation models was designed to incorporate variation in initial attack arrival times and dispatch sequences due to simultaneous fires or other causes. The sensitivity of final fire size to suppression force arrival times is examined for complex situations with this model. Results show that several differences exist between using arrival time distributions and average arrival times. The most important difference is that use of average arrival times can give results that overestimate effects of changes in fire spread in some portion of the spread rate range and underestimate them in others.

Retrieval Terms: fire management, simulation model