Performance of initial attack airtanker systems with interacting bases and variable initial attack ranges

Kazi M.S. Islam and David L. Martell

Abstract: Each day, forest fire managers must deploy airtankers at initial attack bases to minimize initial attack response times. They must decide how many airtankers to deploy at each base and the initial attack range of each airtanker. We develop a daily airtanker simulation model and use it to investigate how airtanker system performance varies as a function of initial attack range, fire arrival rates, and time of day. Our results indicate that the optimal initial attack range decreases as the daily fire load increases. Fire managers can use this information to design airtanker dispatch policies that will minimize initial attack response times.

Résumé : Chaque jour, les responsables de la gestion des feux de forêt doivent déployer les avions-citernes vers les bases d'attaque initiale pour minimiser le temps de réaction lors de l'attaque initiale. Ils doivent décider combien d'avions-citernes doivent être déployés vers chacune des bases et le rayon d'action de chaque avion-citerne pour l'attaque initiale. Nous avons développé un modèle de simulation journalière pour les avions-citernes et l'avons utilisé pour étudier de quelle façon la performance de la flotte d'avions-citernes varie selon le rayon d'action de l'attaque initiale, le taux auquel se déclarent les feux et le moment de la journée. Nos résultats montrent que le rayon d'action optimal pour l'attaque initiale diminue à mesure que le nombre quotidien de feux augmente. Les responsables de la gestion des feux peuvent utiliser cette information pour élaborer une politique d'assignation des avions-citernes qui minimise le temps de réaction lors de l'attaque initiale.

[Traduit par la Rédaction]

Introduction

Amphibious land-based airtankers are used extensively for initial attack on forest fires in Canada and many other jurisdictions. Water dropped from airtankers slows fire growth and helps buy time for ground suppression crews to reach the fire and begin their control action, increasing the likelihood of containment at a small size. Airtankers deployed at initial attack bases fly out to the fire, scoop water into their onboard tanks while skimming low over the surface of a nearby lake, and then drop that water on the fire. They continue to cycle between the lake and the fire and drop water until the air attack boss decides they are no longer required, at which point they either are dispatched to another fire or return to an airport to refuel. Firefighting times can vary over a wide range depending upon fire behaviour and values at risk that determine the number of drops required.

To deploy airtankers to contain fires while they are small and thereby limit damage, duty officers must make daily decisions concerning the number of airtankers required at each initial attack base and the initial attack range (IAR) of each airtanker. They attempt to minimize response times by deploying airtankers close to areas where fires are most likely to occur. For analytic purposes, an initial attack airtanker system (IAAS) can be viewed as a spatially distributed queueing system with fires as customers and airtankers as servers that travel to the customers to provide service. It is reasonable to assume (e.g., see Bookbinder and Martell 1979) that fires arrive according to a nonstationary Poisson process with an arrival rate that varies throughout the day. If there is an idle or free airtanker near a fire when it arrives, that airtanker will be dispatched to that fire. If all the nearby airtankers are busy, the fire is entered into an initial attack queue of fires to be "served" as airtankers are released from other fires.

A maximum initial attack range (MIAR) for an airtanker is determined by its fuel tank capacity. When deciding upon the MIAR for an airtanker, fire managers must allow for travel time to and from the fire, on-scene firefighting time, and an adequate safety margin. Fire managers may restrict their airtankers to an IAR that is less than or equal to the MIAR, depending upon the current and anticipated daily fire load (DFL). The IAR of an airtanker will determine its initial attack zone (IAZ), and airtankers deployed at adjacent bases may have overlapping IAZs. When two or more IAZs overlap (Fig. 1), the dispatching of airtankers to the overlapping zones calls for explicit recognition of airtanker interaction.

Most of the IAAS models that have been developed rely on simulation methods. This is due, in part, to the need for complex models that address fire arrival time and location,

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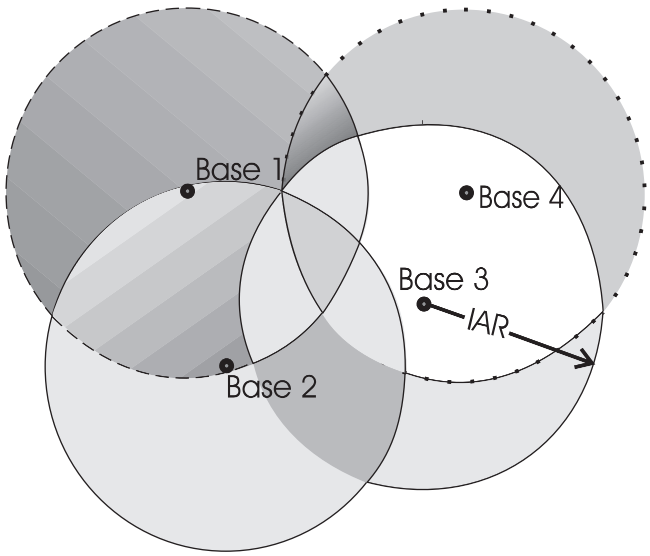
Fig. 1. Initial attack bases and IAR boundaries. Four overlapping circles centred at four bases define the IAZs for the airtankers deployed at those bases.



fire size, current and future fire behaviour, and many other factors that influence fire suppression resource productivity. Simard (1978, 1979) developed AIRPRO to help fire managers identify good combinations of air attack resources and ground support to minimize cost-plus-loss. AIRPRO was designed to evaluate suppression tactics on a single fire; it does not simulate simultaneous fire occurrence and system congestion. Martell et al. (1984) developed a simulation model that does account for simultaneous fire occurrence to evaluate initial attack resource requirements in Ontario. The California fire economics simulator version 2 (Fried and Gilless 1998) also accounts for simultaneous fire occurrence, but does not model airtanker operations in detail.

Mathematical programming models have also been used to investigate daily airtanker deployment issues. Greulich (1967) developed a linear programming model that indicates how airtankers (that return to their home bases each day) should be deployed each day to maximize the amount of fire retardant delivered over the entire fire season. Greulich (1976) extended this work and developed an integrated mixed integer linear programming model that addressed airtanker home basing and daily airtanker deployment and modeled day-to-day changes in fire danger as a Markov process, again to maximize the amount of fire retardant dropped during a fire season. That model tends to deploy airtankers where they are needed each day, but its structure is such that he had to assume that fires are "fought" independently, and does not model the congestion that can become so important in an IAAS. Hodgson and Newstead (1978) developed two set-covering models to allocate airtankers to a subset of a large number of bases. However, their approach does not account for the congestion that can arise if all the airtankers that might cover a new fire are busy fighting fires that were reported earlier in the day. Fortin (1989) and Martell and Tithecott (1991) developed queueing models that do address congestion but do not allow for the coordinated dispatch of airtankers with overlapping IAZs.

The urban emergency response system (UERS) literature provides useful insights for modeling the interaction of spatially distributed servers that serve spatially distributed customers. The UERS literature shows that server cooperation improves system performance (Batta et al. 1989). Although an IAAS does resemble an UERS, it differs in some important respects. In an IAAS, the travel times to and from a fire constitute a very significant portion of total service time whereas in an UERS, travel time tends to be a relatively small fraction of the total service time. Moreover, UERS service times are usually short compared with the time interval over which arrival rates are stationary. UERS modelers therefore often partition the day into a finite number of independent time intervals and predict the steady-state performance of the system during each of those time intervals. But since IAAS service times are long relative to the time over which fire arrival rates are stationary, partitioning the day into a number of time intervals and using steady-state models for each interval could produce unreliable results (Green et al. 1991). Furthermore, there is no close analogy in an UERS to the MIAR of an airtanker, which is determined by its fuel tank capacity. This paper describes an IAAS simulation model and how it can be used to investigate the impact of IAR, DFL, and time of day on system performance.

IAAS simulation model

Our model simulates the arrival of fires in the fire region, the dispatch of the nearest available covering airtanker to each fire, the placing of the fires in the initial attack queues of the covering airtankers when all covering airtankers are busy, and the servicing of fires by airtankers. It compiles statistics concerning diurnal variation in airtanker response time. The simulation starts at the beginning of the day (e.g., 7:30 a.m.) and terminates at the end of the day (e.g., 9:30 p.m.). The fire arrival, airtanker dispatch, and fire service processes used in the model are described below, followed by a discussion of the performance measures that were used.

Fire arrival process

Forest fires are ignited by both people and lightning, and fire occurrence is both spatially and temporally very heterogenous. We model the spatial heterogeneity by partitioning the fire region into a number of rectangular cells, each of which has a fire arrival pattern that is determined by the forest vegetation, weather, and land-use patterns within the cell. Fires arrive in each cell according to a nonstationary Poisson process with a rate that varies throughout the day, and we assume that those fires are uniformly distributed over the two-dimensional cell. Suppose, $\lambda_m(t)$ is the average fire arrival rate (fires per hour) at time t in cell m and cell m is defined by coordinates $\{X1_m, X2_m, Y1_m$ and $Y2_m\}$ as shown in Fig. 2. Green et al. (1991) used a Poisson incident arrival model in which the instantaneous incident arrival rate varies sinusoidally throughout the planning horizon, and histograms of the fraction of forest fire arrivals by time of day in the northwestern region of Ontario confirmed the appropriateness of this model for Ontario. We therefore assume that the fire arrival rate in each cell varies sinusoidally throughout the day, increasing monotonically to a peak arrival rate, and then decreasing gradually. For cell m, we can write

$$[1] \qquad \lambda_m(t) = \overline{\lambda}_m - A_m \cos(2\pi(t - \theta_m)/\Delta)$$

where $\overline{\lambda}_m$ is the mean hourly fire arrival rate in cell m, A_m (≥ 0) is the amplitude, θ_m is the time lag (measured in hours) of the arrival rate function, and Δ is the portion of the day in hours (e.g., 14 daylight hours) over which the system is modeled. The amplitude of the fire arrival rate can vary from 0 to 100% of the average fire arrival rate, and the time lag can vary from –0.5 to 1.5 h. To generate fire arrival times that follow a nonstationary Poisson process, we use the thinning procedure (see Lewis and Shedler 1979).

Let (x_n^f, y_n^f) denote the location of the nth fire that arrives in the fire region (the superscript "f" indicates these are the coordinates of a fire location). Given that the nth fire arrives in cell m:

$$x_n^f \sim U(X1_m, X2_m)$$

$$y_n^f \sim U(Y1_m, Y2_m)$$

where the symbol "~" means "is distributed as" and U(X1, X2) denotes a uniform distribution with upper and lower bounds X1 and X2, respectively.

Airtanker dispatch process with fire queueing

Suppose airtanker i is based at (x_i^a, y_i^a) and its IAR is α_i (the superscript "a" indicates these are the coordinates of an airtanker base). If $d_{i,n}$ is the distance between the ith airtanker and the nth fire, then:

$$[2] \qquad d_{i,n} = \sqrt{(x_i^a - x_n^f)^2 + (y_i^a - y_n^f)^2}$$

Suppose the nth fire arrives at time t_n and C is the set of airtankers that cover it, i.e.:

$$C \equiv \{[i] | d_{i,n} \leq \alpha_i\}$$

When the nth fire arrives at time t_n, then depending upon the status of airtankers in set C, one of two events will take place.

(i) Airtanker i will be dispatched immediately to the nth fire if and only if airtanker $i \in C$ is available and for all $j \in C$, $j \neq i$, $d_{i,n} < d_{j,n}$. If airtanker i is dispatched to the nth fire, it will be busy until it finishes serving the fire at time

$$[3] \qquad A_i = t_n + S_n$$

where S_n is the service time of the nth fire (defined below). We define A_i as the "availability time" of airtanker i. Since airtanker i will be dispatched to the nth fire immediately, it has waiting time $w_n = 0$.

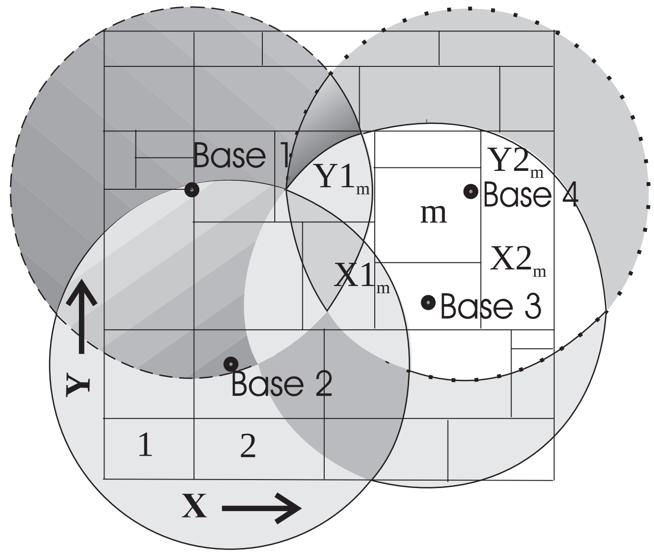
(ii) All the airtankers in C are busy. The fire will be placed in an initial attack queue served solely by the airtankers in set C according to a first-come first-serve (FCFS) service discipline. The nth fire will be served later by airtanker $i \in C$ if for all $j \in C$, $A_i < A_j$, $i \neq j$. If the nth fire is served by airtanker i, then:

$$[4] \qquad w_n = A_i - t_n$$

and the revised availability time of airtanker i will be

$$[5] \qquad A_i = A_i + S_n$$

Fig. 2. The fire region is partitioned into rectangular cells. Cell m is defined by coordinates $\{X1_m, X2_m$ and $Y1_m, Y2_m\}$. Fires that arrive in each cell are covered by one or more airtankers. Although some of the fires that arrive in cell 2 can be served by airtankers at either base 2 or 3, most will be served by airtanker(s) deployed at base 2.



Airtanker i will be available to serve another fire at time A_i.

Fire service process

We assume that duty officers always dispatch one and only one airtanker (or an airtanker group acting as a single large airtanker) to a fire. We also assume that airtankers are never dispatched directly from one fire to another (i.e., after the completion of service, an airtanker must return to its deployment base before it attacks the next fire) and that service time does not depend upon the time the fire waits in the initial attack queue. The number of drops required to contain the fire may vary depending upon the size and intensity of the fire, the values at risk, and the capacity of the airtanker's onboard tanks. We assume that all airtankers are identical and that the number of drops required to control a fire depends only upon fire size and intensity. Although it is reasonable to assume that the number of drops should be an increasing function of fire size and intensity, the literature provides little insight into actual airtanker needs. We therefore assumed, arbitrarily, that the number of drops required is uniformly distributed. Suppose J is the number of drops required for a fire. Then:

$$[6] \qquad J \sim DU(k_{min}, k_{max})$$

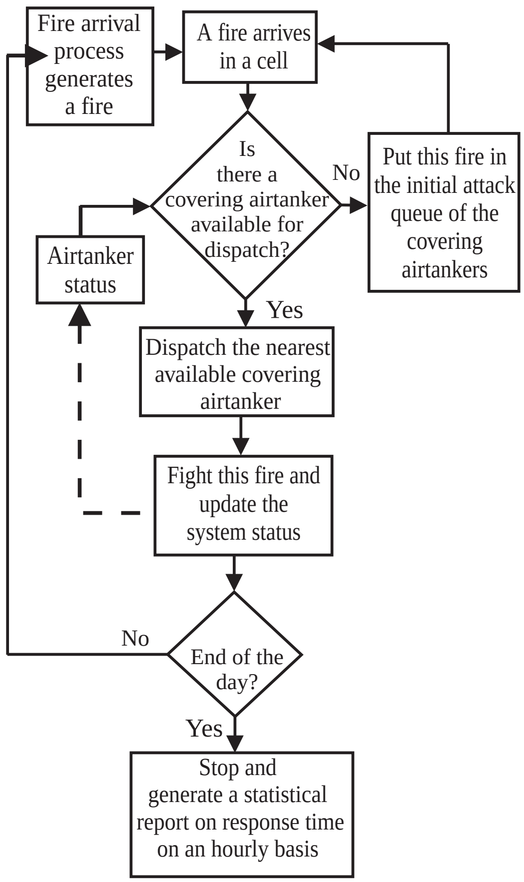
where k_{min} and k_{max} are, respectively, the minimum and maximum number of drops required and DU indicates a discrete uniform distribution.

Suppose D is the distance between the fire and the nearest landable lake which, we assume, is uniformly distributed as follows:

$$[7] \qquad D \sim U(a, b)$$

Now, if M denotes the constant mobilization time for an airtanker and L denotes the time required to drop water on

Fig. 3. Schematic diagram of the simulation model.



the fire, then S_n, the service time of the nth, fire can be expressed as

$$S_n = M + 2d_{i,n}/v_i + J(2D/v_i + L) \qquad [8]$$

where v_i denotes the mean cruising speed of airtanker i and $2d_{i,n}/v_i$ accounts for the two-way travel time from the initial attack base to the fire and $J(2D/v_i + \mathrm{L})$ for the firefighting time.

Evaluation of airtanker performance

Our simulation model was designed to study the impact of IAR on the performance of an IAAS and to provide insight that fire managers can use to develop effective airtanker dispatch policies and daily airtanker deployment strategies. Islam (1998) described five performance measures that can be used to evaluate an IAAS and made the case that the time-dependent expected response time is most suitable for operational decision-making and well understood by fire managers. We therefore ran the simulation model with a specified IAR for all airtankers and compiled statistics on response times to fires on an hourly basis given different DFLs.

Model overview

A schematic overview of the simulation model is shown in Fig. 3. We assume that at the beginning of the day, there are a fixed number of airtankers deployed at each initial attack base and that all airtankers are constrained to fight fires within some specified IAR. We also assume that the deployment of airtankers and their IARs are such that all the fires that arrive in the initial attack region are covered by at least one airtanker. This complete coverage is achieved by assuming that if a fire is not within any airtanker's IAR, it is assigned to the nearest airtanker. The simulation starts at time zero (the beginning of the day, 7:30 a.m.) and ends 14 h later (the end of the day, 9:30 p.m.). When a fire arrives randomly in a cell in the fire region and there is at least one airtanker available that covers the fire, the nearest of those airtankers is dispatched to it. If all the covering airtankers are busy, the fire is placed in the initial attack queueing subsystem of the airtankers that cover that fire. The fires in the queue are fought on a FCFS basis as soon as one of the covering airtankers becomes free. We stop generating new fires at time $t = \Delta$ (14 h). We assume that airtankers can fight fires and do so until the initial attack queues become empty at or later than time $t = \Delta$ (which may be later than darkness in the real world).

The model was coded in the SIMSCRIPT II.5 programming language. Execution time for the model depends upon the size of the airtanker system being evaluated and the number of replications. It takes approximately 5 min to run an 8000-day set of replications for an airtanker system with five airtankers and 30 cells on a Sun Microsystems Sparcstation 10 computer.

Results

A simple hypothetical airtanker system was used to investigate the impact of IAR and DFL on airtanker system performance. We that assumed five airtankers were deployed at five initial attack bases, almost uniformly spaced, in a region 300 × 300 km in size. We assumed that, given a DFL, fires were uniformly distributed over the fire region and that their arrival rates vary throughout the day, as described by eq. 1. For simplicity, we assumed, for all cells m, $A_m = \bar{\lambda}_m$ and $\theta_m = 0$. Four fire load scenarios with DFLs of 20, 25, 30, and 40 fires per day were considered. All airtankers were assumed to be identical with respect to cruising speed (250 km/h), time to pick up and drop water (3 min), and getaway time (5 min). Lake-to-fire distance was assumed to vary uniformly between 1 and 10 km and the number of water drops required to contain a fire between 1 and 20.

Graphs of average or estimated mean initial attack response time over the day as a function of DFL and IAR are shown in Fig. 4. To assess the precision of that performance measure, we assumed that the mean response time at a particular time is normally distributed, allowing for the estimation of 99% confidence intervals (Fig. 5). For each fire load scenario, the model was run with six IARs (100, 125, 150, 175, 200, and 225 km).

Figure 4 indicates that as the DFL increases, the response time increases, and the peak congestion period occurs later in the day. Figure 4A–4D illustrates that IAR can be determined by the fuel tank capacities of the airtankers during the earlier part of the day, when there is very little congestion in the system, and that the IAR should decrease later in the day depending upon the DFL. Furthermore, the higher the DFL, the earlier in the day the IAR should be restricted. For a DFL of 40, the IAR should be restricted between the fouth and fifth hours (Fig. 4D) whereas for a DFL of 25, the IAR

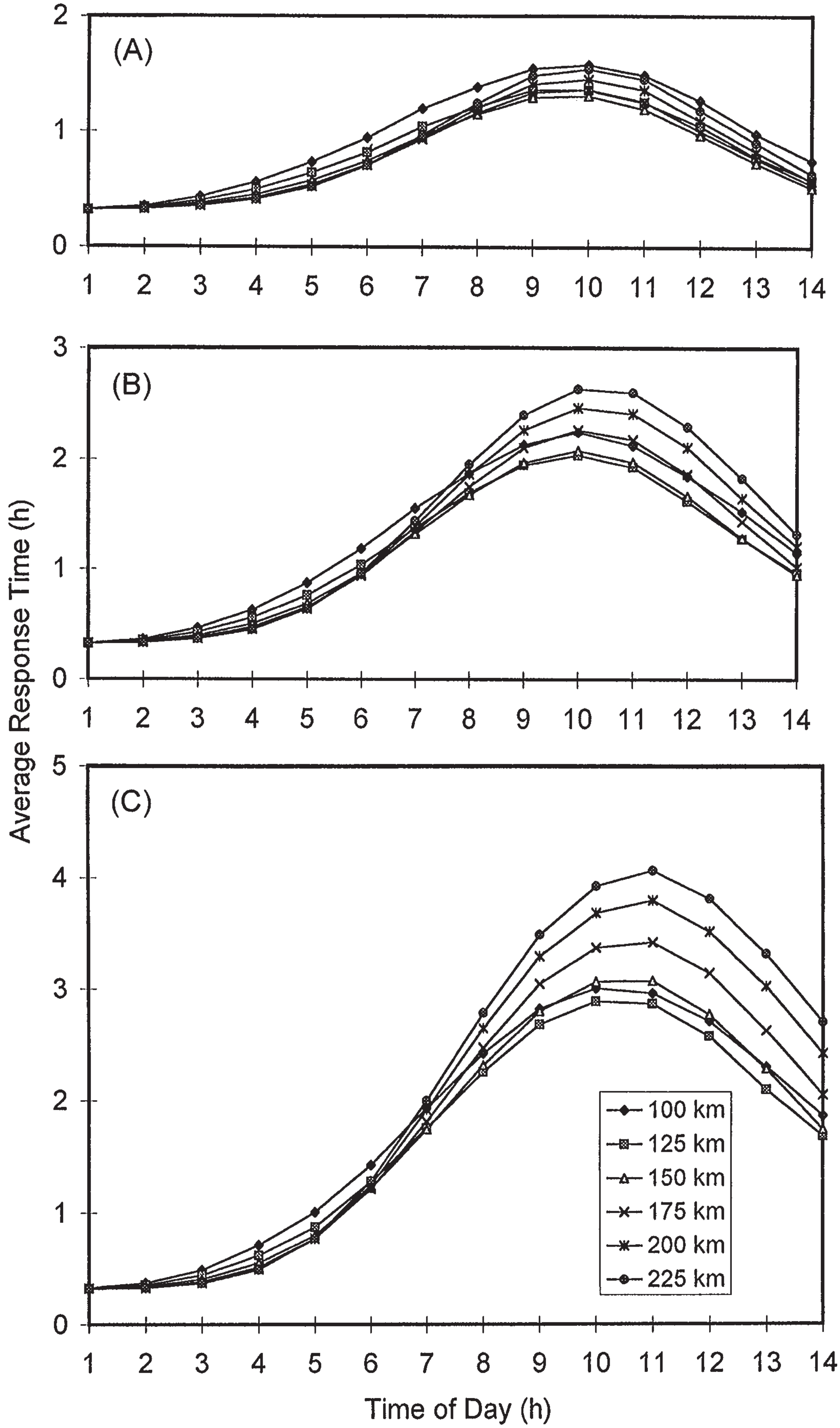
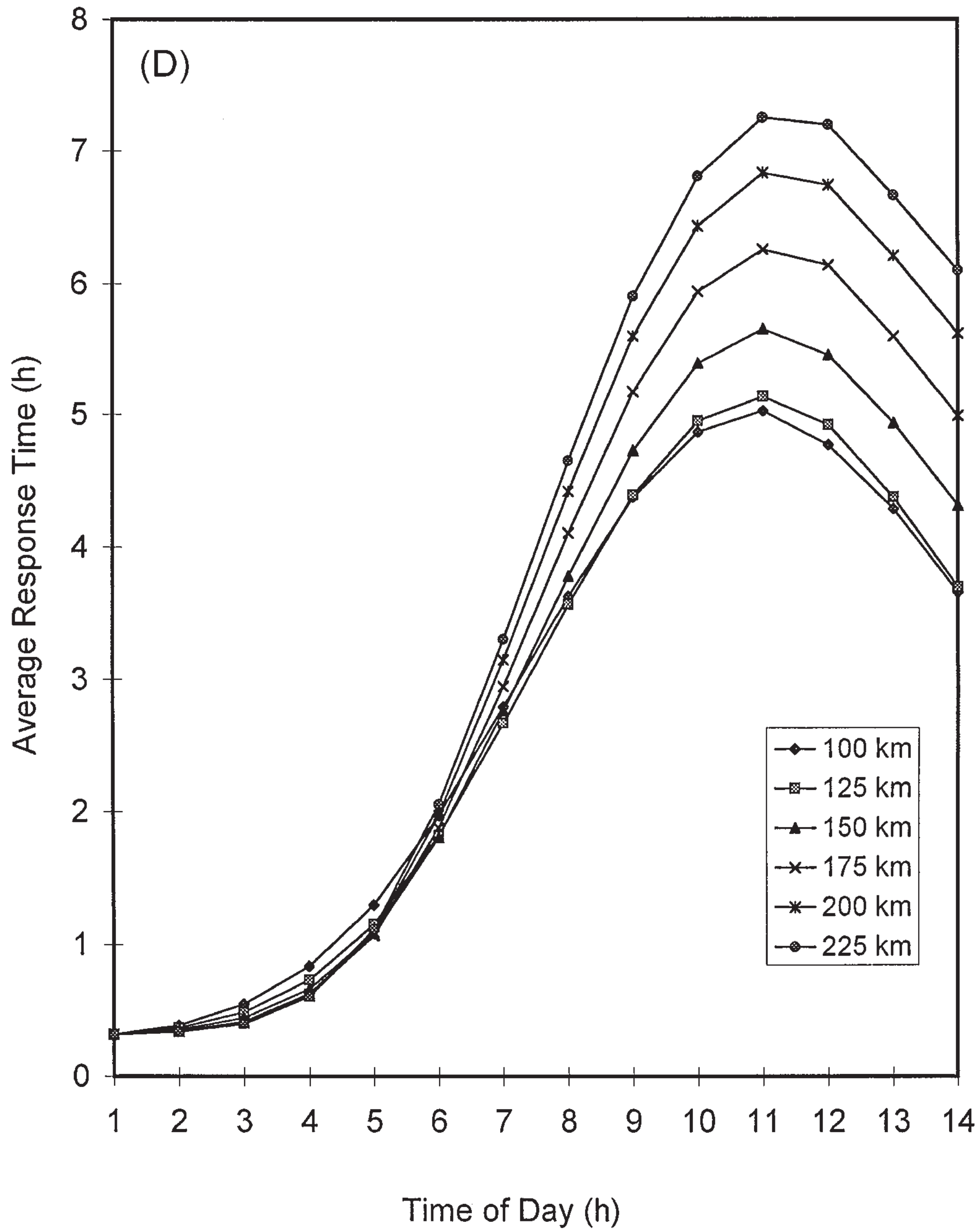

(A)
(B)
(C)
Average Response Time (h)
Time of Day (h)
100 km
125 km
150 km
175 km
200 km
225 km

Fig. 4. Average initial attack response time by time of the day for different IARs with a DFL of 20 fires (A), 25 fires (B), 30 fires (C), and 40 fires (D).



does not need to be restricted until the sixth hour (Fig. 4B). Finally, the higher the DFL, the greater the potential performance improvement from restricting the IAR.

A reasonable explanation can be provided for the variation of response time with the time of day and the change in IAR. When the DFL is low compared with the service capacity of the system, and airtankers have long IARs that allow them to interact extensively, congestion seldom occurs. As a result, the probability that all airtankers will be busy and that a fire will have to be added to the queue awaiting service is low. Moreover, when a fire arrives in the system, it is more likely that a nearby airtanker will be dispatched to it. As a result, the response time, which includes travel time and waiting time, is small. Restricting the IAR reduces the potential for cooperation between initial attack bases. For low DFLs and shorter IARs, it is more likely that some of the airtankers are idle while others have fires waiting in their initial attack queues. The overall system performance deteriorates, as a result, primarily because of the increased waiting time.

For the higher DFLs considered, irrespective of the IAR, the hypothetical IAAS was operating close to (during the earlier part and at the end of the day) or beyond (during the later part of the day) system capacity. As a result, the probability that all airtankers were busy and that fires had to wait in the initial attack queue is high. Moreover, with a FCFS service rule (or any other service rule that ignores the locations of the fires and the bases where airtankers are

Fig. 5. Ninety-nine percent confidence intervals for average response times based on 8000 simulated days and a DFL of 40 fires.

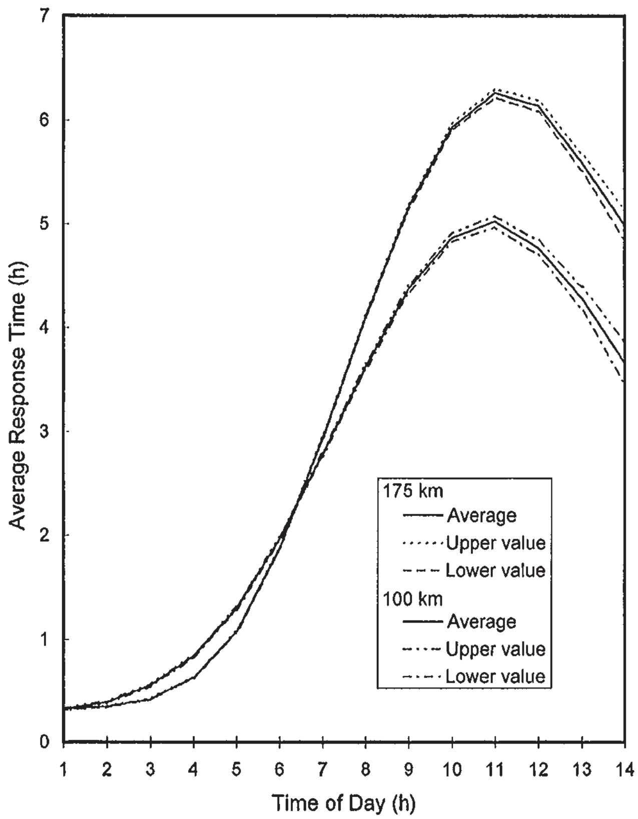
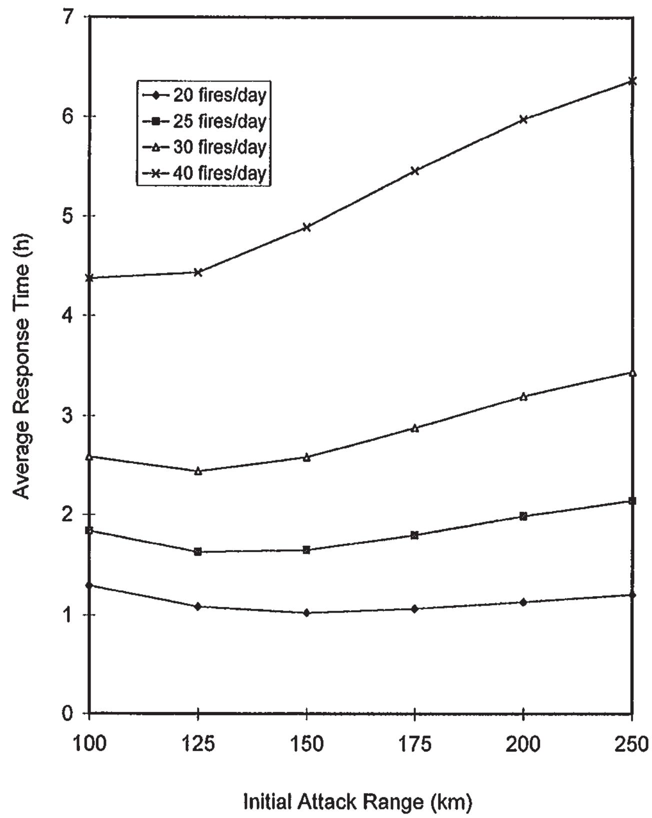


Fig. 6. Variation in average response time during the time interval from the eighth to the 14th hour as a function of IAR and DFL.



deployed), it is more likely that a fire will be served by a remote airtanker. High IARs that allow airtankers to travel long distances can result in long travel times. When system congestion is already high, high IARs that allow extensive interaction do not reduce the waiting time very much. System performance deteriorates due to long travel times that increase service times.

Since queueing delays early in the day have a cumulative effect on system congestion later in the day, the results suggest that at any time of the day, IAR should be set to minimize average response time. For example, for a DFL of 30 (Fig. 4C), fire managers should start the day with a 225-km IAR, decrease it to 150 km after the fifth hour, and decrease it to 125 km after the seventh hour.

Finally, the impact of IAR on system performance as a function of DFL during the most congested hours is shown in Fig. 6. The optimal IAR was more narrowly defined and decreased as the DFL increased.

Discussion

IAR is an important decision variable that influences the performance of IAASs. However, the nature and the extent of the impact of the IAR on the performance of airtankers have not been throughly investigated. We performed experiments with our IAAS simulation model by varying the IAR and the DFL. The results indicate that the optimal IAR depends upon the anticipated DFL, the fire arrival and behaviour patterns, and the time of day. For relatively low DFLs or during the early part of the day when congestion is low, IARs should not be constrained below the maximum permitted by the fuel tank capacities of the airtankers. This increases the potential for cooperation among initial attack bases and reduces the waiting time at some cost in travel times. But since airtanker utilization will be low when the fire arrival rate is low, the overall result will be a net reduction in response time. On the other hand, when the fire arrival rate is high, or congestion is being experienced later in the day, the IAR should be restricted. This reduces travel time, but also reduces the potential for cooperation. However, some cooperation among airtankers must be maintained to balance decreases in travel time with increases in waiting time.

In a real IAAS, IARs would be set for individual airtankers or initial attack bases. The best IAR would then depend not only upon the time of day and the fire arrival and behaviour patterns, but also on the number of drops required on a fire, the size of the fire region, the spacing of the bases, and airtanker speed and capacity. The use of variable IARs as a simple heuristic in this case would amount to approximating a more complex policy that dispatches the airtanker with the shortest expected response time, rather than the closest available airtanker. Although we have used a simple hypothetical problem to investigate the impact of IAR constraints on IAAS performance, our model can easily be enhanced to deal with more realistic airtanker systems.

Acknowledgements

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