The War on Error:
Psychology and Aviation Maintenance

Professor Gerard Fogarty
Professor of Psychology and Deputy Dean in the Faculty of Sciences
University of Southern Queensland, Toowoomba, QLD (fogarty@usq.edu.au)

Introduction

The research that I am about to describe is best captured by the term "Human Factors" - a branch of psychology that draws upon many other fields of psychology for its theoretical and methodological foundations. As stated in a popular introductory text to this field (Wickens, Lee, Liu, & Becker, 2004), the goals of human factors are to:

- reduce error,
- increase safety,
- increase productivity, and
- increase comfort.

These goals are shared by aviation organisations to the extent that they form part of aviation culture. It is no surprise then that psychology has enjoyed a long and close association with the aviation industry. Aviation psychologists typically provide advice and conduct research on topics such as workload, stress, selection and training, automation, perception and information processing, and the management of human error. In recent years, the topic of security has also been prominent.

Apart from an emphasis on particular areas, interest can also focus on different groups such as air traffic controllers, pilots, regulators, and maintainers. I started out working with air traffic controllers but for the past six years, my research has been primarily in the area of maintenance errors.

I became involved in this area when 18 Army personnel were killed in a tragic mid-air collision between two Black Hawk helicopters outside Townsville on June 12, 1996. Maintenance error was not the cause of that crash but in the subsequent accident investigation, it was identified as a factor that needed further investigation. The Defence Science and Technology Organisation asked me to undertake that research and I have been doing it on a part-time basis ever since.

My commitment to this area of research has been driven by my awakened interest in the contribution that psychology can make to areas that don't attract a lot of attention or public funding but that are vital to the whole aviation industry. Before describing that research, let me explain why the topic of errors has become so important in recent years.

Error in Aviation

Consider the following graph.

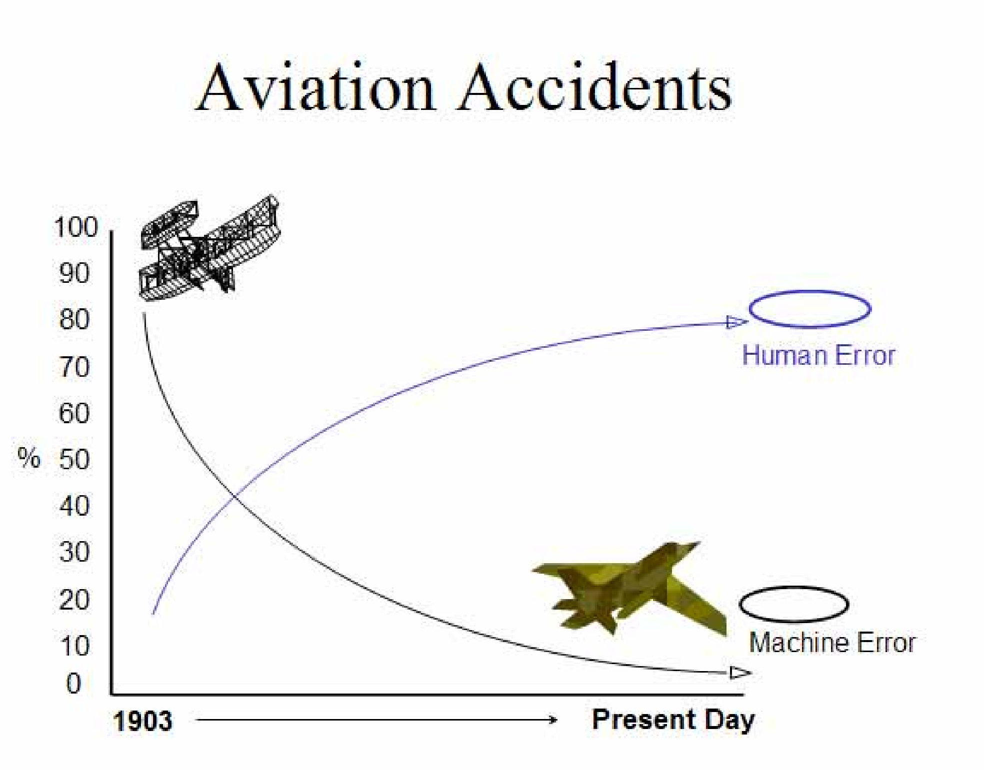


FIGURE 1: T*he relationship between aviation accidents and sources of error* (ICAO reference added)

What this graph shows is a rough approximation of the relative contribution of mechanical and human causes to aviation accidents since 1903. The graph shows that although mechanical failure might once have been the major cause of aviation accidents, human error is now the dominant cause[1].

More specifically, it used to be thought that some 12-18% of aircraft accidents in civilian and military operations could be attributed to maintenance error. A report published in the US in 2004 argues that in civilian aviation, the figure is closer to 30%.

Now let me give a brief description of what has been happening in the field of psychology in relation to theoretical developments on the topic of human error. The answer is, until recently, surprisingly little.

A Psychologist's View of Error

If one looks at the early literature on human error, one is struck by the emphasis placed on individual culpability. Errors occurred because people couldn't handle whatever it was they were

[1] I acknowledge a recent paper (Hobbs, 2004) has asserted that many of the early aviation accidents attributed to 'mechanical failure' might be reclassified nowadays as 'human error' due to the human contributions to maintenance and design failures.

asked to do. In a classic study of this kind carried out in 1913, Munsterberg recommended that errors in tram drivers could be reduced by not hiring people who were accident prone, as though there is some kind of personality trait called "accident proneness". This view persisted until well into the middle of the century despite the fact that there is no strong evidence that there is such a thing as accident proneness.

Psychology has moved away from the view that some individuals are by nature somehow more or less accident prone, to a position where accident proneness was seen as a temporary state, caused by such things as stress, fatigue, illness, cognitive overload, or poor mental attitude. We can all identify with this view, because there are undoubtedly times when most of us are absent-minded, careless, and forgetful.

This shift in emphasis from permanent states of accident proneness to more temporary states was a welcome change but it still left the individual operator right in the spotlight. Until very recently, this view of accident causation was reflected in most accident investigation reports across a range of industries. Phrases such as "pilot error", "driver fatigue", and "failure to follow procedures" were common explanations for accidents. These phrases all point to the last person involved in the accident chain.

In the last decade or so, spurred mostly by the work of English psychologist, James Reason, the emphasis has switched to a more encompassing view of error, what is often called the *systems approach*. This approach is best illustrated by Reason's (1990) famous Swiss Cheese Model.

Reason's model distinguishes between the immediate situation surrounding the accident or error and the various organisational layers that should have acted as barriers to the accident. To give an example from the military context, at the **organisational level** it is important for proper resource planning to occur. If this does not happen, a hole is created in that particular slice of cheese.

However, that's not likely to cause an accident by itself. Even if senior management is not providing the resources that are required, it is more than likely that experienced supervisors will still ensure that work is carried out to a high standard. If, however, there is a shortage of trained supervisors perhaps because they have been recruited by civilian maintenance organisations, then holes are created in the second slice of cheese at the **supervisory level** as well.

This is still not sufficient to cause an accident because there are other layers of defence. The maintenance engineers themselves are well trained and generally capable of working to a high standard with or without supervision. However, if the maintenance engineer is tired or stressed or perhaps suffering from a hangover, holes appear in this **preconditions layer** as well. But even then it is unlikely that an accident will occur; most of the time the work is still completed on time and at a satisfactory standard.

What you have now, however, is a series of breached defences or holes in the slices. Every now and then, the holes in the slices line up, and an accident occurs, often due to a final **unsafe act or active failure**.

To give some idea of how this model works in practice, consider the following case study which is taken from civil aviation.

Case Study: American Airlines Flight 191

At 3.00 PM, May 25, 1979, American Airlines Flight 191, A McDonnell-Douglas DC-10 crashed into an open field just after departing Runway 32R at Chicago-O'Hare International Airport, Illinois. All 271 people on board were killed. The following information is drawn from the US National Transportation Safety Board's accident investigation.

The immediate cause of the accident was the separation of the left engine and pylon assembly and about three feet of the leading edge of the left wing. The plane rolled to the left and crashed to the ground.

The separation resulted from damage caused by improper maintenance practices which led to failure of the pylon structure. In terms of Reason's model, we are talking about an active failure. So where were the defences?

First of all, let's look at the improper practices. Engines and pylons need to be removed periodically for scheduled maintenance. The aircraft manufacturer's specifications state that the engine (which weighs about 5 tons) and the pylon (which weighs about 1 ton) are to be taken off separately. Engine first, then pylon. American Airlines and Continental Airlines *devised a procedure* whereby a forklift was positioned below the engine with a special cradle to take the weight of the whole structure, the pylon was then disconnected and the whole assembly lowered so that access could be gained to bearings located in the wing structure. When this task was completed, the forklift moved the assembly back into position again and the attaching hardware was reinstalled.

This was *a very efficient procedure* and was actually part of approved maintenance procedures within American and Continental Airlines. It was a procedure that had been carried out many times without incident. The problem was that tolerances were very low and mechanics had to be extremely cautious when moving the assembly back into position. A minor error by the forklift operator could result in damage to the wing structure. Damage that would be difficult to detect.

McDonnell-Douglas, the manufacturer, was aware of the precision that would be required to fit a 6-ton assembly to the wing and specified in its original maintenance procedures and subsequent service bulletins that the engine be separated from the pylon before the pylon is removed from the wing.

We can see already that the problem extends some way back into Reason's error chain: How is it that an airline was able to establish procedures that contravened those published by the manufacturer?

American Airlines is a designated alteration station, as are the other major carriers that conduct heavy maintenance programmes. It has the authority to establish its own procedures and document these in its maintenance manuals. It is not at all unusual for a carrier to develop procedures which deviate from those specified by the manufacturer if its engineering and maintenance personnel believe that the task can be accomplished more efficiently using an alternate method. Three major carriers had developed alternative procedures to deal with this particular maintenance task. From almost any perspective, the alternative procedures made good sense.

The facts indicate that in this particular instance, the manufacturer was right and the engineering sections were wrong. A potential defence had been breached and an opportunity for human error was created.

Let's go further back up the chain, should the manufacturers or the regulators, or the government bear some responsibility too? I think so.

Continental Airlines, the other major carrier that used this procedure, had damaged two aircraft in the same way. The aviation industry is very open and publishes most of its mistakes for anyone to scrutinise, so this incident was published as an Operational Occurrence Report in January 1979. A second incident was reported in February 1979. American Airlines was on the distribution list for these reports.

However, the main requirement of these reports was that they indicated how the damage was repaired so that the FAA could ascertain that the aircraft was indeed airworthy. Continental Airlines was not required to describe how the damage occurred and in both of these cases the cause was simply noted as **personnel error**. Neither McDonnell-Douglas nor the FAA chose to investigate these identical incidents any further.

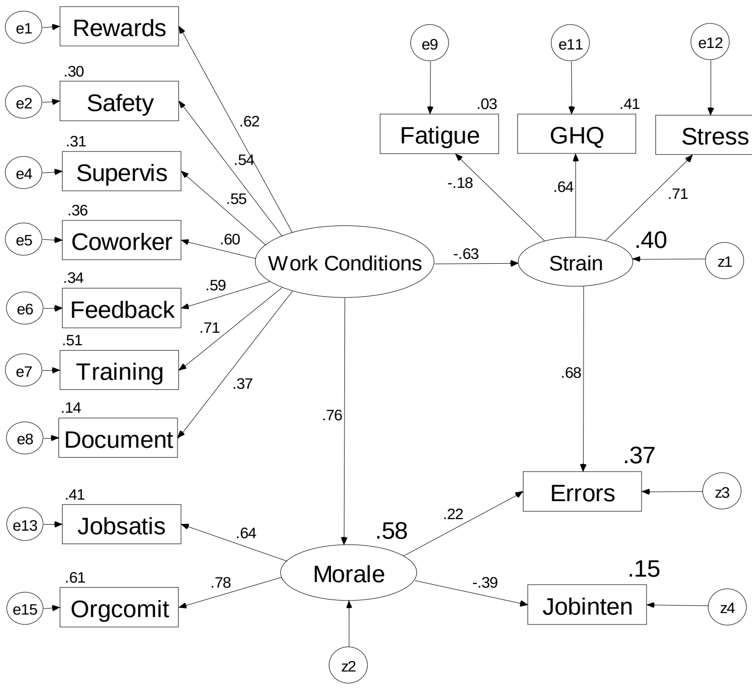
Predicting Maintenance Error

I have spent some time on this incident to emphasise the complexity of most accident scenarios. The point is not to shift the blame up the ladder but to understand the tight couplings that exist in any high-tech system. Operators are fallible but their fallibility is often unnecessarily exposed by weaknesses elsewhere in the organisation. Scenarios like the one I have described above are not confined to American Airlines, they are found in all areas of aviation, both civilian and military, and they are found in almost all industries.

Reason's model is now widely accepted in aviation, health, the nuclear power industry, offshore oil, and various other high-risk industries. It's the model I used as the basis for my research on maintenance error in Army Aviation (Fogarty, 2003; 2004). My task was to develop tools that would help the Army to monitor the state of the various layers in a proactive, rather than a reactive fashion. This involved developing a model showing how the various key elements of the working environment interacted with psychological variables to influence safety outcomes and then subjecting the model to statistical testing.

A team comprising postgraduate research students and Army Aviation human factors specialists began by developing a questionnaire to measure Reason's latent background variables. We relied on the knowledge gained through interviews with maintenance engineers and their supervisors to assemble what we now call the Maintenance Environment Survey (MES). We conducted the first study in Townsville and Oakey in 1998, collecting survey responses from 448 military and civilian maintenance staff and supervisors. We also conducted follow-up interviews with 166 maintenance personnel in Townsville and Oakey in that same year.

I do not have space to report all the models that we have tested over the years, but I will show the first one because it formed the baseline model and included many of the variables that we used in subsequent studies.



<u>FIGURE 2: *Model Showing Predictors of Morale, Health, Errors, and Turnover Intentions*</u>
(from Fogarty, Saunders, & Collyer, 1999).

Note to graphic design: please ensure good graphics quality for figures 2 and 3 – let me know if you have problems and we can collaborate to find a solution.

For those among you not familiar with structural equation modelling, the variables in rectangles represent total scores on various scales included in the Maintenance Environment Survey. The modelling software allowed us to extract so-called latent traits or factors from groupings of these scales - these factors are shown in ellipses. The arrows from one ellipse to another indicate the direction of the effect and the parameter value printed on the arrow represents the strength of the relationship. High absolute values indicate strong effects, with the upper limit being a weighting of 1.0 and the lower limit -1.0. A weighting close to zero indicates very little effect.

Thus, the -.63 on the arrow from Work Conditions to Strain indicates that the more positive the workers' perceptions of the workplace, the less likely they are to suffer psychological problems. The .68 on the arrow from Strain to Errors indicates that poor psychological health is associated with more maintenance errors. Low Morale is associated with higher scores on a scale designed to measure job turnover intentions. The percentages alongside the variables in the ellipses indicate the amount of variance that can be predicted reliably by the set of predictors (the variables with pathways leading to that variable). Thus, we can see that Work Conditions affect Strain, which in turn affects Errors. In other words, the psychological state of the individual mediates the relationship between what is happening at the organisational level and self-reported maintenance errors.

We validated this model in a follow-up study in 2000-2001. By the time we got to our third study, surveys of this kind were becoming popular across the safety industry. Different versions of what are broadly called *safety climate surveys* were appearing overseas in the offshore oil industry, mining, the nuclear power industry, and aviation. We were able to compare their scales with ours and fine-tune some sections of our own survey.

Around that same time, staff from the Directorate of Flying Safety were engaged in similar work and presenting their own reports on safety culture within ADF aviation maintenance. In 2001 we teamed up with them to conduct a survey involving aviation maintenance personnel from the Army, Navy, and Air Force. As far as maintenance is concerned, it was the largest and most comprehensive survey of this kind in the ADF.

We were able to use these data to cross-validate the model developed in earlier studies and to extend the model in some important directions. Most notably, in earlier work, we focused on maintenance errors; in the collaborative study with the Directorate of Flying Safety, we included violations as an additional safety outcome variable. Violations are defined as deliberate deviations from standard operating procedures and they are considered to be a major cause of errors and accidents. A simplified version of the model is shown here.

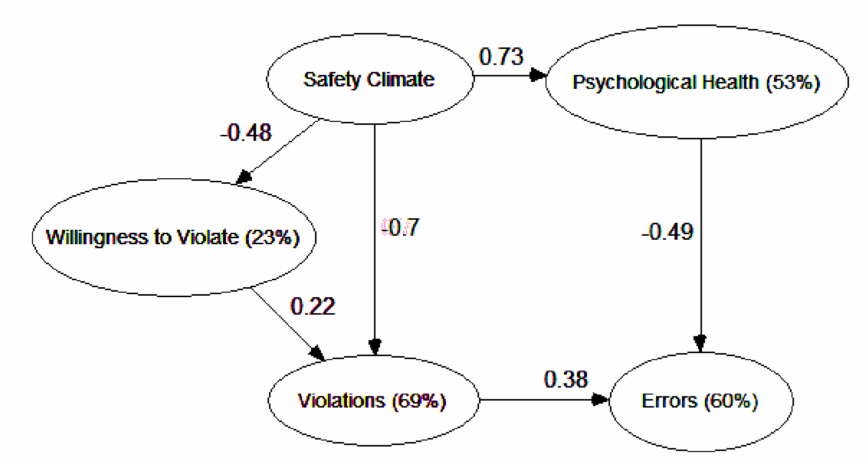


FIGURE 3: *Precursors to Errors and Violations in Aviation Maintenance*
(from Fogarty & Worth, 2003)

To conserve space, I have presented just the core constructs which have been re-labelled to bring them into line with terms used in the literature. Psychological Health (formerly Strain) has now been scored in a position direction. Keep in mind that where you see an ellipse, there may be as many as 50 questions assessing various aspects of that particular dimension. Safety Climate, for example, is made up of seven scales, assessing such things as the support maintainers receive from management, the quality of their work manuals, the adequacy of their own training, support they receive from co-workers, and so on. Psychological Health is made up of three scales: fatigue, stress, and mood.

Three Key Outcomes

Three features of the model are worthy of comment.

1. **Violations appear to occur whether or not the individuals concerned are actually willing to commit these violations.** We can see that from the strong direct link between Safety Climate and Violations. Focus group interviews with respondents confirm this impression: they see themselves as often forced to work outside strict procedural guidelines because of resource shortages, work pressures, and the like. Interestingly, the interviews reveal that they do not see themselves as working unsafely when using these shortcuts, relying on their knowledge and skill level to achieve a safe outcome using non-standard procedures.

2. **There is a significant link between violations and errors.** This suggests that, despite the belief in feature 1 above, violations are often a precursor to errors.

3. **There exist separate pathways to errors and violations** (a finding replicated in a follow-up study). The finding that errors and violations have different origins is something that needs to be conveyed to practitioners in the safety industry. Too often these qualitatively different safety outcome variables are treated as one and the same. Indeed, some definitions of error include violations as a type of error. I reject that point of view entirely. Although violations are less under the control of the individual than I supposed at the outset of this research program, they are nevertheless directly influenced by safety climate. Errors are also influenced by safety climate but only in an indirect way. *Attempts to reduce error must therefore aim at both individual and organisational levels.*

Conclusions

The safety literature tends to be dominated by discussions of error taxonomies and descriptive models of accident causation, such as the Reason model. I see these contributions as valuable but I also believe that they must be supported by empirical research. Structural equation modelling is a technique that can be used to test assumptions embedded in popular descriptions of accident causation.

Through these various studies, we have developed, tested, and cross-validated models that explain how errors can occur in safety-conscious industries. We have also shown how they are linked with violations. In ongoing research, we are seeking to extend the model to include incident reporting, another key psychological variable in the quest to achieve safer and more productive working environments.

Looking back, one of the lessons we have learned is that human error cannot be eliminated but it can be reduced if we take the trouble to look beyond its immediate causes and study the complex set of circumstances that lies behind any accident or incident. Many disciplines have a role to play in this process and psychology is right at the forefront.

Spearman, one of the pioneers in the field of human intelligence, wrote in 1928 that psychologists deliberately avoided the topic of error. Thankfully, much has changed since that time and psychological theories and methods are now being applied to the management of error in high risk industries. We have yet to win the war on error, but our efforts are helping to make industries such as aviation, both civilian and military, safer for everyone.

References

Fogarty, G. (2003). *Errors, violations, and reporting behaviour in aviation maintenance.* In R. Jensen (Ed.), *Proceedings of the Twelfth International Symposium on Aviation Psychology* (pp. 385-390). [CD-Rom]. April 14-17, Dayton, Ohio: Ohio State University.

Fogarty, G. (2004). The role of organizational and individual differences variables in aircraft maintenance performance. *International Journal of Applied Aviation Studies, 4,* 73-90.

Fogarty, G., Saunders, R., & Collyer, R. (1999). Developing a model to predict aircraft maintenance performance. In R. Jensen (Ed.), *Proceedings of the Tenth International Symposium on Aviation Psychology* (pp. 1-6). [CD-Rom]. May 3-6, Columbus, Ohio: Ohio State University.

Fogarty, G., & Worth, E. (2003). Modelling errors and violations in high-risk industries. In M. Katsikitis (Ed.), *Proceedings of 38th APS Annual Conference* (pp. 65-69). Oct 2-5, Perth WA: Australian Psychological Society.

Hobbs, A. (2004). Human factors: The last frontier of aviation safety? *International Journal of Aviation Psychology, 14 (4),* 331-345.

Reason, J. T. (1990). *Human error.* United Kingdom: Cambridge University Press.

Spearman, C. (1928). The origin of error. *Journal of General Psychology, 1,* 29-53.

Wickens, C. D., Lee, J. D., Liu, Y., & Becker, G. S. E. (2004). *An introduction to human factors engineering* (2nd Ed.). New Jersey: Pearson Prentice Hall.