United States
Department of
Agriculture

Forest Service

**Pacific Southwest
Forest and Range
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Research Note
PSW-387

October 1986

Locating Suppression Resources by Travel Times to Wildfires

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Minimizing travel time to a wildfire is an important criterion when suppression resources are dispatched from several locations. When a fire is reported, a dispatcher must make several decisions: How many resources should be sent, which ones, and from where? The real-time problems of how many and which ones will not be dealt with in this paper because of the additional complexity needed to incorporate fire behavior, fire-fighting effectiveness, costs, and resulting net value changes.[1]

This note examines seven existing (1985) and two alternative ground resource locations on the Clearwater National Forest in Idaho. The analysis is based on 5 years of fire occurrence (1975-1979) data. The objective was to minimize the number of resource locations and the resulting travel cost.

The two mathematical models described are for the use of the Forest or District dispatcher on a National Forest. They are prescriptive models designed to provide personnel at a fire site according to one of several possible objectives.

The user has two options: (1) minimizing the travel time with the statistical model, or (2) meeting required travel time standards with the linear programming model. The various outputs from each model complement each other to assist with the selection and interpretation of the locations.

The models require a detailed road network to describe two-way travel times and barriers. The construction, validation, and maintenance of a road network model is a time-consuming and costly task. The travel times provided by the required road network can be used by nonfire protection functions to locate other facilities and can be made part of a geographic data base. Once these data are incorporated into such a data base, updates in travel time, fire patterns, fuels, and values-at-risk can be used to reevaluate resource locations.

ROAD NETWORK DATA

One way to describe the time required for ground resources to travel from point-to-point on a National Forest is to construct a model of the road network using line segments and nodes (*fig. 1*). Each line segment between two nodes is used to represent two-way travel times.[2] Nodes represent possible or existing resource locations, road intersections, bridges, sharp turns in the road, and other conditions which may cause substantive changes in travel speed. The minimum required travel time from point A to point B is computed using a shortest route algorithm.[3] The road network used for the Clearwater National Forest contains 999 nodes. Each of the nine resource locations for the ground suppression units is located on one of these nodes. Seven locations are currently in use and two are alternative sites.

For fires located farther than 1 mile from a node, the shortest route algorithm

Mees, Romain M. *Locating suppression resources by travel times to wildfires.* Res. Note PSW-387. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1986. 5 p.

Two mathematical models are given to determine the best locations for initial attack resources in terms of travel time: a linear programming model and a statistical model. An example for the Clearwater National Forest in Idaho illustrates some of the differences between the two models.

Retrieval Terms: initial attack, arrival time, road network, resource locations

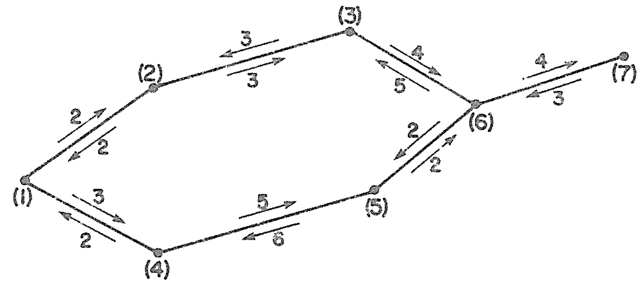

Figure 1—Two-way travel times (in minutes) are used to compute the travel time in either direction between point (1) and point (7) using seven nodes.

finds the minimum time to a fire as shown in *figure 2*. Crews drive to the nearest point on the road and walk to the fire at an average speed specified by the user of the shortest route algorithm. Two additional nodes are created and temporarily added to the road network to represent the fire and the nearest point on the road. For fires located within 1 mile of a node, the algorithm computes the walking time from the nearest node to the fire. The time required to dispatch ground resources is added to the time spent traveling, to obtain the total required time.

The shortest route algorithm generates an array of arrival times:

$$g_{ijk} \text{ where } i = 1, 2, 3, \ldots N_k$$
$$j = 1, 2, \ldots, 9$$
$$k = 1, 2$$

The subscript i indicates the fire location, j the resource location, and k the cause (k = 1 for lightning or k = 2 for person). Cause and type of resource (e.g., air or ground) affect arrival times. Each ground resource location is compared with other available ground locations in terms of travel time. High travel and location costs may be incurred if any of the nine ground locations are eliminated on the basis of longer travel times when compared with those for helitack locations. The output from this algorithm is strictly based on arrival times, and results must be evaluated against other variables such as the cost of establishment and operation of each location, budget limitations, and the economic impact of each fire.

The travel times stored in the array g_{ijk} do not apply if two or more fires occur at the same time, and if resources are dispatched from one fire to another without returning to their home location or are occupied at other locations. Some of the arrival times stored in the array g_{ijk} have been verified with actual dispatches to the same fire locations. Differences between the reported and computed travel times are due to an incorrect road network representation, faulty historical reporting, or intentional delays in actual initial attack.

RESOURCE LOCATIONS

Two models are suggested here to find the minimum number of resource locations in terms of the arrival times computed by the shortest route algorithm. The output from both models will be compared and evaluated for ground resources only.

Linear Programming Model

A mathematical procedure known as the "covering problem"[4] can be used to determine the smallest number of ground locations that will provide preselected required arrival times (dependent on fire location) to a set of fires. The required arrival times are subjectively selected by the user. The selection of a required arrival time for each fire can lead to model outputs that suggest a number of ground locations exceeding any reasonable budget level. The procedure consists of applying the following integer linear programming (LP) model:

$$\text{Minimize} \sum_{j=1}^{N_r} X_j$$

where N_r is the number of ground locations, subject to

$$\sum_{j=1}^{N_r} a_{ijk} X_j \geq 1,$$

$i = 1, 2, \ldots, N_k$ (k = 1 or 2, for fire cause)

where

a_{ijk} (input variable) = 1 if location j will satisfy the specified required arrival time for fire i
= 0 if location j is unsatisfactory.

and

X_j (output variable) = 1 if location j is used.
= 0 if location j is not used.

The results of the LP model consist of a list of prospective resource locations that satisfy the required arrival time to each fire location. However, the suggested solution may not be unique. For example, consider the following arrival time array (minutes) consisting of four fire and three resource locations (X_1, X_2, X_3):

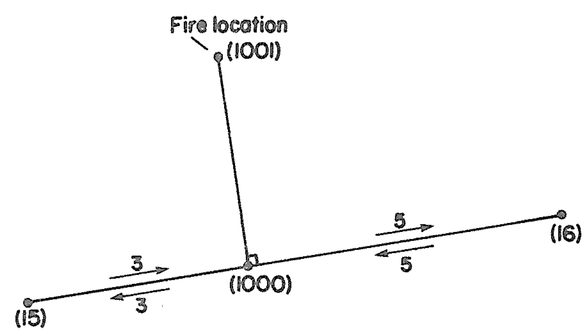

Figure 2—For fires located farther than 1 mile from any node, two additional nodes are created between nodes 15 and 16 and temporarily added to the road network. The ground resources drive to node 1000 and walk at the speed of 3 miles per hour to the fire now located at node 1001.

Fire locations	Time from resource locations X_1	X_2	X_3
		Minutes	
1	15	17	18
2	14	13	12
3	28	16	17
4	18	17	21

Requiring arrival times of 15, 14, 17, and 18 minutes for fires 1 through 4 gives the following constraints:

Fire	Constraints						
1	1	0	0		X_1		1
2	1	1	1	×	X_2	≥	1
3	0	1	1		X_3		1
4	1	1	0				1

There are two solutions:

$$X_1 = 1, X_2 = 1, X_3 = 0$$

and

$$X_1 = 1, X_2 = 0, X_3 = 1$$

with the same minimum for the objective function (two locations).

The LP model does not tell the user whether selecting the first and second resource locations would be better than selecting the first and third resource locations. Both solutions would satisfy the arrival time requirement for each fire as given in the coefficient matrix, but no other conclusions can be drawn.

Statistical Model

Historically the Clearwater National Forest dispatcher sends one or two resources from the same location. Using the array g_{ijk} of arrival times, the statistical model computes the following quantities:

$$A_B = \min_j \sum_{i=1}^{N_k} g_{ijk}$$

and

$$A_W = \max_j \sum_{i=1}^{N_k} g_{ijk}$$

where N_k is the number of person- or lightning-caused fires and

$$j = 1, 2, 3, \ldots N_r.$$

For a given cause ($k = 1, 2$), A_B and A_W represent the best and worst resource locations in terms of an expected sum of travel times, assuming only one resource location is available.

The model repeats the procedure for two available resource locations and identifies the best and worst pair of resource locations. Assuming N_r ground locations, the model computes the minimum and maximum sums of travel times over the following location pairs (identified by the integers 1 through N_r):

$$\begin{array}{l} (1, 2), (1, 3) \ldots (1, N_r), \\ (2, 3), (2, 4) \ldots (2, N_r), \\ (3, 4) \ldots (3, N_r), \\ (4, 5) \ldots (4, N_r) \ldots (N_r - 2, N_r), \\ \quad (N_r - 1, N_r) \end{array}$$

where the travel time to a given fire can be attributed to either location in a pair.

The model likewise computes the minimum and maximum sums of travel times for all possible combinations of resource locations taking M ($M = 3, 4, \ldots, N_r$) resource locations at a time. The model also computes the number of fires served from each resource location and the average travel time to the fire locations served by each selected resource location. Minimizing the sum of travel times to all fires on a forest places resource locations in areas of high fire incidence. If a fire does occur in an area with low fire occurrence, resources may take an unusual amount of time to reach the fire site. For each combination of resource locations, the model lists the number of times the first arrival time does not equal the first arrival time from all possible locations and the average delay time to such fire sites.

The minimum sum of travel times for a given number of resource locations to all fires may not be unique. Taking two resource locations at a time from the above example illustrates two identical sums:

Location	Minimum sum of travel times
	Minutes
X_1 and X_2	$15 + 13 + 16 + 17 = 61$
X_1 and X_3	$15 + 12 + 17 + 18 = 62$
X_2 and X_3	$17 + 12 + 16 + 17 = 62$

Direct comparison of the output of the LP model and the statistical model may be limited to agreement on the number of resource locations to be used.

DATA ANALYSIS

The Clearwater National Forest had 339 lightning fires during 1975 through 1979. The nine initial attack locations for ground suppression units are identified below:

Location	Name
1	Mex Mountain
2	Powell
3	Kelly Creek
4	Canyon Black Mountain
5	Pierce
6	Lochsa
7	Musselshell
8	Bungalow
9	Cedars

The Bungalow and Cedars locations were not part of the 1985 initial attack organization and were suggested as alternate locations by the Clearwater National Forest dispatcher. For off-the-road fires, a walking speed of 3 miles per hour was used.

Linear Programming Model

If a required arrival time is specified for each of the 339 lightning fires, the LP model solution will indicate the number of needed locations and which ones. The distribution for the first required arrival time (*fig. 3*) is obtained by equating the required arrival time to each fire to the minimum arrival time from the nine resource locations. The LP solution will have to include all nine resource locations.

The distribution for the second required arrival time (*fig. 3*) is obtained by equating the required arrival time for each fire to the second of the first two arrival times from the nine resource locations. The LP solution consists of the following five locations:

Location	Name
1	Mex Mountain
3	Kelly Creek
4	Canyon Black Mountain
5	Pierce
6	Lochsa

The arrival times for any suppression units sent to a given fire are from these five locations and can come from the A or B distribution shown in *figure 3*.

The distribution for the third required arrival time (*fig. 3*) is obtained by equating the required arrival time to each fire to the third arrival time of the first three arrival times from the nine resource locations. The LP solution consists of the following four locations:

Location	Name
3	Kelly Creek
4	Canyon Black Mountain
5	Pierce
6	Lochsa

The arrival times for any suppression units sent to a given fire are from these four locations and can come from any of the three distributions shown in *figure 3*.

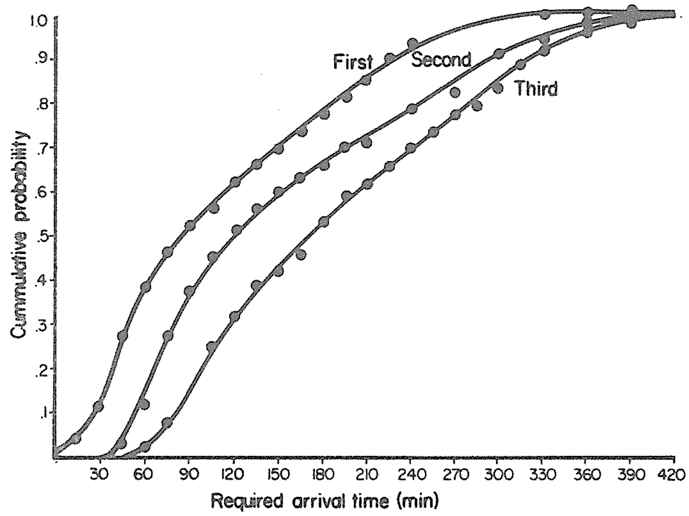

Figure 3—Arrival time distributions used by the linear programming model for the first, second, and third arrival times at all fires.

Statistical Model

Outputs from the statistical model for the Clearwater National Forest are these: minimum and maximum sums (minutes) of arrival times for one through nine available resource locations (*fig. 4*), the average travel time from all available resource locations, the location combination which gives the minimum sum, the number of fires served by each selected location, and the average arrival time from each location (*table 1*). For example, the selection of five locations (2, 4, 6, 7, 9) gives a minimum sum of 40,431 minutes. One additional location decreases the sum by 602 minutes, which amounts to an average of 1.78 minutes per fire.

Differences Between the Two Models

Both the LP and the statistical model suggest five locations:

LP model	Statistical model
1 Mex Mt.	2 Powell
3 Kelly Creek	4 Canyon Black Mt.
4 Canyon Black Mt.	6 Lochsa
5 Pierce	7 Musselshell
6 Lochsa	9 Cedars

The statistical model provides the sum of arrival times of 44,892 minutes using locations 1, 3, 4, 5, and 6 from the LP solution. The statistical model also lists the number of times the first, second, and third arrival times provided by each combination are equal to the first, second and third arrival times from all possible locations. The LP solution has 196 fires for which the first arrival time provided by the five selected locations equals the first arrival time from all nine locations, 236 fires for which the second arrival time equals the second arrival time from all nine locations, and 98 fires for which the third times are equal. Using locations 2, 4, 6, 7, and 9 gives 295, 143, and 134 fires for which the first through third arrival times were selected.

For combinations for which the first arrival time is not equal to the first arrival time from all possible locations, the model computes the average delay time. The LP model finds 339 minus 196 or 143 such fires with an average delay time of 39 minutes. The statistical model (2, 4, 6, 7, 9) combination finds 339 minus 295 or 44 such fires with an average delay time of 26 minutes.

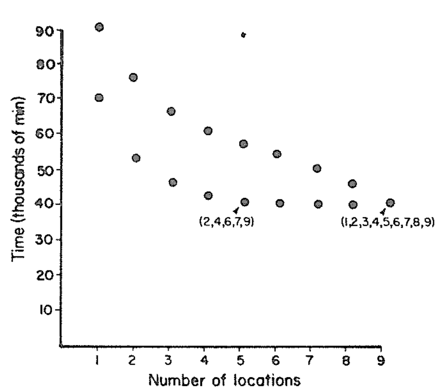

Figure 4—The statistical model gives minimum and maximum sums (minutes) of arrival times for one through nine resource locations.

Comparing the total number of first and second arrivals shows how the LP model (196 + 236) and the statistical model differ (295 + 143). The statistical model has the advantage of selecting locations on the basis of the first arrival time (shortest travel time). This selection may be more useful when the dispatcher values the arrival time of the first resource at the fire site higher than the arrival of the second resource. The first resource to arrive can evaluate the fire behavior, containment requirements, and values-at-risk.

The LP model gives greater weight to optimizing other than the first arrival performance because of the required arrival time selections for each fire. The LP model lists the number of fires not covered within the required arrival time for a given combination of locations. The location combination (2, 4, 6, 7, 9) selected by the statistical model leads to 24 of the 339 lightning fires that cannot be reached within the required arrival time (second of the first two arrival times) to each fire.

During the years 1975 through 1979, the Clearwater National Forest also had about 80 person-caused fires. Because of the small sample size, the lightning- and person-caused fires were combined with similar results.

DISCUSSION AND CONCLUSIONS

The current configuration of resource locations on the Clearwater National For-

Table 1—*Number of locations, minimum sums, average arrival time from all locations, location numbers, number of fires served by each location, and average arrival time, Clearwater National Forest, by number of locations*

Number of locations	Minimum sum	Average arrival time from available locations	Location numbers[1]	Fires served by each location	Average arrival time by location
	Minutes				*Minutes*
1	69,182	204	(5)	(339)	(204)
2	53,020	156	(4,6)	(213,126)	(162,145)
3	45,702	134	(4,6,9)	(157,125,57)	(146,145,79)
4	42,482	125	(2,4,7,9)	(72,118,56,55,55)	(114,153,128,74)
5	40,431	119	(2,4,6,7,9)	(72,118,56,55,55)	(112,153,141,75,74)
6	39,829	117	(2,4,6,7,8,9)	(55,111,56,50,13,54)	(112,156,141,69,68,74)
7	39,416	116	(1,2,4,6,7,8,9)	(20,55,111,55,31,13,54)	(71,112,156,142,55,68,74)
8	39,319	115	(1,2,3,4,6,7,8,9)	(20,55,7,111,55,31,12,48)	(71,112,104,156,142,55,69,67)
9	39,257	115	(1,2,3,4,5,6,7,8,9)	(20,55,7,109,5,55,28,12,48)	(71,112,104,158,46,142,55,69,67)

[1] Locations and names are as follows: 1, Mex Mountain; 2, Powell; 3, Kelly Creek; 4, Canyon Black Mountain; 5, Pierce; 6, Lochsa; 7, Musselshell; 8, Bungalow; and 9, Cedars.

est consists of the first seven locations with a minimum sum of arrival times of 42,200 minutes and 279, 307, and 223 fires for which the first through the third arrival times were selected.

The decision to go from the existing seven resource locations to five locations—(2, 4, 6, 7, 9) or (1, 3, 4, 5, 6)—is complicated by the fact that the first seven are in existence and do not require the capital investment of opening new locations.

One possible drawback of minimizing the total arrival time to all fires using a limited number of locations is that locations would be selected solely on the basis of fire incidence without regard for spatial differences in suppression costs and values-at-risk. In low-demand areas, even though fire suppression is important, the shortest travel times may be long. The selection of the final number and which locations must be carefully reviewed, using both the LP and statistical model outputs, knowledge and experience of the dispatcher, and budgets.

The primary goal of an initial dispatch of resources is to get the necessary resources to a fire within the appropriate time. The number and kind of resources needed and the appropriate response times differ from fire to fire. Travel time is one of the most important measures used in evaluating alternative arrangements of initial attack locations. The shorter the travel time of the first unit to the fire, the sooner the hazard (potential loss of life, property, and possible benefits) can be subjectively evaluated.

END NOTES AND REFERENCES

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