Pilot Performance With Predictive System Status Information

Anna C. Trujillo
NASA Langley Research Center
Hampton, VA 23681-0001

ABSTRACT

Research has shown a strong pilot preference for predictive information of aircraft system status in the flight deck. However, the benefits of predictive information have not been quantitatively demonstrated. The study described here attempted to identify and quantify these benefits if they existed. In this simulator experiment, three types of predictive information (none, whether a parameter was changing abnormally, and the time for a parameter to reach an alert range) and four initial times to an alert (1 minute, 5 minutes, 15 minutes, and ETA+45 minutes) were found to affect when subjects accomplished certain actions, such as accessing pertinent checklists, declaring emergencies, diverting, and calling the flight attendant and dispatch.

INTRODUCTION

Much anecdotal evidence exists regarding the benefits predicting aircraft system failures would bring to increasing the safety of flight. Documented instances exist where some type of early notification to the flight crew of a system parameter deviation could have prevented or lessened the consequences of an aircraft's system failure [1], [2]. The benefits of predictive information, some have argued, are in the realm of improved decision making [3]-[5]. Thus, to describe and quantify the benefits of predictive information, a research program was undertaken to systematically explore these potential benefits.

Earlier research has shown a strong pilot preference for predictive information [6] and for certain types of predictive information, specifically, whether a system parameter (e.g., oil temperature) was changing abnormally and the time remaining until that parameter reached a predefined value [7]. Pilots also indicated when they wanted to be told of a possible problem. For example, pilots only wanted to be notified that the parameter was moving if it would reach an alert range in less than 5 minutes; otherwise, they would rather know the approximate time remaining until the alert [7].

Objectives

There were several objectives of this experiment. The primary objective was to identify the benefits of predictive information in an operational setting during non-normal system events. Benefits were defined as decision making pertaining to handling of the fault, which included taking actions to affect the onset of an alert, retrieving checklists, diverting and declaring emergencies, and workload associated with the non-normal system events. The secondary objective was to determine the most appropriate form of predictive information and range of prediction times. Lastly, this experiment was conducted to corroborate previous research.

Experimental Variables

Of the three experimental variables, two were directly manipulated: the predictive information available and the initial time to an alert. The predictive information available, a between subject variable, was one of three types: (1) none (baseline), (2) whether a parameter was increasing or decreasing abnormally (direction), or (3) the time to an alert (time). The initial time to an alert, a within subject variable, had four levels: (1) 1 minute, (2) 5 minutes, (3) 15 minutes, and (4) ETA+45 minutes (Estimated Time to Arrival). Baseline predictive information and ETA+45 minute initial time to an alert were control conditions. The third experimental variable, which was partially controlled in that the parameter would degrade in a regulated manner, was the four independent faults each subject encountered.

Predictive Information: In the baseline condition, no predictive information was available. Thus, when a parameter reached an alert range, the subjects saw the typical alert message (e.g., CABIN ALT) with the accompanying aural alert (table 1).

Table 1 - Examples of Predictive Information

Condition	Predictive Information	Alert Information
Baseline	none	"CABIN ALT"
Direction	"CABIN ALT INC"	"CABIN ALT"
Time	"CABIN ALT 7MIN"	"CABIN ALT"

In the other two conditions, direction and time, subjects were notified that a parameter was moving towards an alert range. In all cases, the predictive information presented to subjects was always correct and had an alert category of advisory. Furthermore, parameters increased or decreased at a constant rate dependent on the state of the aircraft. Lastly, when the parameter reached an alert range, the related standard alert information message replaced the predictive information message (table 1).

For the direction condition, subjects were told that a parameter was increasing or decreasing abnormally (table 1). For the time condition, subjects were told when a parameter would reach an alert range for the given aircraft state (table 1). The time to an alert was updated in increments of whole minutes if the time remaining was greater than 1 minute. If

the time to an alert was less than 60 seconds, the message updated for every 15-second change in the time to an alert.

Initial Time to an Alert: Each subject saw four initial times to an alert (the time to an alert at the beginning of a failure): (1) 1 minute, (2) 5 minutes, (3) 15 minutes, and (4) ETA+45 minutes. The configuration of the aircraft affected the actual time to an alert; for example, throttling back the engine with the EGT (Exhaust Gas Temperature) increase would increase the time to an alert.

Faults: Each of the four data runs, or scenarios, and the training run included a fault in which a parameter would eventually reach an alert range if the subject took no action. The faults were (1) cabin altitude increase, (2) forward cargo overheat, (3) EGT increase, and (4) oil quantity decrease. The training run was an avionics overheat. All failures were designed to behave as realistically as possible [8]-[11] and are described below.

For the scenario with the cabin altitude increase, the cabin altitude increased to the airplane altitude. The outflow valve, if checked, was in the fully closed condition once the failure started. Although the increase could not be controlled through the environmental system, the cabin altitude warning would not be reached if the subject descended to no more than 10 000 ft and if he had at least 4_ minutes until the alert range was to be reached—the time needed to descend from the initial altitude of 37 000 ft to 10 000 ft.

In another data run, the forward cargo hold, initially set-up for carrying animals, had a temperature increase until it reached the fire warning limit. If the subject changed to the cargo mode, the temperature increase would slow. Also, if he discharged the forward cargo fire bottle before the alert range was reached, the forward cargo temperature would never reach the alert range. If the subject discharged the forward cargo fire bottle after the fire warning, as the forward cargo fire checklist instructs him to do, the temperature would drop below the alert range.

During the scenario with the EGT increase, the EGT rose steadily and if it reached the alert range, the subject would have to follow the engine failure/shutdown procedure. The increase could be slowed if the subject throttled back the engine with the increasing EGT or stopped if the affected engine was shut down. If the subject restarted the engine, the EGT would again increase until it reached the alert range.

The scenario with the oil quantity decrease also involved an oil pressure decrease because of the loss of oil. The oil pressure triggered the alert once it reached an alert range. The only way to decrease the rate of oil loss was to shut down the affected engine.

For the avionics overheat training run, the rate of temperature increase could be decreased by changing the avionics mode to override from its initial position of normal. Furthermore, by disconnecting bus 3, the temperature would stay below the warning limit. Thus, the load on bus 3 was the primary cause of the overheat.

EXPERIMENT DESIGN

Subjects

Twelve glass-cockpit airline pilots familiar with ETOPS (Extended Twin engine OPerationS) rules participated as subjects. Seven were currently first officers with the remaining five captains. The average age was 48 years old and the average commercial airline flight experience was 16 years.

Test Design

The experiment was run in the Advanced Civil Transport Simulator at the NASA Langley Research Center. This simulator had flight performance characteristics similar to a Boeing 757. The flight deck resembled a Boeing 747-400 or MD-11. The subject acted as captain, pilot-not-flying. A confederate first officer (F/O) was pilot-flying and he was well versed in the operation of the simulator. A confederate air traffic controller (ATC) and company dispatch operator provided the necessary coordination with the ground.

The flight was from Dulles airport to Charles de Gualle airport with a 60-minute ETOPS rule; i.e., the plane was never more than 60 minutes from an alternate airfield. The 60-minute rule was used in order to have several PETs (Point of Equal Time); i.e., the point where the plane was 60 minutes from any suitable alternate airport. The scenarios were set-up such that each segment of flight started before a PET; thus, this experiment only included the cruise phase of flight. If the configuration of the aircraft did not change during the fault, the affected parameter would reach an alert range a few minutes before the aircraft intersected the PET except in the ETA+45 minute condition.

Any materials and information the subject needed were provided to him. Plotting charts, landing plates, a dispatch weather briefing, and a flight plan were available in paper form. Checklists were electronic and mimicked the Boeing model of the quick reference handbook [12]. Voice communication was used for ATC and dispatch. Both ATC and dispatch were able to supply current weather information at any of the diversion airfields. Basically, the weather at all diversion airfields was acceptable for landing—drizzle with a ceiling around 1 000 ft and visibility approximately 1_ miles with winds at no more than 10 knots. ATC also reasonably expedited any requests subjects had regarding course changes. The confederate F/O was able to answer operational questions from the subject; i.e., he supplied all the operational information normally found in the aircraft manual. Lastly, subjects made any passenger announcements or held conferences with the head flight attendant, or purser, to the experimenter sitting in the back of the simulator.

As mentioned earlier, the faults and initial times to an alert were within-subject variables while the predictive information was between subjects. Since subjects could only see each failure once, each subject had four data runs in addition to a training run. Thus, the overall results is that all subjects saw each of the four faults once and each of the four initial times to an alert once with one of the three types of predictive information.

Dependent Measures

The dependent measures consisted of variables that defined whether the predictive information was beneficial: when and where certain actions occurred, and workload ratings, which were measured using the NASA-TLX questionnaire on perceived workload [13]. Variables not directly dependent on a particular failure were: when the subject turned off-track, diverted to an ETOPS alternate airport, brought up the appropriate checklist, and initiated action pertaining to it; the time and space definition of the aircraft; and the workload ratings. Variables that were directly dependent on the failure involved actions the subject could take to affect the time to an alert, such as when an engine was shut down for the EGT increase scenario and the oil quantity decrease scenario.

Procedure

When a subject first arrived, he received an overview on this experiment including instructions about the NASA-TLX questionnaire. After this introduction, the confederate F/O gave a detailed description of the simulator and its operation, and the flight plan to the subject before the training run started. The training run included the avionics overheat fault 15 minutes into the flight. The time to an alert was 5 minutes given the initial aircraft configuration. No data were recorded during training.

A short break was taken after the training run and before data run 1. An hour lunch break followed the first data run. After lunch, the subject completed data runs 2 through 4. Each data run took approximately 30 minutes. At the end of each data run, the subject was asked about the failure, his actions, and his workload. The presentation order of predictive information and initial time to an alert were counterbalanced while scenario order was only partially balanced due to the number of subjects.

Data Analysis

For time data, a normalized time was calculated to extricate the fact that different initial times to an alert occurred during the flight. If the times were not normalized, the data clustered around four discrete categories dependent on the initial time to an alert. The normalized time was

$$\text{normalized time} = \frac{\text{time at which } X \text{ occurred}}{\text{actual time to alert}}$$

Times were taken from failure start. The actual time to alert was when the alert truly occurred or would have occurred had the subject not done something to prevent it such as shut down an engine. These times were then analyzed using the general linear model in SPSS [14].

The specific actions analyzed were accessing the appropriate checklist, turning off path, diverting, declaring an emergency, checking the weather at the diversion airports, calling the flight attendant, and calling dispatch. Categorical data related to these actions were analyzed with the independent samples Chi-squared (χ^2) test in SPSS [14].

All failures had a checklist associated with them. Thus, if a parameter reached an alert, the subject should follow the

checklist. A subject could access the checklists before the alert range was reached if he so desired.

Under ETOPS rules, subjects had to divert for the oil quantity decrease and EGT increase failures when they shut down an engine. The ETOPS rules do not specify a diversion is necessary with cabin pressure loss, but for fuel efficiency reasons and passenger comfort, the logical choice would be to divert. If a subject had a forward cargo fire warning, he would have to divert under ETOPS rules. If a subject discharged the fire bottle before the warning, thus preventing the temperature from increasing into the alert range and averting a fire warning, he did not technically have to divert but prudence recommended diverting anyhow because of the strong possibility of fire.

Three of the faults required subjects to descend: (1) the cabin altitude increase, and after engine shutdown for both (2) the EGT increase and (3) the oil quantity decrease. Also, checking weather at the diversion airport, telling the flight attendant what was happening and calling dispatch to let the company know the current situation was not explicitly required but was considered good airmanship. Subjects were not penalized in the data analysis if they did not perform these actions.

The six NASA-TLX individual workload ratings—mental, physical and temporal demand, performance, effort, and frustration—were normalized on a scale from 0 to 100 with 0 as low workload and 100 as high workload. They were combined into an average workload rating for each subject by data run. These average normalized workload ratings were then analyzed using the analysis of variance procedure in SPSS [14].

In the analysis of the data, significance (for both p and χ^2) was taken at the 0.05 level. Also, for main-order effects, a Tukey HSD post hoc test was done [15].

RESULTS

Benefits of Predictive Information

If a subject did nothing at all, an alert would occur during flight for the 1-, 5-, and 15-minute initial times to an alert. Subjects could affect the time to an alert for the EGT increase and forward cargo overheat faults, or they could prevent the parameter from reaching an alert range altogether but, in all cases, they had to actively confront the failure. For the initial time to an alert of ETA+45 minutes, subjects did not have to do anything since an alert would not be reached until after landing.

Alert Occurrence: For the 1-, 5-, and 15-minute initial times to an alert, whether or not an alert occurred depended on the initial time to an alert ($\chi^2 \leq 0.01$). Out of a possible 48 alerts, only 19 occurred (table 2). As seen in table 2, the greater the initial time to an alert, the more often subjects avoided an alert. Hence, subjects were taking actions to lessen the severity of the failure, to lessen the time pressure associated with the alert, and to lessen its consequences.

Table 2 - Number of Alert Occurrences

Alert	Initial Time to Alert (minutes)		

Present	1	5	15	ETA+45	Total
Yes	10	8	1	0	19
No	2	4	11	12	29

Divert	Yes	0	7	9	16
	No	11	4	2	17
Declare	Yes	2	5	8	15
Emergency	No	8	3	1	12

Action Before or After Alert: Since subjects had time to deal with the failure before an alert, whether they acted before or after an alert occurred was of interest. In both the direction and time conditions, subjects brought up the checklist before any alerts ($\chi^2 \leq 0.02$) (table 3). This is not surprising because in the direction and time conditions, subjects had foreknowledge of the alert and which checklist was pertinent. F urthermore, the number of checklists accessed before an alert in the baseline condition may be artificially high because subjects were primed for a failure. Thus, they may have been more diligent in scanning the instruments looking for deviations.

Table 3 - Number of Checklists Retrieved for the 1-, 5-, and 15-Minute Initial Times to an Alert

Before Alert	Predictive Information			
	Baseline	Direction	Time	Total
Yes	8	12	12	32
No	4	0	0	4

Predictive information was also significant in determining whether pilots accessed checklists for the ETA+45 minute condition ($\chi^2 \leq 0.02$) (table 4). No subjects in the baseline condition accessed a checklist but subjects did when they had direction or time information. Again, this was because they had an advisory message telling them which checklist was relevant to the failure.

Table 4 - Number of Checklists Retrieved for ETA+45 Minute Initial Time to an Alert

Retrieved	Predictive Information			
	Baseline	Direction	Time	Total
Yes	0	4	3	7
No	4	0	1	5

As the initial time to an alert increased up to the 15-minute condition, the number of subjects diverting and declaring emergencies before an alert range was reached also increased ($\chi^2 \leq 0.01$ for both) (table 5). Since they knew the information to be accurate, subjects decided to confront the problem before the alert; the more time they had before an alert, the more likely they would declare an emergency (in order to get preferential handling from ATC) and divert before the alert. In three cases, subjects did not divert if the alert was going to occur during the flight. These three cases involved the cargo fire failure and the subjects discharged the forward cargo fire bottle before an alert was reached. On the other hand, one subject in the ETA+45 minute direction condition did divert for the oil quantity decrease failure even though it was not required.

Table 5 - Number of Diversions and Emergencies

	Initial Time to an Alert (minutes)			
Before Alert	1	5	15	Total

Workload: For workload, predictive information and initial time to alert were significant, $p \leq 0.04$ for both. As expected, the ETA+45 minute initial time to an alert had the lowest workload rating (table 6). This was because subjects did not have to confront the failure, if they even noticed the problem, since the alert was going to occur after landing.

Table 6 - Workload Ratings

Factor		Mean	St Dev
Initial Time	1	41	19
to Alert	5	41	19
(minutes)	15	41	9
	ETA+45	26	13
Predictive	Baseline	28	15
Information	Direction	43	18
	Time	40	18

Note: 0 = low workload, 100 = high workload

For p redictive information, workload was rated significantly l ower for the baseline condition than the direction c ondition (table 6). The b aseline predictive information was familiar to the subjects since this is the information they currently use and this contributed to its low workload rating.

Unlike the time condition, subjects had to estimate how much time they had before an alert range would be reached for the direction predictive information. The only way to do this was to approximate the parameter's rate of change. This appeared to increase the workload.

The greatest contributor to workload appears to be choosing which actions to carry out. No procedures were given regarding t he use of direction and time predictive information and this, most likely, accounted for subjects rating workload for time predictive information closer to direction predictive i nformation than to the baseline condition. Apparently, deciding on the proper course of actions for the direction and time conditions increased workload more than estimating the time to an alert for the direction condition.

Predictive Information Type and Prediction Times
As mentioned earlier, subjects could take several actions during each failure ranging from trying to affect the onset of an alert to diverting to an alternate airfield. As expected, the predictive information available and the initial time to an alert a ffected when subjects initiated a particular action during the 1-, 5-, and 15-minute initial times to an alert.

The time of checklist access was heavily influenced by the availability of predictive information ($p \leq 0.01$) (table 7). The baseline condition was statistically later than the direction and t ime conditions. As explained above, this was not surprising since s ubjects knew which checklists were pertinent before the alert occurred in these two conditions.

Table 7 - Normalized Checklist Access Time (minutes)

Predictive Information	Mean	St Dev
Baseline	0.87	0.54
Direction	0.12	0.11
Time	0.10	0.16

With regard to descending, diverting, checking weather, declaring an emergency, calling the flight attendant, and calling dispatch, the initial time to an alert was significant ($p \leq 0.03$ for all) (table 8). In all cases, the 5- and 15-minute conditions were statistically earlier than the 1-minute condition. Basically, the more time subjects had before an alert, the earlier they performed the actions relative to the time to an alert.

Table 8 - Normalized Times (minutes)

Action	Initial Time to an Alert	N	Mean	St Dev
Descend	1 minute	7	2.16	1.26
	5 minutes	9	0.87	0.40
	15 minutes	9	0.46	0.34
Divert	1 minute	11	4.19	2.15
	5 minutes	11	1.10	0.64
	15 minutes	11	0.56	0.37
Check Weather	1 minute	6	5.28	3.87
	5 minutes	7	1.63	1.19
	15 minutes	8	0.55	0.55
Declare Emergency	1 minute	10	2.81	1.63
	5 minutes	8	0.95	0.53
	15 minutes	9	0.56	0.35
Call Flight Attendant	1 minute	10	4.48	2.24
	5 minutes	11	1.25	0.62
	15 minutes	9	0.38	0.28
Call Dispatch	1 minute	9	6.04	2.54
	5 minutes	9	1.54	0.80
	15 minutes	10	0.55	0.33

Since the above results held for all actions, the 1-minute condition was separated out from the 5- and 15-minute conditions because the 1-minute condition did not allow for much time to prepare for the alert whereas the other two conditions did. The analysis was then redone using the data from the 5- and 15-minute initial times to an alert

With the reanalysis for the 5- and 15-minute conditions, descent time, diversion time, and time to declare an emergency were found to be dependent on predictive information (table 9). In all cases, time predictive information was significantly lower from baseline. Depending on the action, direction predictive information may or may not be different from the baseline condition or the time condition (table 9). Hence, the direction predictive information does decrease the time of when a subject performs a certain action but this decrease in time is not as differentiable from the baseline condition as is the time predictive information.

For all actions described above, the 5-minute condition had significantly later times than the 15-minute condition. Furthermore, even though previous research suggested this, no interaction occurred between predictive information and initial time to an alert. In fact, time predictive information

always had an earlier action initiation time. Thus, although pilots reported wanting the direction type of predictive information for times to an alert of 5 minutes or less, in practice, time predictive information appears also to have the greatest benefits for the 5-minute initial time to an alert.

Table 9 - Normalized Times for 5- and 15-Minute Initial Times to an Alert (minutes)

Action	Predictive Information	N	Mean	St Dev
Descend	Baseline	12	0.94	0.41
	Direction	12	0.77	0.39
	Time	12	0.44	0.33
Divert	Baseline	13	1.18	0.60
	Direction	13	0.84	0.62
	Time	14	0.81	0.25
Declare Emergency	Baseline	12	1.04	0.39
	Direction	7	0.69	0.31
	Time	12	0.38	0.24

Note: [= statistical groupings

In general, for a short time to an alert (1 minute), subjects did not have much time to use the advance notification. For longer times to an alert (5 and 15 minutes), subjects had time to affect the timing and occurrence of the alert and to prepare for the alert. In fact, the time and direction predictive information aided them in accessing the appropriate checklist, declaring an emergency, and diverting before an alert occurred.

DISCUSSION

To identify the benefits of predictive information, to determine the form of predictive information and range of prediction times, and to corroborate previous research, a simulator experiment testing three types of predictive information and four initial times to an alert was conducted. The three types of predictive information were (1) baseline, (2) direction, and (3) time, and the four initial times to an alert were (1) 1 minute, (2) 5 minutes, (3) 15 minutes, and (4) ETA+45 minutes. These factors were found to affect when subjects accomplished certain actions, such as accessing pertinent checklists, declaring emergencies, diverting, and calling the flight attendant and dispatch.

Knowing the remaining time to an alert seemed to produce the most benefits. For instance, the more time subjects had to deal with the failure, the more often they avoided getting an alert by performing some action such as descending, shutting down the affected engine, or discharging fire bottles. The initial time to an alert also affected when subjects performed certain actions. As the initial time to an alert increased, subjects were more likely to declare an emergency and to divert before a parameter reached an alert range.

Predictive information also affected when subjects were more likely to access the appropriate checklist. With direction or time predictive information available, they often accessed checklists before an alert occurred.

Finally, the direction and time predictive information had higher workload associated with it than the baseline

information. This was most likely because subjects had to decide how to use the new information.

Regarding the prediction time, subjects diverted, checked weather, declared an emergency, and called the flight attendant and dispatch earlier for the 5- and 15-minute initial times to an alert than for the 1-minute initial time to an alert.

Within the 5- and 15-minute initial times to an alert, descent time, diversion time, and time to declare an emergency were less for the time and direction predictive information than they were for the baseline condition, although the direction condition was not always different from the baseline condition. This might have been due to the heightened awareness of the subjects to possible failures. Also, within these two initial times to an alert, descent time, diversion time, time to check weather, time to declare an emergency, and time to call flight attendant for the 5-minute condition were statistically more than the times for the 15-minute condition. Lastly, although pilots indicated in previous research an interaction between predictive information and initial time to an alert, in practice, there appears to be no such interaction.

CONCLUSION

The data do suggest that predictive information may be beneficial to increasing the safety of flight although, in this experiment, the initial time to an alert more heavily affected the performance. This, most likely, was due to subjects being primed for failures, so they were more actively scanning the instruments for these failures. In any case, providing the time to an alert for the longer initial times to an alert allowed subjects to prepare for checklists and to declare emergencies earlier in order to receive preferential handling from ATC so that they could descend and divert more easily and timely. Subjects also let others know of the situation earlier, such as dispatch and the flight attendants, when they had the predictive information. But for workload to decrease to the level it currently is with no predictive information, flight crews need to become familiar with and fully understand this information.

Other aspects must also be investigated before the full usefulness of predictive information can be understood. Further research into the optimal prediction time, acceptable false alarm rate, and accuracy of the predictive information must be done. Also, it would be of benefit to ascertain how useful the information would be when pilots are not primed for a failure. On the more operational side, the ability to estimate the time to an alert with the false alarm rate and accuracy required by the pilots needs to be investigated before procedures are developed using the time to an alert predictive information.

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