Quantifying accident precipitating events

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Abstract
After showing a continuous reduction from the early days of flight up to the 1980s, the accident rate to commercial aircraft has since remained close to static. With the increasing size of the aviation fleet, the annual total number of accidents is actually increasing. This paper takes the view that a primary aim of aviation safety is the reduction of the accident rate and, hopefully, also the total number of accidents. Targets were set by the US President in 1997 and, while the targets themselves may be criticised, we propose that there is a need to set targets against which future progress can be measured. Under present rates of improvement the targets set will not be achieved, by a considerable margin.

A large proportion of accidents are attributed to crew error. A large amount of work has gone into measuring crew error and in devising operating methods which will both minimise the error rate and catch errors which do occur. Nevertheless, over the period of this activity, the accident rate has remained close to constant.

This paper proposes that there is a disconnect between errors observed in the cockpit and the rate at which accidents occur. It further proposes that the principles of fail-safety may provide a productive method for examining this disconnect. If this proves to be the case, then the principles of fail-safety, which have been enormously effective in reducing the error rate (ie, in increasing the safety) of the engineering systems within aircraft, may prove fruitful in examining the socio-technical system of the aircraft cockpit.

Introduction

The central thesis of this paper is that the aim of all safety-related activities in the cockpit is to reduce the aircraft accident rate. We believe that this cannot be achieved without quantifying the effects of actions taken with this intent. Simply to carry out actions because they appear to be "the right thing" in the light of a particular philosophy is unscientific and unlikely to achieve the desired result.

There has been a great deal of activity in recent decades in the domains both of technology and human factors, aimed at increasing the safety of airline operation but the accident rate has remained stubbornly near constant for over two decades. It is trending down, very slowly, but nowhere near enough to meet targets set by the USA in 1997.

One issue which has been constant now for many years is the contribution of crew error as a causative factor in accidents. The figure is so high – currently 66% of all accidents (Boeing 2003) – that it must attract, and has attracted, the attention of the aviation safety community. The enormous growth in aviation psychology and the implementation of its findings in operational methodologies is a result of this attention. Nevertheless, over the period of this growth in activity, the accident rate has shown little change.

Accident Statistics

Statistics on aircraft accidents are voluminous. While there are minor differences between the numbers reported and analysed, these differences are unimportant in relation to the "big picture" which emerges. Figures used in this paper come from Boeing (Boeing 2003) but the situation they show is reflected by others. A foundation stone of this paper is that accident statistics are one hard, undeniable set of numbers that we have as a measure of aviation safety. It is accepted that this is not the only measure but as it is, in the end, accidents which kill and injure people, it is a useful measure.

Figure 1 shows accident rates per million departures for airline operators from the USA and Canada and the "rest of world".

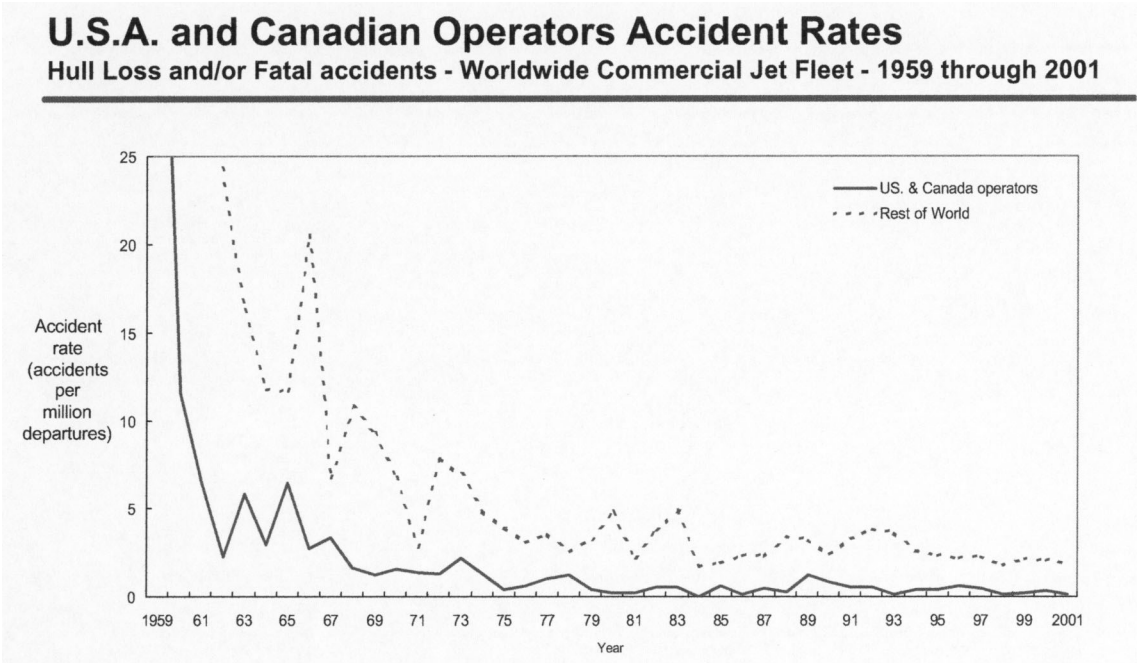

Figure 1. Accident statistics from Boeing

Raising the bar

The first point to make is that the accident rate is very low, especially for USA and Canada. It is so low that sample sizes are barely adequate to show trends reliably, which is good for airline customers but not so good for statisticians. Despite this, the accident rate is unacceptable to all stakeholders, and this prompted the President of the USA in 1997 (Clinton) to set a target for accident reduction. This was announced by Vice-President Gore, with the target set at an 80% reduction in 10 years [1] (Gore 1996). There was also discussion of a 90% reduction in 25 years. This did not eventually see the light of day in the announced target but it is worth bearing in mind.

If we are to set out to meet these targets, a good place to start is to project current accident trends and see how near these will get us. To do this we need to fit a curve to the current accident statistics so that we can project them forward. This is shown in Figure 2, again based on (Boeing 2003).

Once again the variability in the small numbers of accidents makes curve fitting difficult. The figures are characterized by a low average value, slowly falling over time, with relatively large fluctuations above and below this. There is little point in fitting a curve which follows the rises and falls of the statistics when what we are seeking is an underlying trend. We need to force a curve of the desired shape. An exponential represents a constant rate of improvement over time, which appears a reasonable option. There is quite a range of curve parameters which give equally good fit, and in fact, for the USA figures, a straight line covering the last 20 years is as good a fit as any. It is worth pointing out that the falling trends are for accident rates. If we look at number of accidents, this trend is rising, as is also shown (as a straight line) in Figure 2.

[1] It is acknowledged that this was a "political" target, but it is useful for this discussion.

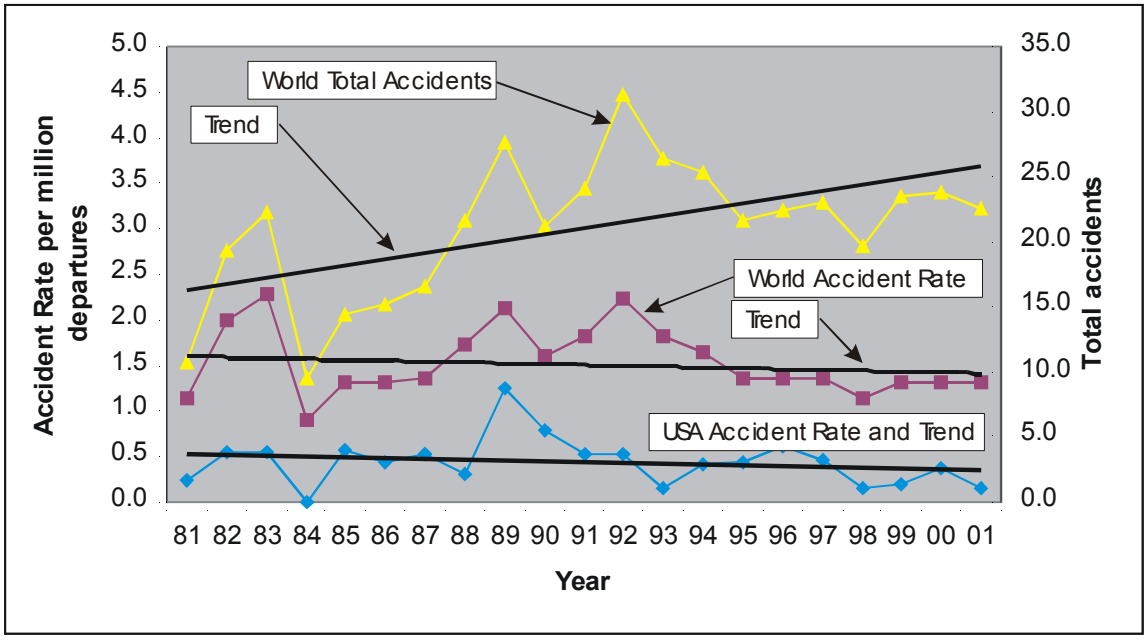

Figure 2. Accident data over last 20 years

Figure 3 takes the world accident rate per million departures from Figure 2 and extends it forward over the next 25 years, using the exponential trend line fitted to the data. This chart also shows an exponential curve which is needed to achieve the 90% reduction in 25 years. It is not possible to fit one exponential through both targets. The actual points achieved between 1997 and 2001 are also shown. The curve drawn is "generous", allowing a near miss for the 10 year target but achieving the 25 year goal, but still requires a 17-fold improvement in the current rate of improvement. Clearly, on current trends, neither of the targets will be achieved.

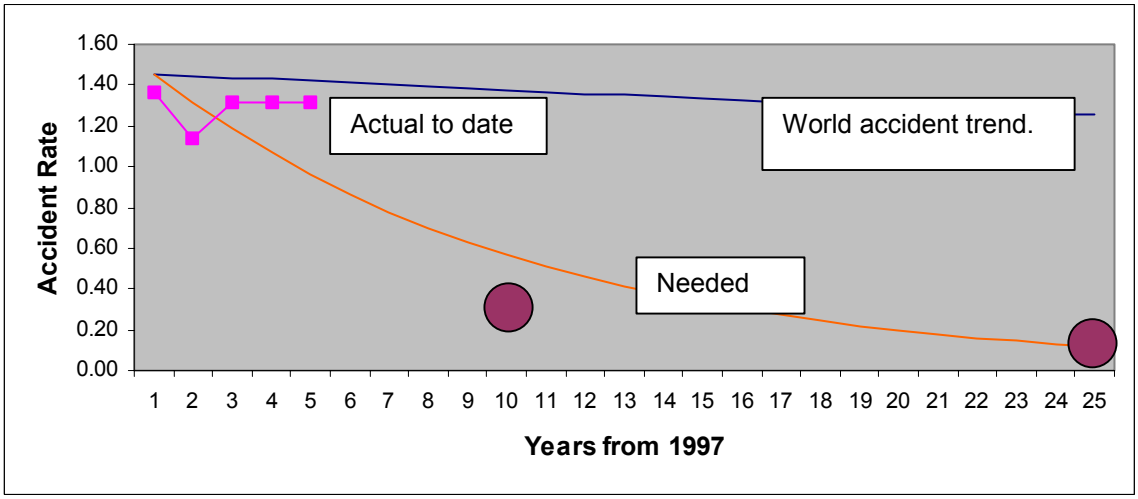

Figure 3. Accident trends extended forward

Figure 4 is a repeat of Figure 2, but with a number of significant events superimposed. These are the introduction points for:-

1. CRM. At this time it was Cockpit Resource Management, but has since been expanded to Crew Resource Management (DOM 2003).
2. TCAS. Traffic Collision Avoidance System (ALLSTAR 2003).
3. GPWR (Ground Proximity Warning System, since expanded to include other ground proximity warning systems) (AirServices, 2003).

4. Vision enhancing systems, specifically HUDs displaying radar and infra-red images to enhance pilot vision of the view ahead, principally targeting landing approach in low visibility (FVCS 2003).
5. LOSA. The first Line Operations[2] Safety Audits. The web site for the University of Texas (U Texas 2003) has many publications relating to LOSA, with first publications in 1995.

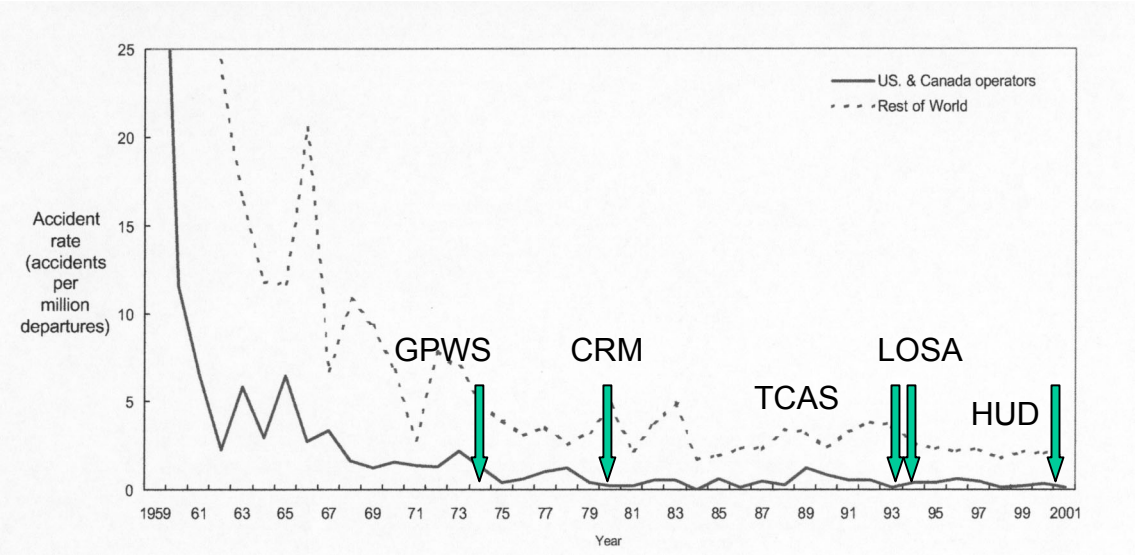

Figure 4. Initiation of some safety improvement initiatives

Items 2, 3 and 4 above are engineering systems targeting specific accident causes. TCAS is aimed at reducing the possibility of collision, GPWS targets the major issue of Controlled Flight Into Terrain (CFIT), while Vision Enhancing systems (shown as HUD as they are implemented using Head-Up Displays) enhance pilot capability in the hazardous situation of landing approach in extremely poor visibility. Together, CFIT and landing approach accidents account for around 80% of fatal accidents (FSF, 2003). In Human Factors terms they arise from situation awareness errors. There can be no doubt that these technologies have been successful. Considering just one, the number of CFIT accidents fell from 7 in 1992 to an average of 3 per year over the last three years. This factor alone can account for a significant part of the improvement in accident rates registered over these ten years. This period is, of course, around 20 years after first introduction, which is a fairly normal time-lag between introduction of a new technology and seeing an effect on accident rates.

Does this mean that the efforts in Human Factors have had no detectable effect on accident rates? This does not necessarily follow. The accident rate is the result of factors reducing it and others which could increase it, and the latter certainly exist. Increasing pressure on maintaining schedules in all weather is an example. Nevertheless, the final result of efforts at safety improvement must reflect in reduced accident rates.

LOSA

Line Operation Safety Audit seeks to measure crew performance in the cockpit to try to identify events and actions which occur, under normal operating conditions, and which could form part of a chain of events which could lead to an accident. By identifying them, its data should underpin methodologies for minimising them. These would be implemented through CRM procedures. The raw data of a LOSA evaluation is the number of errors made by individual crew members during a flight. Note that this depends on the definition of "error" and the assumption of a connection with accident probability. The raw data is then processed down to "consequential

[2] Sometimes "Line Oriented Safety Audit"

errors, remaining uncorrected by the crew". While there is quite wide variation, the LOSA findings on error rates can be summarised as:-

- Individual members of the flight crew (pilot and co-pilot) make several errors per flight. The average is around two, but up to fourteen have been counted at times.
- Of these errors, around 85% are considered "inconsequential". The definition of "consequential" implies that an error, if not corrected, has the potential to lead to serious consequences. So around 15% remain consequential.
- Of the consequential errors, around 80% are caught and corrected by the crew.
- This leaves 3% of the original errors which are consequential and which are not caught by the crew. This amounts to an average of around one such error in 33 flights.

CRM

Crew Resource Management sets out to minimise errors which penetrate the piloting system (ie the crew plus their support systems). It addresses issues both of safety culture and of the detailed interactions of the crew to minimize error occurrence and to maximize opportunities for trapping errors which do occur. While CRM was commenced on the basis of psychological research, in particular by Reason (Reason 1990), Helmreich (U Texas 2003), and others, it now draws upon the large and growing data base generated by the University of Texas' Line Operations Safety Audit (LOSA) program (Klinect, Wilhelm & Helmreich 1999). Viewed in this way, CRM and LOSA are seen to be closely linked. LOSA gathers the data while CRM implements the findings into the aircraft operational environment. In addressing the question raised earlier of the effectiveness of human factors work to date in reducing accident probability, it is therefore appropriate to use data available from the LOSA program. CRM is not the only methodology doing this. There are several other procedural techniques in use, applying human factors and psychological principles to crew operation.

LOSA findings are fed into training and CRM procedures. However, there appears to be no attempt to quantify what the effect of techniques implemented through CRM should be on reducing accident probabilities. We cannot avoid the conclusion, from the accident statistics, that it has been, at best, very small.

LOSA provides a valuable service in collecting data on cockpit events. As a research activity it is laudable. However, it is also used as a tool to evaluate and compare airlines. Given that it is difficult to show a connection between a LOSA score and a measurable reduction in accident probability, this use appears to be questionable.

From the other end

It is helpful to work back from the actual airline accident rate which currently stands at around 1 per million departures (for USA and Canada) (Boeing 2003). This provides a vantage point from which to evaluate "reasonableness" of the statistics.

Anecdotal evidence from discussion with experienced (and retired) pilots in several countries indicates that these pilots believe that it is reasonable to state that, in an average flying career (say, around 25,000 hours) there would be two to four occasions when they found themselves in a situation which could very well have led to an accident. These are occasions where the accident was avoided by a combination of skill and chance. This implies a mean time between such events of around 6,000 - 12,000 hours – say 9,000 hours. With an average flight time of 2 hours (Boeing 2003) this implies one such event, on average, in 4,500 flights. We see these as "Accident Potential Situations"

It would appear that these events should be the same as the consequential errors which get through the crew, as reported by LOSA. However, as can be seen, they differ by a factor of about 150. Put another way, this implies over 30,000 LOSA-observed "consequential" errors for each one which becomes an accident. It is hard to believe that this is "reasonable". Chance is not that benevolent!

The situation described above is shown in Figure 5. The y-axis is the number per departure, in scientific notation, on a logarithmic scale.

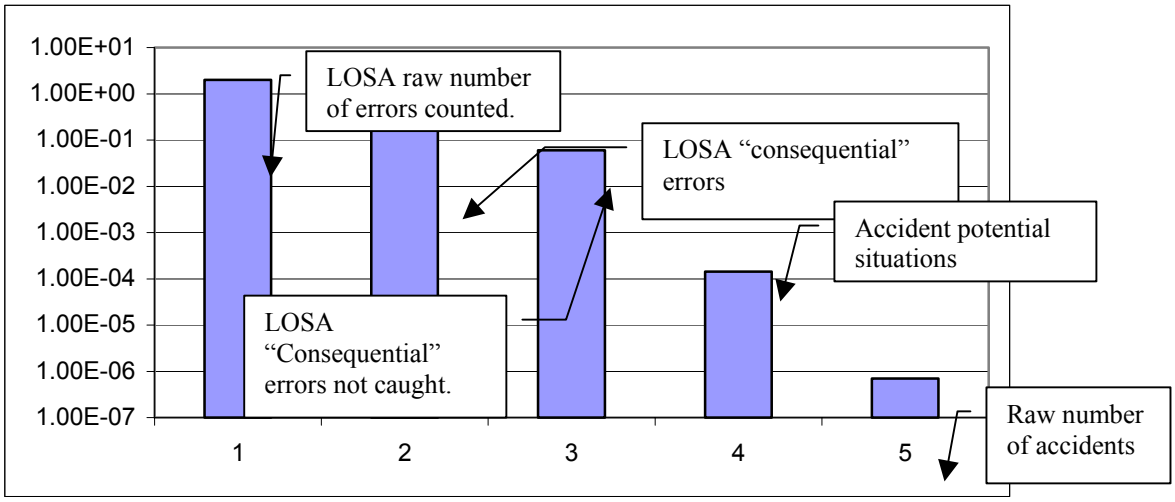

Figure 5. LOSA errors and accident potentials

The issue addressed here is the difference between points 3 and 4. The target is to reduce the number at point 5 by 80%. This appears to require that we reduce the number at point 4 by 80% as well, assuming that the probability of converting an accident potential situation into an accident remains the same. At present, CRM and related measures aim to reduce point 3 (although no targets appear to be put forward for how much any actions should reduce it.) There is clearly benefit to be gained by investigating the gap as this shows the potential for eventually influencing the accident rate.

Addressing the gap

The items (actions, events) nominated by LOSA as "errors" and which are then counted raise some fundamental issues. These items have been determined by experienced people both in the University of Texas and in discussion with their airline collaborators. They are clearly things which experienced pilots, and particularly pilot trainers, regard as "things which should not happen". There is also the assumption (which seems logical) that an unintended aircraft situation precedes every accident. CRM procedures have been developed with the aim of preventing these errors from occurring or, if they occur, to prevent them from escaping from the crew and thus preventing unintended aircraft situations.

In the early days of human factors work on aircrews the focus was on reducing the errors made by individuals. It has since been recognised that this is an unproductive path. People make errors at rates which have to do with the fact that they are human beings (and un-modifiable in the short term) and although their environment does affect error rate its effect today is probably minor. This is because the piloting environment has been evolving over time to provide the best possible situation for the operation of the individual humans within it. There is probably not a lot more to be gained in this respect to reduce individual error rate.

More recently, the focus has shifted to crew performance and the way that the crew members can work together as a team (or a system) to trap errors and to recover from them. It is interesting to note that this is exactly the methodology which has been used so successfully in the engineering systems which make up the aircraft.

In addressing the topic of this paper – the gap between measured error rates and the accident statistics – we need to address why this gap exists. There appear to be two possibilities:-

- There are as yet undiscovered linking factors between these errors and accidents,
- There is a disconnect between LOSA defined errors and accident precipitation.

We lean towards the second of these options. In fact, we propose that the gap relates to the issue of fail-safety.

Fail-safety

The single most important reason for the current high levels of safety in aviation engineering systems is the implementation of fail-safety (Howard 2000). In this concept the fact of failure is accepted but the system is structured to prevent any single failure from becoming catastrophic. The successful use of fail-safety in engineering systems rests upon the mathematics of probability. We suggest that, if it is to be applied to the people in the socio-technical system of the cockpit, then statistical methods will be needed here too.

A fail-safe system has three underlying, fundamental requirements:-

1. The use of individual sub-systems which have a reasonably high level of reliability. It is not possible to make an adequate fail-safe system from unreliable sub-systems.
2. A method for generating and communicating an error signal when an error occurs within the fail-safe system.
3. A system architecture which is able to receive the error signal and to implement action which will ensure that other system elements take over the task of the failed element.

We suggest that the gap between the measured cockpit error rates and the near-accident events reported by pilots reflects the fact that there are multiple levels of fail-safe architecture in place which receive the error signals generated by crew error and prevent these errors from moving through to an accident causing situation.

We are not yet in a position to be specific about the fail-safety issues operating here, but it is perhaps worth pointing out that humans are not only inherently fail-safe but also are capable of full recovery in response to an error signal. If a pilot is pursuing an incorrect course of action due to an incorrect situation awareness, and if he becomes aware of the incorrect situation awareness, he can correct it, usually very quickly, and then continue to function at full capability. Engineering systems, generally, cannot do this – a failed system element remains failed until repaired.

We believe that the application of the principle of fail-safety to crews or, more generally, to the piloting system, appears to offer fruitful opportunities. Investigating crew performance in terms of the requirements of fail-safety opens up approaches which are not only sound but offer the possibility of quantifying results through modelling. In this way, the potential for new approaches to accident rate reduction can be evaluated for efficacy before they are implemented.

Setting a Standard

An issue which bedevils the implementation of extremely high levels of safety is the time lag between implementation and visibility of result. It is so long that the implementers will probably have moved along their career paths and the personal connection between cause and effect may be lost. This is, of course, further confounded by the fact that there will be many concurrent factors influencing safety outcomes. Identifying and linking cause and effect may well be impossible.

Nevertheless, it is important to set goals and to measure results against them. This implementation of the scientific method is essential if reality is to be separated from surmise. The method which appears to offer hope in this regard is mathematical modelling which allows rapid repeating of scenarios and separation of the effects of input variables. It does, however, bring with it the need to model human behaviour. This paper puts forward the view that, treated at the level of populations rather than individuals and modeled as a fail-safe architecture, this should be possible. It will be important to pin down and validate those factors which can be modeled reliably, so that modelling may takes its place as a powerful tool in standardising approaches to improved safety.

Conclusions

The current rate of aircraft accidents is extremely low – so low that flying in a commercial jet is one of the safest activities one can undertake. The achievements of the industry in reaching and maintaining this result is praiseworthy. However, the pressures on reducing it even further are leading to new approaches which will benefit more than the aircraft industry. The concepts of achieving extraordinarily high levels of safety will be highly beneficial in the implementation and

operation of the wide range of large and complex systems upon which the world is becoming increasingly dependent.

The reduction in aircraft accident rates over time is the result of a great deal of work in both engineering systems and human factors. It is likely that the improvement in engineering systems was the most significant contributor up to, perhaps, the 1960s, but by this period the safety of these systems became so high that its contribution to accidents has been dwarfed by the contribution of the human crew. Nevertheless, in targeting some specific accident causes, technological improvements can still provide major gains.

Human factors work, with data collected through crew observation and measurement programs and implemented through CRM and related activities, has faced up to the tough challenge of taking an already very safe system and trying to make it even safer. Unfortunately, over the last few decades, this work appears to have had little effect on an almost static accident rate.

The CEASS program, working back up from accident statistics, highlights a gap between the number of potential accidents recognised by experienced pilots and that arrived at by LOSA, working top-down from pilot errors. It is suggested that investigation of this gap my be fruitful in leading to a better understanding of just what chains of error lead to seriously threatening situations, and what can be done to arrest and handle them. It is proposed that a fail-safety approach, recognising errors and error rates and building them into a fail-safe system, has worked well in the engineering domain and may be fruitfully applied to the socio-technical system of the cockpit.

Acknowledgement

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