Kuk, G., Arnold, M., & Ritter, F. E. (1999). Using event history analysis to model the impact of workload on an air traffic tactical controller's operations. Ergonomics, 42(9), 1133-1148.

Paper No. ERG 100705

ERGONOMICS, 1999, VOL. 42, NO. ~~00~~, ~~000-000~~
9 1133-1148

Effects of light and heavy workload on air traffic tactical operations: a hazard rate model

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Keywords: Hazard rate analysis; Air traffic tactical controller; Spell; Weibull distribution; Cox regression.

This paper introduces a class of event history analysis used to examine how the operations of an air traffic controller change under light and heavy traffic workload. The analysis begins by assessing the hazard rate, $h(t)$, of a transition (or spell) between the controller's communication and flight progress activities. $h(t)$ is the instantaneous rate of going from one state (i.e. an activity of communication or flight progress) to another in a unit of time, given that the controller has been in the first state until time t. Results indicated that the spell distribution closely followed a Weibull distribution, a prerequisite for this analysis. The results also indicated that $h(t)$ was more likely regulated by time in heavy than in light workload conditions, and that under heavy workload, indirect speech from the planner controller would decrease the $h(t)$ for communication to flight progress spells. The results suggest that a dynamic model for the analysis of air traffic control may be necessary, and that the implications of using modular automation may not be straightforward. This technique may be of general use to examine temporal regularities in operating real-time control tasks.

1. Introduction

Research into the influence of workload on air traffic control (ATC) has continuously focused on its depleting effects on air traffic controllers' psychological and physiological outcomes (Costa 1993, Zeier 1994). Recent endeavours have sought to examine the dynamic aspects of the integral relationship between time and actions (Vortac *et al.* 1994, Edwards *et al.* 1995), notably, the effects of time on decision-making and behaviour in complex and reactive environments (Casner 1994).

Inevitably, in emergency situations where time is too short to allow an in-depth search of options or meticulous planning, decision-makers have to rely on other cognitive and perceptual means when assessing the situation and in deciding the course of actions to be taken (Chase and Simon 1973, Klein 1989). At a behavioural level, individual decision-makers will have to prioritize their activities by completing important and time-consuming operations first, and the least important ones later (O'Hare 1992, Raby and Wickens 1994).

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Ergonomics ISSN 0014-0139 print/ISSN 1366-5847 online
http://www.tandf.co.uk/JNLS/erg.htm
http://www.taylorandfrancis.com/JNLS/erg.htm

This paper introduces a new methodology to examine how time effects decision-making and behaviour. It is used to examine how light and heavy air traffic workload can affect ATC tactical operations, specifically, the variation of time distribution among discrete activities during ATC operations.

1.1. *System design for air traffic control*

Numerous attempts have been made to build safer systems that will alleviate the adverse effects of time pressure on real-time control tasks (e.g. Spettell and Liebert 1986). In ATC, there have been at least two general approaches to do this: (1) by decomposing the ATC operations into subroutines for automation—this makes cognitively demanding tasks less taxing on individual operators and monotonous tasks less interfering with high-priority tasks (Debbache and Abida 1995, Debelack *et al.* 1995); and (2) by incorporating a cooperative framework into system design—this seeks to promote an optimum load balance by ensuring that work is efficiently and effectively distributed among a team of operators (Findler and Lo 1993a,b). These approaches aim to improve the controllability and manageability of complex systems specifically when multiple participants are engaging in time-constrained activities (Samurcay and Rogalski 1993).

In the UK, the airspace in en-route ATC is divided into sectors manned by teams of air traffic controllers. They are responsible for maintaining a continuous exchange of up-to-date information both within and between sectors, and from radar screens and aircraft. The information is necessary for meeting four high-level goals: (1) planning and control that includes monitoring an error-free and on-time routing; (2) reducing the uncertainties that may lead to conflicts; (3) assuring safe separation between aircraft and smooth air traffic flow; and (4) conserving both aircraft and airport resources.

The acquisition of this information requires a high level of concerted effort in the coordination of activities among all controllers and within a single controller's operations. Coordination in its simplest form represents effective timing and scheduling of activities. The temporal regularities of these activities presents a dynamic description of how controllers manage time in their operations. It is likely that the temporal regularities may change under different air traffic conditions. For example, to cope with heavy air traffic and time-stressed conditions, the increasing numbers of tactical operations may subject the controllers to engage in more active planning of how to make effective use of the available time (cf. O'Hare 1992). In other words, the controllers have to structure and time their activities for maintaining safe and robust control of the situation. To address the underlying structural and temporal relationships among various discrete activities in ATC operations, we need a model that gives a more complete description of how air traffic controllers adjust to the air traffic conditions.

1.2. *A dynamic model of ATC operation*

How does time affect ATC operations? Given that ATC involves dealing with multiple concurrent tasks (e.g. monitoring aircraft on radar and at the same time giving clearance to an aircraft coming into the sector), and the possibility that the air traffic controllers may engage in more than one task (e.g. writing on flight progress strips while communicating with another controller), the question becomes one of how time is distributed within and across various, sometimes concurrent activities.

The discrete activities of an air traffic tactical controller can be grouped into three main categories: (1) communication that includes actions or utterances initiated by the tactical controller, such as accept, navigate, goodbye, query and negotiate; (2) flight progress activities that deal with the paper strips including manipulation and remove; and (3) radar activities such as tidy the radar screen. In addition, there are three external trigger events: pilot hello, pilot information and get strip. At a cooperative level, there are also three external interactions with the planner controller: planner instruction, planner information and planner advice. Details of these categories and their codes (Cox 1994) are listed in table 1.

Figure 1 helps to illustrate the theoretical analysis and study design by portraying the distribution and temporal properties of a tactical controller's operation along a time-line vector directed to the right. The time-line vector is made up of time spells. A transition from the onset of one discrete activity to the next represents a completed time spell. An incomplete spell (or censoring) occurs when the exact time for the beginning or the end of a specific time spell is not known. This can happen when the beginning of the time spell cannot be determined, a left censored spell or when the end of the time spell cannot be determined, a right censored spell.

In figure 1 there are six completed time spells, one left censored spell (at the beginning) and one right censored spell (at the end). Within each time spell, there can be a range of multiple discrete activities. For example, starting from the left of figure 1, the first completed time spell (i.e. from accept to navigate) includes the planner controller event which occurred at time T_{pinfo} before the onset of navigate, the second time spell (i.e. from navigate to goodbye), includes the external trigger event get strip at T_{strip} before goodbye.

Table 1. Codes and their grouping by type used in the analysis.

I. Communication (Com)	
Accept	Accept control of an aircraft from another sector
Navigate	Details of flight route and instruction to the aircraft
Goodbye	End of escorting an aircraft through the sector
Query	Request of information from the pilot
Negotiate	Resolution of flight plan conflicts
II. Flight progress activities (FP)	
Manipulation	Mark and/or shuffle flight paper strips on the rack
Remove	Get rid of redundant flight paper strips
III. Radar background tasks	
Tidy	Clean up the radar screen
IV. External trigger events	
Pilot hello	Greetings
Pilot information	Aircraft current flight route
Get strip	Newly presented, incoming aircraft flight plan
V. External cooperation events	
Planner instruction	Direct instruction for immediate attention or action
Planner information	Information about the aircraft(s) without specifying the course of actions for the tactical controller
Planner advice	Response(s) to the enquiries

The durations of these time spells are rarely normally distributed. They are typically truncated, discrete, positively skewed and leptokurtotic (cf. Singer and Willet 1991). Figure 2 displays the distribution of time spells examined in the present study, which illustrates all of these properties. The departure from the normality assumption has made traditional correlational and regression analyses unsuitable for the study of time distributions such as these. Because the ATC operations consist of multiple concurrent tasks (i.e. two activities happening at the same time), conventional log-linear and sequential analysis that apply strictly to data with the ordered form of a linear succession of activities are also not suitable (Bakeman and Gottman 1986, Agresti 1989, Sanderson and Fisher 1994).

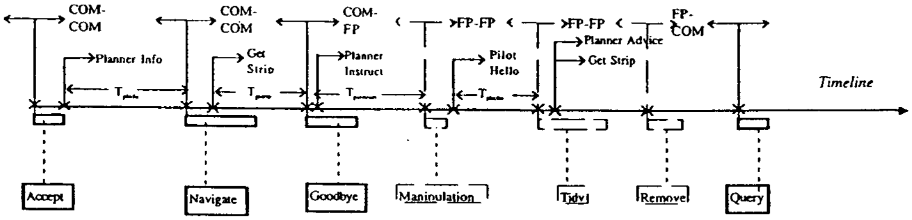
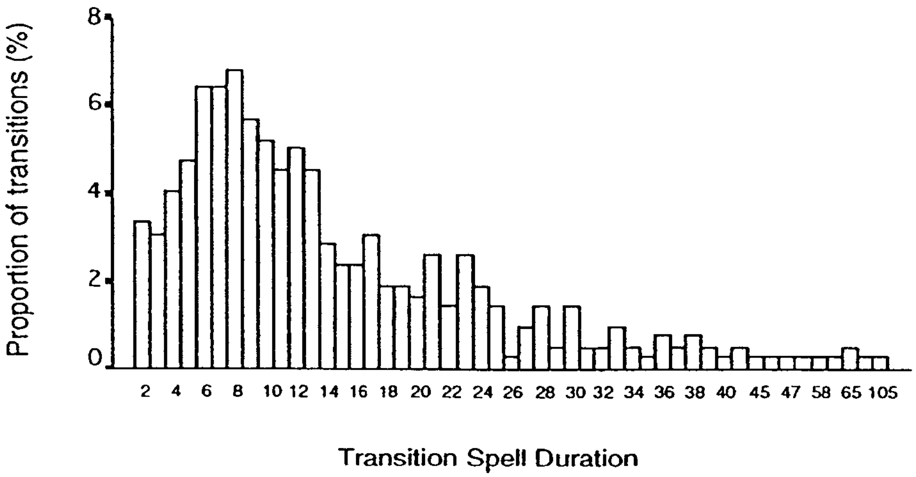


Figure 1. Re ATC's spell event history. The timeline has six completed spells (i.e., from left to right, COM-COM, COM-COM, COM-FP, FP-FP, FP-FP and FP-COM), one left-censored spell and one right-censored spell. COM, communication activities including accept, navigate, goodbye, query and negotiate (not shown); FP, flight progress activities including manipulation, remove and tidy (the radar). The length of the shaded rectangle represents the duration of each activity. Tpinfo, Tgstrip, Tpinstruct and Tphello, respectively, are the time from the onsets of the activities of planner information, get strip, planner instruct and pilot hello to the next ATCs operation.



Seconds

Figure 2. Spell distribution of the controller's operations. Mean (SD) = 14.46 (12.03)s, kurtosis = 12.26 s, and skewness = 2.66.

1.3. *Hazard rate models*

An appropriate resolution to the problem of representing the distributional and temporal properties of time spell transitions is to treat them as a typical Weibull time-to-fail distribution. The distribution was first introduced by Waloddi Weibull (1951). It has been used, for example, in engineering to understand trouble-shooting and to estimate the failure rate for system reliability engineering (Dodson 1994). Here, the time-to-fail distribution is generated by the hazard function $h(t)$ of moving from one state (activity) to another within a time spell. That is, $h(t)$ represents the instantaneous rate of change from one state to another, given that the tactical controller has been in the first state until time t. As the hazard rate increases, the duration of the time spell decreases and the transitions occur faster. $h(t)$ can be written as:

$$h(t) = \lim_{\Delta t \to 0} \frac{\Pr(t,\ t+\Delta t)}{\Delta t}, \tag{1}$$

where Pr is the probability of state transition occurring from t to $t+\Delta t$.

In discrete time models when $\Delta t = 1$, the product $h(t).\Sigma\Delta t$ is the conditional probability (Lawless 1982). In continuous time models, as Δt approaches zero, the hazard rate is no longer a conditional probability but a conditional, instantaneous rate that can take values from zero to positive infinity. The continuous-time hazard rate can be regarded as the unobserved rate from the onset of observation period to the occurrence of a target event (Allison 1984).

The Weibull distribution can be generated by an $h(t)$ that is a two-parameter generalization in which $h(t)$ is a function of time

$$h(t) = \lambda p(\lambda t)^{p-1}, \tag{2}$$

where λ is a scaling parameter and p is a shaping parameter. $h(t)$ increases with time for $p > 1$ and decreases for $p < 1$; the higher the p, the faster the $h(t)$ is increasing. If $p = 1$, $h(t)$ is constant at a λ.

A given Weibull distribution can be fit using a Cox (1972) regression model. The model allows $h(t)$ to vary freely over time and be dependent on a set of predictors z, which can include nominal and time-varying variables (Kalbfleisch and Prentice 1980). This relationship is expressed as:

$$h(t, z) = \lambda p(\lambda t)^{p-1}(e)^{z\beta}. \tag{3}$$

Taking the log of equation 3 and pulling the coefficients out as terms gives:

$$\ln[h_{is_t s_{t+\Delta t}}(t)] = \ln[h_{s_t s_{t+\Delta t}}(t)] + \beta_1 x_{i1} + \beta_2 x_{i2} + \ldots + \beta_p x_{ip}, \tag{4}$$

where ln is the natural logarithm; $is_t s_{t+\Delta t}$ is an individual ith change from one state to another; $h_{s_t s_{t+\Delta t}}(t)$ is a time-varying intercept term, β is a regression coefficient for a predictor, and x_{ip} is an individual's observed value for that predictor.

The coefficients, βs, in equation 4 can be found by Cox regression analysis. This then allows equation 3 to be expanded to examine the estimated effects of events that happened during and prior to spells.

For example, the hazard rate of the transition leading to the second completed time spell COM-COM in figure 1 can be expressed in the form of:

$$\ln[h_{ic_t c_{t+\Delta t}}(t)] = \ln[h_{c_t c_{t+\Delta t}}(t)] + \beta_1 x_{s_{\mathrm{lag}(0)}} + \beta_2 x_{T_{\mathrm{lag}(0)}} + \beta_3 x_{s_{\mathrm{lag}(-1)}} + \beta_4 x_{T_{\mathrm{lag}(-1)}} + \beta_5 x_{s_{\mathrm{lag}(-2)}} + \beta_6 x_{T_{\mathrm{lag}(-2)}} \ldots, \tag{5}$$

where $ic_tc_{t+\Delta t}$ represents an individual time spell from navigate to goodbye (i.e. a transition from one state of communication to another); $x_{s_{\mathrm{lag}(0)}}$ and $x_{T_{\mathrm{lag}(0)}}$ are the type of event and its time within the time spell, in this case, getstrip and time T_{getstrip} from its onset to goodbye; and lag(-1) and lag (-2) are the backward first and second lag positions of an individual's observed values for the previous set of actions and durations. Equation 5 illustrates the extent to which a series of predictors including both nominal and time-varying variables can be incorporated.

In a situation when there are two activities that occurred at the same time, the duration of the time spell between them would be zero. This does not create any problems, because $h_{ic_{t+\Delta t}}(t)$ can range from values of zero to positive infinity. To determine the type of the time spell that occurs next, the previous activity with the longest duration is chosen as the reference for the next state. For example, if accept (communication, COM) and manipulation (flight progress activities, FP) occur simultaneously at the first state with remove as the next state, a COM-FP spell rather than a FP-FP will be used if accept has a longer duration span than manipulation.

1.4. *Testing models and procedures*

The application of the Weibull time-to-fail distribution to represent behaviours is novel in real-time control tasks in general and air traffic control in particular. A statistical model of the hazard rate of an ATC's operation was first constructed to test the assumption that the spell distribution in the data set was indeed a Weibull. This could be achieved by estimating the survival function $\bar{S}(t)$, that is, the proportion of time spells that have not ended at any time t, where $\bar{S}(t) = P(T \geqslant t)$, $t \geqslant 0$. $\bar{S}(t)$ decreases from a maximum at $\bar{S}(0) = 1$ (i.e. all spells survive at $t = 0$) to $\bar{S}(t) = 0$ as $t \to \infty$. Similar to $h(t)$, $\bar{S}(t)$ also follows a Weibull distribution,

$$\bar{S}(t) = \exp.\ [-(\lambda t)^p]. \tag{6}$$

By taking the logarithm, equation 6 becomes

$$\log\ (S(t)) = -(\lambda t)^p$$

$$-\log\ (S(t)) = (\lambda t)^p$$

$$\log(-\log(S(t))) = p(\log \lambda + \log t). \tag{7}$$

As a direct check for the Weibull distribution, a plot of $\log\ (-\log\ (S(t)))$ against $\log t$ should be roughly linear, with its slope a rough estimate of p, and its intercept an estimate of $-\log \lambda$. Regression of $\log\ (-\log\ (S(t)))$ on $\log\ (t)$ should account for most of the variance (Kalbfleisch and Prentice 1980).

Hazard rate models can then be constructed to compare which variables affect the hazard rate of the time spells under heavy and light workload conditions. This model can be based on equation 5 by performing a Cox regression.

2. Method

2.1. *Data acquisition*

Four Air Traffic Controller Officers (ATCOs) participated in the simulation of two en-route ATC sectors over two sessions. Each sector was operated by a pair of controllers performing specified roles as either tactical controller or planner. The tactical controller is responsible for ensuring separation between aircraft within the sector and communicating with the aircraft. The planner aided the tactical controller in this task, however, he or she did not normally communicate directly to aircraft. Psuedo-pilots controlled multiple planes acting as their pilots, implementing instructions from the ATCOs.

Each session lasted for approximately 1 h. Prior to the sessions, all four participants had approximately 60 h practice using the simulator. The analyses presented in this paper refer to one of the four participants in the study. The subject participant was female, in her early 30s. She had in > 10 years experience working as an ATCO in the UK. During the simulation, she acted as the tactical controller. One of the other three ATCOs took up the position as the planner controller for providing the tactical controller with information as in the normal operating procedures.

For each of the participants, video recordings were taken from two camera angles. One video angle showed the participant's face, the other angle showed the radar plan view display (PVD), mouse, paper flight strip rack and the back of the participant. Audio recordings were taken for each of the active radio telephone channels. A microphone recorded verbal communication not directed via the radio telephone.

The simulator was housed in a purpose-built room. It included two DEC VT 1300 terminals for the pseudo-pilot positions, simulated radio telephone equipment for communication between ATCOs and pseudo-pilots, a paper flight progress strip printer, and two paper flight progress strip racks, one for each tactical controller. Radar information was displayed on four 28-inch high-resolution colour plan view displays (PVD), one for each ATCO. The planner's PVD differed from that of the tactical controller, showing electronic flight strips in addition to the radar image.

The area simulated was centred on proposed UK New En-Route Centre (NERC) sectors. The airspace was divided into two sectors; approximately 80% of the aircraft in the simulation were routed to pass through both sectors.

Traffic entered the simulation according to a predefined script. The traffic samples were based on projections in 1992 for the year 2002. Aircraft performance was modelled using AirSim. AirSim uses an extension of the Eurocontrol sim aircraft model and the Base of Aircraft DAta (BADA) aircraft performance database. Within the limits of the AirSim model, aircraft could be given manoeuvre and navigation instructions by the pseudo-pilots. All the aircraft within a sector were controlled by one pseudo-pilot plus an assistant controller. When an aircraft moved between sectors, control of the aircraft was transferred to the relevant pseudo-pilot.

2.2. *Workload measurement*

The simulation consisted of two sessions each lasting one h with two different traffic flow rates: 34 aircraft per h for the first (light workload condition) and 44 for the second (high workload condition). Every 2 min during the simulation, a bright yellow cue box appeared at the bottom right-hand corner of each PVD. The participants were instructed to respond to the prompt by rating their level of workload at that time on a 5-point scale, where 1 = underutilized, 2 = relaxed, 3 = comfortable, 4 = high and 5 = excessive. Response ratings between 1 and 2 were typical for the light traffic flow and also for the first 15 min for the heavy traffic flow session. The rest of the heavy traffic flow session scored consistent ratings of 4. To form two workload conditions, the recordings were divided into two on the basis of the ratings. The light condition was defined as the periods when the participant rated her workload with a rating of $\leqslant 2$ whereas the high condition was defined as the periods when the participant rated her workload with a rating of $\geqslant 3$.

2.3. *Coding ATC operations*

The coding was based on a task analysis of a current UK en-route ATC sector (Cox 1994). The coding consisted of three main categories: five codes for ATC's communication over the radio telephone, three codes for ATC's activities in relation to paper flight progress and three codes for external trigger events. A description of the codes is given in the table 1. Transcriptions of the two sessions of the simulation were coded independently by two coders with 99% agreement.

3. Results

After showing that the assumptions for the analysis were met, the results of the regression are explained. Both hazard models were fit with the survival function analysis in SPSS 6.1.

3.1. *The Weibull assumption*

To apply Cox regressions for modelling the hazard functions of ATC operations, the ATC spell transitions have to fulfil three general features of a Weibull distribution: (1) a plot of log $(-\log(S(t)))$ against log t has to be linear; (2) the K-M quartiles have to be exponentially declining; and (3) the survival function $(\bar{S}(t))$ has to be exponential.

Figure 3 shows a plot of $\log(-\log(S(t)))$ against log t. The Weibull assumption can be retained as the plot is roughly linear with 98% of the variance accounted for.

Table 2 shows the exponential declines from 25 to75% quartiles based on the K-M estimates of the survival functions of all types of spells. Figure 4 shows their

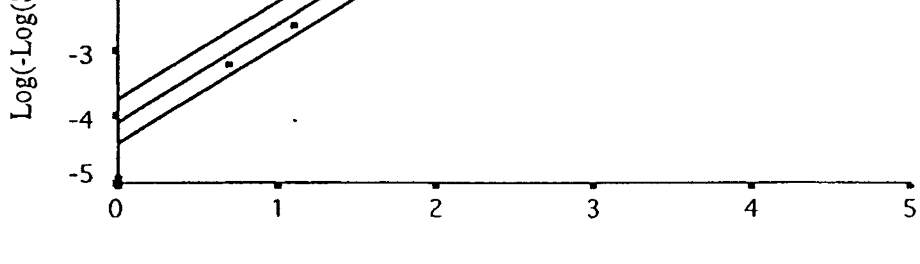


Figure 3. Relationship between the log $(-\log(\text{survivor function}))$ and the log of the spell duration. Data are well fit ($R^2 = 0.981$) by a linear relationship as indicated by the central line. The band around the regression line represents the 95% confidence interval. Not all 422 data points are visible because some overlay.

Table 2. Descriptive statistics, K-M estimates of the survival functions of ATC's tactical operations under heavy and light workload conditions.

Operational transition spells[a]	n	Mean duration	K-M quartiles[b] 75%	50%	25%
Heavy workload condition					
COM-COM spells	43	12.37 (0.82)	9 (1.31)	12 (0.65)	15 (1.00)
COM-FP spells	45	11.47 (1.03)	7 (0.85)	10 (0.96)	13 (0.96)
FP-COM spells	53	8.43 (0.63)	6 (0.70)	8 (0.32)	11 (0.98)
FP-FP spells	39	9.97 (1.32)	4 (0.48)	6 (1.34)	12 (5.26)
Total spells	180	10.47 (0.48)	6 (0.47)	9 (0.50)	13 (0.56)
Log rank = 4.40, d.f. = 1, $p<0.05$.					
Light workload condition					
COM-COM spells	27	24.85 (3.90)	13 (3.19)	19 (1.73)	30 (3.78)
COM-FP spells	59	16.82 (1.66)	7.5 (0.72)	13 (1.71)	21 (1.59)
FP-COM spells	57	16.42 (2.00)	5 (1.90)	13 (2.09)	22 (2.32)
FP-FP spells	99	16.33 (1.20)	7 (0.54)	12 (1.66)	23 (1.72)
Total spells	242	17.42 (0.91)	8 (0.52)	14 (1.14)	23 (1.09)
Log rank = 3.17, d.f. = 1, $p<0.08$ (ns).					

N, number of discrete time spells; COM-COM, transition from communication to communication; COM-FP, communication to flight progress activities; FP-COM, flight progress activities to communication; FP-FP, flight progress to flight progress activities. Mean duration and quartiles are in seconds. Standard errors are in parenthesis. [a]The time spell is an interval marked by the onset of one known activity to the next one of either communication or flight progress ATCs operations. [b]K-M quartiles stands for Kaplan–Meier non-parametric estimates of the survival function. The 50% column is the median of the distribution. The log rank test indicates whether there is any significant trend difference among the types of time spells.

estimated survival functions. These both provide further evidence that the distribution of spell durations can be treated as a Weibull.

3.2. *Workload*

The log rank test as shown in table 2, also known as the Mantel–Cox test, has a χ^2 distribution. It is the most widely used method to compare any trend differences of two or more survival curves. The test indicates significant differences among the four types of time spells in the heavy workload condition. Further pairwise comparisons indicate that the flight progress initiated FP-COM spell is significantly shorter than that of the communication COM-COM (log rank = 10.03, $p<.001$) and COM-FP (log rank = 6.57, $p<.05$) spells.

In terms of $h(t)$ estimates, the mean total spell is significantly shorter in the heavy than in the light workload conditions, χ^2 (1, 418) = 44.18, $p<0.0001$. This indicates that the overall transitions among discrete ATC activities occur faster in the heavy than in the light workload condition.

Table 3 displays the results of fitting a two-step Cox regression analysis in predicting the $h(t)$ of the four types of time spells in heavy and light workload conditions. Step 1 estimated the effects of variables within the spell and step 2 the effects

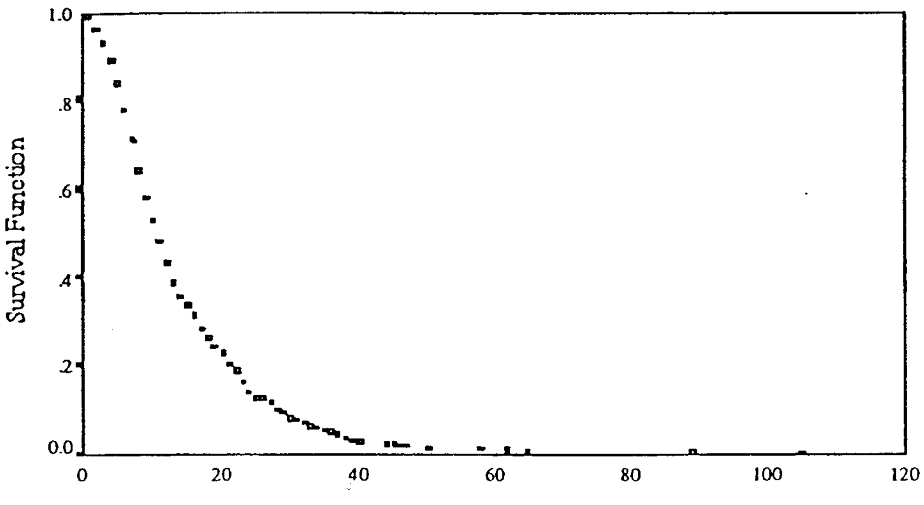


Figure 4. Estimated spell survival function.

of lagged variables (at lag 1 and lag 2). At each step only variables that significantly accounted for the variance of $h(t)$ of the time spells were allowed to enter.

The coefficients β represent changes to $h(t)$ in an exponential relationship. Interpretation of significant β for spell time, a continuous variable, is straightforward. For a unit increase in the duration of a previous spell, its effect on the hazard rate is a factor of (exp $(\beta) - 1$). For discrete variables, their exponential coefficients represented the relative hazard by contrasting their presence to their absence (Allison, 1984).

For spells between communication activities (COM-COM) in the heavy workload condition, table 3 shows that at the second step the dummy coded variables goodbye (at lag 1, indicating it occurred during the previous spell), where the ATC operators finished the on-route escort, and manipulation (at lag 1), where the ATC operator manipulated a paper flight strip, entered with coefficients (β) of -2.1 and 0.84. The presence of goodbye at lag 1 reduced the $h(t)$ of the COM-COM spells by a factor of 0.12 or when it was absent. The opposite effect was found for manipulation at lag 1. When present, it increased $h(t)$ by a factor of 2.31. In addition, a unit increase in the duration of the spell at lag 2 decreased $h(t)$ of the COM-COM spell by a factor of 0.29.

For COM-COM transitions in the light workload condition, communication activities including accept and goodbye at lag 1, and accept at lag 2, and flight progress activities manipulation and tidy at lag 1 significantly accounted for the $h(t)$ of the COM-COM spell. In contrast with their absence, the presence of accept and tidy increased their $h(t)$ by factors of 8.02 and 3.12. On the other hand, goodbye, manipulation and accept at lag 2 were adjusted by factors of 0.88, 0.74 and 0.90 of the $h(t)$ when they were absent. To summarize, the presence of accept and tidy in previous spells made the current spell longer (i.e. lower $h(t)$), and the presence of

Table 3. Weibull stepwise regression models of transition spells under heavy and light workload conditions.

Transition spell	Step	Variables entered	Heavy workload condition β	SE	(Exp[β])	Wald statistic	$\Delta\chi^2$	Variables entered	Light workload condition β	SE	(Exp[β])	Wald statistic	$\Delta\chi^2$
COM-COM	1	(no variables entered at this step)						(no variables entered at this step)					
	2	Goodbye (−1)	−2.10	0.95	0.12	4.92*	40.935****	Accept (−1)	2.08	0.80	8.02	6.73*	25.10**
		Manipulation (−9)	0.84	0.36	2.31	5.46*		Goodbye (−1)	−2.13	0.85	0.12	6.35*	
		Time (−2)	−0.34	0.07	0.71	22.46****		Manipulation (−1)	−1.36	0.57	0.26	5.75*	
								Tidy (−1)	1.14	0.52	3.12	4.73*	
								Accept (−2)	−2.30	0.76	0.10	9.09*	
Initial log likelihood function = 248.82, $\chi^2 = 42.57$, d.f. = 18, $p < 0.0001$.								Initial log likelihood function = 129.72, $\chi^2 = 31.14$, d.f. = 14, $p < 0.001$.					
COM-FP	1	Planner info (−1)	−0.11	0.04	0.90	5.90*	9.44**	Get strip (−1)	−0.12	0.064	0.89	3.53^{u}	10.41*
	2	Time (−2)	−0.07	0.03	0.94	4.36*	4.96*	Accept (−1)	−1.69	0.63	0.18	7.16**	18.33*
								Goodbye (−1)	1.00	0.48	2.71	4.23*	
								Manipulation (−1)	0.86	0.41	2.36	5.75*	
								Time (−1)	0.12	0.05	1.13	4.91*	
Initial log likelihood function = 254.65, $\chi^2 = 22.28$, d.f. = 16, $p < 0.05$.								Initial log likelihood function = 372.65, $\chi^2 = 48.75$, d.f. = 16, $p < 0.001$.					
FP-COM	1	(no variables entered at this step)						(no variables entered at this step)					
	2	(no variables entered at this step)						Remove (−1)	−1.66	0.61	0.19	7.43**	17.69**
Initial log likelihood function = 331.86, $\chi^2 = 21.63$, d.f. = 19, $p < 0.5$.								Initial log likelihood function = 331.59, $\chi^2 = 42.13$, d.f. = 18, $p < 0.001$.					
FP-FP	1	(no variables entered at this step)						Pilot info (−1)	0.29	0.14	1.34	4.44*	10.83**
	2	(no variables entered at this step)						(no variables entered at this step)					
Initial log likelihood function = 216.92, $\chi^2 = 27.73$, d.f. = 16, $p < 0.05$.								Initial log likelihood function = 715.60, $\chi^2 = 76.94$, d.f. = 17, $p < 0.00001$.					

$^{u}p < 0.06$; $^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$; $^{****}p < 0.0001$. $\Delta\chi^2$ is the chi-square changes from the initial log likelihood of the first step to that of the second step. Only variables contributed significantly in accounting the hazard rate of the time spells were allowed to enter at each step. Step 1 estimated the effects of variables within the spell, and step 2 variables at backward lag 1 (or −1) and lag 2 (or −2) positions. Discrete variables are dummy coded.

goodbye and manipulation in previous spells, and accept at lag 2 made the spell shorter (i.e. higher $h(t)$). Accepting aeroplanes and tidying strips were strong predictors that communication activities were to shortly follow.

Transitions between communications and flight progress activities (COM-FP) in the heavy workload condition were delayed by the presentation of flight information from the planner controller (planner info with $\beta = -0.11$) within the spell, by a factor of 0.90 compared with its absence. The slowing down of the transition may simply suggest that the tactical controller spent more time to interpret the newly presented information from the planner controller. And a unit increase of time at lag 2 ($\beta = -0.17$) also made the spell slightly longer by 6%.

However, for COM-FP transitions in the light workload condition, an external trigger events, get strip (when the tactical controller attended to newly represented flight progress paper strips) significantly affected the spell $h(t)$. The external event get strip would slow down the COM-FP transition ($\beta = -0.12$). That is, the presence of get strip reduced $h(t)$ by a factor of 0.89 compared with COM-FP spells without it. The previous directions of predictions of accept, goodbye and manipulation were inverted for this transition. That is, the presence of accept lead to a reduction to 0.18 of those without; goodbye and manipulation made $h(t)$ 2.71 and 2.36 times larger than the hazards for those without. A unit increase in time spent at backward lag 1 position increased the $h(t)$ by 13%.

For transitions between flight progress activities and communication (FP-COM), no variables entered in the heavy workload condition. In the light workload condition, the flight progress activity remove at lag 1 entered at step 2. The presence of remove indicated about 19% of the hazard for those FP-COM spells without it.

For transitions between different flight progress activities (FP-FP) no variables entered in the heavy workload condition. In the light workload condition, an external trigger pilot information, when the pilots radio-called and identified themselves to the tactical controller, entered to predict transition in the light workload condition ($\beta = 0.29$). By providing information, the pilot would speed up the FP-FP transition. That is, when the pilots identified themselves they were simply providing the tactical controller with specific information that did not need further processing. This facilitated rather than delayed the transition.

In exploring which variables at backward lag 1 and lag 2 positions are potential predictors, relatively more variables entered in the Weibull regression models for the light rather than heavy workload conditions. Table 2 shows that there is less variance in these spell times. Because the initial log likelihood functions for COM-FP and FP-COM spells under the heavy workload conditions are non-significant, these suggest that the spell time alone was sufficient to account for the observed variability despite the significant entry of variables planner information and time at lag 2 to the final model for the COM-FP spell in the heavy workload condition.

Overall, the findings can be interpreted as an ATC's operation was more likely regulated by the effects of time under heavy rather than light workload conditions. Indeed, for the FP-COM and FP-FP spells under heavy workload, the set of potential predictors included in this analysis failed to enter. More importantly, for both the COM-COM and COM-FP spell in the heavy workload condition, how much time the previous spell occupied at backward lag 2 position made a significant contribution to the overall hazard rate models.

4. Discussion

This study has demonstrated that hazard rate models can be used to increase our understanding of how air traffic tactical operations change as workload changes. The findings suggest that the effect of time allocation is more prominent in heavy rather than in light workload conditions. This generally reflects that time has to be more efficiently used and distributed among activities for combating the increasing task demands when workload increases. In this respect, time is a greater determinant than other variables examined in this study.

On the other hand, under the light workload condition, as time becomes less crucial and more abundant, other activities related to communication and flight progress, particularly at backward lag 1 position, exert greater positive and negative effects on the transitions to the next activity. Considering the wide range of activities included in COM-COM spells, action sequences are definitely contingent upon and determined by previous actions. This also applies to the COM-FP spell but not the FP-COM and FP-FP spells. The latter may relate to the possibility that in contrast with spells begun by communication, those begun by flight progress are less susceptible to what comes before. This is particularly true for the heavy workload condition.

The findings suggest that it is imperative for ATC system designers to consider how workload and stress affect time management in decision-making. It is the case that under the heavy workload condition, it appears that time alone determines what gets done. Because the tactical controller's operations follow the rhythm and the availability of time more closely under heavy than light workload conditions, the operations appear essentially time-based scheduling activities. It might be the case that by active scheduling the tactical controller seeks to prioritize activities by leaving the least important ones until last (e.g. Raby and Wickens 1994). When time becomes available, they are done in batches. If there is no time, they do not get done.

One possible implication consistent with the general notion of modular automation is that flight progress-initiated spells may be more suitable for automation than communication-initiated spells (Vortac *et al.* 1994). However, in view of the effects that flight progress activities have on communication-initiated spells, the intertwined nature of ATC's operations in both heavy and light workload conditions has made the notion of modular automation untenable. That is, as far as the dynamic nature of ATC's operations is concerned, these results suggest that flight progress activities are not structurally independent from communication activities, and cannot be simply isolated and regarded as an independent cluster for modular automation. There are not cleanly separable, uniform sets of activities in air traffic control, particularly when the traffic rate is high. Future automation has to consider this and has to allow the operators the flexibility of prioritizing their activities.

Another interesting finding is that cooperative work was only obtained in the heavy workload condition. Cooperative work in the form of planner information has the effect of prolonging the COM-FP spell. This is not surprising as the communication between the tactical and the planner controllers is expected to be more frequent and intense in the heavy than in the light workload condition. What remains unclear is how communication of this kind can mitigate the increasing influx of situational demands. Considering the trade-off between the potential increase of cognitive resources due to cooperation and the additional time that it takes, it is important to ensure that both tactical and planner controllers share a similar mental model of how things should be in the airspace. In many counts, effective cooperation depends on the clarity and the adequacy of information exchanged, and less indirect speech is expected (e.g. Linde 1988).

By presenting an in-depth single-case analysis, this paper departs from the conventional approach in understanding naturalistic decision-making specifically in emergency situations. Most techniques such as the critical decision method (Hoffman *et al.* 1995) will aggregate decisions and correlate with the outcomes, but they fail to circumvent an important ontological issue pertaining to the properties of and interaction between time and actions. Recent advances in longitudinal analysis have provided some insight into how behaviours can be systematically fragmented and bootstrapped for the purpose of model building (e.g. Peterson 1993).

The introduction of hazard rate models adds to the diversity of methods for modelling ATC operations and other sequential behaviour. Analysis of this kind incorporates time distributions and action sequences into a dynamic model.

However, there are caveats in using event history analysis in this way without being cautious about the form and the inherent properties of the data to be collected. This is to ensure that the analytical findings are robust and conclusive. Although, unlike parametric statistics, event history analysis is less restricted by the distribution of the data, the hazard rate model or the Cox regression still has several assumptions. These include issues of spell independence, population heterogeneity and sample size. Strictly speaking, the spells have to be statistically independent. In a single-case design, as reported in this study, this assumption was violated. A way around this problem, as in this analysis, is to include in the hazard model a set of possible variables that tap into the individual's prior states (Allison 1984 has an alternative approach to the problem of dependence). The second assumption, which is the occurrence of differences between people in their underlying hazard rate, is less of an issue here as the data were derived from the same subject. Regarding the third assumption, it is not clear how large the sample size needs to be for it to be sufficient. A general practice is to check the distribution of the data in terms of the Kaplan–Meier non-parametric estimates of the model and also provide graphical displays (Lawless 1982).

Our research into the effects of time pressure on ATC's operations makes a simple case about the limitations in applying conventional task analysis for the purpose of prescription without considering the wider impacts of situational characteristics. That is, if the understanding of system operation is limited to simple 'if A then B' transitions, there may be a failure to unpack the underlying dynamics of how situational demands can affect ATC at various levels of tactical operations.

Acknowledgements

We thank Peter Gouliou for providing useful advice on the data acquisition, and Gordon Baxter and Fernand Gobet for comments on the manuscript. Support has been provided by DERA (Portsdown, UK), Contract no. 2024/004.

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