

APPLICATION OF THE EPIDEMIOLOGICAL MODEL IN STUDYING HUMAN ERROR IN AVIATION

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SUMMARY

The classic methods of epidemiology provided one basis for the original design of NASA's Aviation Safety Reporting System (ASRS) and have figured importantly in the subsequent research investigations conducted where ASRS information was used. An epidemiological model is described in conjunction with the analytical process through which aviation occurrence reports are decomposed into the events and factors pertinent to it. Discussion of three research investigations, each of which manifests the application of the epidemiological method, exemplifies its use and effectiveness.

INTRODUCTION

Four years ago, at this conference, Dr. Billings presented a paper (ref. 1) in which he and his associates at Ames outlined an approach to the study of operational safety problems in air transportation. In that approach an epidemiological method analyzing the causes of disease propagation was to be used in conjunction with aviation occurrence reports. The reasoning set forth in that paper provided the conceptual foundation of the NASA program known as the Aviation Safety Reporting System (ASRS) which had at that time been in operation only four months. This paper is a review of the still-continuing development of the program, generally along the lines expected then, and a discussion of the current embodiment of the method in ASRS program activity.

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EPIDEMIOLOGICAL METHOD

Figure 1 illustrates schematically the epidemiological model and its aviation system analogy. The model represents a process in which disease, emanating from environmental conditions, manifests itself in symptoms that may lead to fatal illness, recoverable illness, or no illness depending on individual circumstances of patient vulnerability, preventive actions, and intervention. In the aviation system the analogy of the disease process is the predilection for error of human participants. This arises from factors in the operating or physical environment and results in errors of commission or omission that, again depending on the individual circumstances, may lead to accidents, system perturbations, or harmless corrections.

Epidemiology was described by Waller (ref. 2) as "... the study of the distribution and determinants of disease or other phenomena in a population". The method of study is to obtain data on real world populations (as opposed to theoretical or controlled experiment situations), detect in them non-random distributions of phenomena, and then identify the reasons for the non-random distributions. The role of the model and its aviation system analogy as depicted here is to categorize the factors whose distributions are studied by the epidemiological method. The method has been used successfully for more than a century to examine factors in the environment that contribute to a great variety of problems besetting humans and animals. Its application to the study of human error appeared conceptually feasible provided a sufficient study population could be obtained. The aviation accident database assembled from NTSB investigations, although containing many instances of human error, was not considered suitable for the purpose because of its relatively small size and the impossibility of retrospectively examining, or even determining, the causes of many of the errors. Recognition of the need for a large population of occurrences susceptible to more exhaustive study of its error content was the stimulus for institution of the ASRS program.

ASRS PROGRAM

In the four-plus years of its operational existence, the ASRS program has received more than 25,000 reports covering a large variety of safety-related occurrences and situations. Of these, more than 22,000 have been studied by aviation safety analysts and the abstracted safety related information, including the original narratives and followup data, has been stored in a computerized information system.

The reports, usually presented on standard NASA forms, have been submitted voluntarily by pilots and controllers in roughly equal numbers. The existence and purposes of the program were publicized throughout the aviation community by means of Advisory Circulars and various informal means including, recently, the publication of a monthly newsletter.

Reporters are guaranteed anonymity and, as a further incentive to report, they are accorded a limited form of immunity from penalties for FAR violations if they can show that report submission has been timely and meets certain other reasonable conditions.

These three tenets: voluntary reporting, anonymity of reporters, and limited immunity, have had a very important effect on the evolution of the ASRS program. More than 80 percent of the reports received describe human errors on the part of aircrew or controllers. The remainder deal with equipment failures or difficulties involving ground facilities, publications, and other material conditions. Even these, however, are often associated with human errors that either caused the failures or occurred in dealing with the problems resulting from them. Thus the need for an extensive population of human error occurrences has been met. The main reason for this human error focus is that many reporters appear not only willing but eager, under the anonymous, non-punitive conditions of reporting, to reveal their own errors and those of others. Because of the voluntary aspect the reports are not of uniform quality. They vary considerably in accuracy, readability, and background coverage. Some do not reveal the pre-disposing conditions or environmental factors causing the errors disclosed but many others do; these are of inestimable value in analysis using the epidemiological method.

The database is mounted on Battelle's BASIS software which provides a flexible retrieval capability in the on-line mode. Datasets consisting of specified report records pertaining to a large variety of topics can be assembled readily using search terms from the 150-plus information fields in the report record architecture.* The system is also capable of rapid sorting to expose statistical distributions. Three tabulations--cross sections of the database from various viewpoints--will give some feeling for what is there.

Table 1 shows the distribution of sources of the reports. It is noteworthy that controllers are reporting about as much as are pilots and other crew members and that together they account for over 90 percent of the reports received. The Air Force and Navy sources denote the reports received from those organizations via official channels. This distribution of sources shows that ASRS receives reports principally from the flight operations sector of the aviation system (as opposed to maintenance, equipment supply, etc.) and this is reflected in the contents of the reports, which deal almost exclusively with operational matters.

*The reports are coded sufficiently richly that they can be retrieved at quite detailed indentures. For example the following retrieval can be made directly without inferential searching strategy: all reports describing deviations from assigned altitude on the part of heavy air carriers in passenger service in the state of California occurring between the hours of midnight and 0600 during the Captain's leg where the deviation was caused by an error on the part of the flight crew but no conflict resulted from the deviation (one report).

Table 2 shows the distribution of the reports in the database as to the "primary problem"* with which they are concerned. Each report is given a unique classification from this group. The significance of the tabulation lies in the definition of the first two items as human error occurrences. This is the quantitative confirmation of the earlier assertion: the ASRS database is overwhelmingly concerned with human error. However, the holdings on equipment failures, navigation aid problems, etc. are not negligible and have given rise to the issuance of more than 700 Alert Bulletins advising the aviation community of reported hazards embedded in conditions or failures in these categories.

Table 3 shows the distribution of reports as to their final outcomes. The final outcome is the last link in the chain of events comprising an occurrence before recovery (chance or some kind of human intervention) takes place. Several kinds of final outcomes are tabulated. Some represent instances where the event chain has progressed to the point where all the elements of an accident are present. The "aircraft separation anomalies", "controlled flight toward terrain", and "aircraft out of control" items fall in this category. Another kind of outcome includes a variety of intermediate events: human errors, aircraft out of position, and equipment failures--cases where the event chain ended without all elements of an accident being present. Thus, the table indicates that 10.1 percent of the reports in the database describe occurrences that culminated in a controller error which was corrected before it could cause further difficulty. There are, of course, many other controller errors contained in the occurrences whose final outcomes were aircraft separation anomalies or controlled flight toward terrain. Finally, the category "situations" refers to reports that describe continuing hazards at specific locations (i.e., inadequate lighting at an airport) as opposed to the occurrence reports making up the rest of the database.

Figure 2 names and describes the generic categories of human error identified in the ASRS database. Although the consequences of human error recorded in ASRS reports vary widely, this list of categories is relatively small because effort has been devoted to isolating and defining generic categories of error at a useful level of detail. The thinking leading to this listing is based on definitions of behavioral functions in aviation from Barnhart, et al (ref. 3). These, then, are the elements considered at the human error node of the epidemiological model of the aviation system, Figure 1.

*The "primary problem", not to be confused with probable cause, is defined in the ASRS Operations Manual as "a judgement as to the type of problem leading to or revealed by a particular occurrence or situation."

A TAXONOMY OF AVIATION OCCURRENCES

To apply the epidemiological method in aviation safety analysis, it is necessary to order the information contained in the human error reports in categories commensurate with the elements of the model. This means that the narrated occurrences must be decomposed into outcomes, human errors, predisposing conditions, etc.

A means of doing this generally applicable to all occurrence reports was found in viewing the occurrences as chains of discrete events. A great many different kinds of events are depicted in the reports. Some are near-accidents, as when two aircraft narrowly avoid colliding, or a pilot's faulty navigation heads an aircraft toward high terrain instead of the proper approach track. Others describe potentially hazardous irregularities in the operation of the aviation system, such as deviation from an assigned altitude or course, failures in coordination between ATC facilities, failures of many kinds in air-ground communications, or events reflecting procedural or operational mistakes on the part of pilots or controllers. Finally, some reports describe hazardous conditions deeply embedded--latent--in the system such as a deficiency in a letter of agreement between two ATC facilities, poor training procedures, visually confusing lighting at an airport, or easily misread charts. Nearly all the reports describe sequences of such events and many cover the full spectrum running from the existence of a latent hazard condition through a series of irregularities to the onset of a near-accident.

Figure 3 illustrates an event sequence involving an altitude deviation that led to a conflict. The occurrence was reported to ASRS in this way:

Captain was flying. I was copilot. He began descent far enough out to make altitude restrictions but did not keep descent rate high enough to comply with STAR (profile descent). He made several corrections and comments which led me to think he was going to make the prescribed altitude/fix but he didn't keep the corrections in long enough. I was distracted by turbulence and weather. We were several thousand feet high at the fix. Controller advised he lost separation between us and an outbound but we didn't see the other aircraft. A factor was that we had a 0500 departure which means (for me) getting up at 0230 to leave home by 0300 and I have difficulty getting enough sleep prior to that kind of schedule. Although I didn't feel sleepy during the descent and he didn't appear to be, we apparently weren't sharp as usual. Although I mentioned the crossing altitude once or twice, I should have "bugged" him more about it.

This occurrence scenario is representative of the large body of reported altitude anomalies now in the database. In this case, the deviation was caused by simultaneous performance failures of the pilot and copilot in which the pilot missed a crossing restriction while flying an

approach and the copilot, momentarily relaxing from his monitoring role, failed to observe and call out the error. The altitude deviation resulted in a conflict because of the chance event that the aircraft's actual altitude was occupied by another aircraft. The crew error was attributed to fatigue.

The "occurrence" in this case was reported to ASRS as a single entity but is readily decomposed into the seven events depicted. Each event is discrete, involving an actor and a related action taking place in a finite interval of time and having a definite beginning and ending. Each event could occur in quite different sequences (i.e., with different precedent and subsequent events) and the particular sequence depicted here could have terminated at any point (i.e., a fatigued crew might not necessarily make any errors so the sequence would have stopped at the second event--and yet could have drawn an ASRS report from one of the crewmembers describing fatigue resulting from long, boring flights). An important aspect of the event chain concept is that each discrete event can be viewed as a cause of the subsequent one and an effect of the preceding one.

In the course of analyzing a large number of reported occurrences in this way, the ASRS research staff developed the event classification schema indicated in Figure 3. It is termed the "time/sequence event classification" and has been of great usefulness to the research staff in framing trend analysis studies and in other tasks where it was necessary to deal in terms of event frequencies rather than report or occurrence frequencies. Figure 4 presents the definitions for the four categories.

The significance of the time/sequence event classification, however, lies in its pertinence to the epidemiological model. This is indicated in the lower part of Figure 3 showing how the two classifications interrelate. Although the registration is not exact (the "latent hazards" group includes both the "environment" and "predisposition" components), it does reveal how well the event chain concept lends itself to decomposing the occurrences into the separate components of the model. The event chain elements in each occurrence have been identified by separate descriptors entered into the record for each report. Reports can be retrieved by searching the database with each descriptor of interest. The example report, for instance, would have the descriptors: "WORK SCHEDULING/FLIGHT CREW", "FLIGHT CREW FATIGUE", "ALTITUDE CROSSING RESTRICTION", "CLEARANCE INTERPRETATION", "COCKPIT COORDINATION/MONITORING", "ALTITUDE DEVIATION/ALTITUDE UNDERSHOT", "UNAUTHORIZED DESCENT THROUGH OCCUPIED ALTITUDE", "POTENTIAL CONFLICT". Datasets consisting of all reports coded with each of these event descriptors could readily be formed with the retrieval powers of the BASIS software. Thus, there are 5 reports in the present database in which the work scheduling descriptor appeared, 17 with flight crew fatigue, 149 crossing restrictions, etc. These are the "counts" of model components present in the database relevant to the type of occurrence depicted above.

Figure 5 shows the most prevalent events or conditions in the present ASRS database at each of the model component locations. It is significant that the most frequently reported human error is faulty operating technique in communicating; perceptual and vigilance problems are next in rank. The leading predisposing condition reported is distraction which, of course, takes many forms in the cockpit and the ATC control facility. Distraction is followed closely by excess workload and there is an obvious relationship between these two conditions. Complacency, although most difficult to define because of its subjectivity, is frequently reported or implied as is the existence of strained interpersonal relationships among the human participants. The prevalent sources cited in the operational and physical environments are self explanatory but it is noteworthy that in the context of studying human error in aviation, equipment failure is treated as an environmental factor capable of setting up a predisposing condition for errors.

At the outcomes level in the model, the only kind of near-accidents reported frequently to ASRS are aircraft separation anomalies (conflicts). This is confirmed by the data in Table 3. Many aircraft position anomalies are reported of which altitude deviations ("busts") are most prevalent. Cases where an aircraft inadvertently gets into an incorrect category of airspace, as when ATC mishandles a handoff between sectors, are frequently reported. As indicated in the upper right part of the figure, human errors are most often corrected before a system perturbation can occur by timely intervention on the part of controllers or by the quick response of flight crews.

The citations in Figure 5 show only the more prevalent events or factors at the various model component locations. There are many others reported; the database index contains thousands of terms. However, there is no explicit causal relationship among the events and factors in Figure 5--they are merely independent listings at each component. The way the model actually manifests itself in the conduct of a research investigation is best understood through examination of past studies in which epidemiological methods were employed.

EPIDEMIOLOGY IN ASRS RESEARCH

Three example ASRS studies will illustrate the use of the method. Reports on two of them appeared in NASA ASRS Quarterly Reports; the third was separately reported.

- o Human Factors Associated With Profile Descents (ref. 4)
- o Distraction--A Human Factor in Air Carrier Hazard Events (ref. 5)
- o Fatigue and Associated Performance Decrements in Air Transport Operations (ref. 6)

Epidemiology is not mentioned in any of these reports nor are the model's structure or terminology employed explicitly in the discussions of the investigative steps or conclusions. As will be shown, epidemiology was the underlying method used in obtaining the results in each case even though it was not discussed in their descriptions.

Human Factors Associated With Profile Descents

Profile descents are published terminal arrival procedures intended to save time and fuel. They provide an unrestricted descent from cruising altitude or flight level to interception of glide slope. Headings and crossing altitudes during the descent are specified. The procedures were experimentally implemented at several terminals during 1976. Shortly, a considerable number of reports arrived at ASRS indicating difficulties with the profile descents, the majority of which were altitude deviations. ASRS then performed a study with the purpose of discovering the nature and causes of the problems.

In terms of the epidemiological model, the only known factors at the outset of this study were outcomes--primarily system perturbations in the form of altitude deviations, some of which progressed to near-accidents when the deviant altitudes proved to be occupied. The study hypothesis was that the profile descent procedures were operational environment factors related to these undesirable outcomes by some chain of human error and predisposing condition. The study consisted of examining reports on the profile descent problems at two terminal areas (Denver and Atlanta) to catalogue the errors and conditions present.

The occurrence analyses resulted in identification of five "problem areas" that clearly connected the outcomes with the profile descent procedures thus establishing logically the validity of the hypothesis that the procedures and observed outcomes were causally related. The five problem areas were:

- o Profile descent charts
- o Profile descent clearances
- o Profile descent rules and procedures
- o Aircraft operations in profile descents
- o Human factors in profile descents

The chart problems were crewmembers' misreading or selecting the wrong chart for the assigned descent--perceptual errors related to the poor design of the charts which made them complex and cluttered. The descent clearance problems were all flight crew errors in communications technique whereas the problems with rules and procedures pertained to flight crew misunderstanding of them due to complexity and/or ambiguity. The problems cited regarding aircraft operations reflected misjudgement

errors involving descent rates. Thus, the first four of the problem areas were enumerations of the various human errors causing the observed outcomes.

The fifth problem area was mainly a recitation of the predisposing conditions causing the errors. Several were logically relatable to the profile descent procedures themselves; i.e., poor chart design giving rise to chart complexity and clutter, extra workload and distraction imposed by the nature of the procedures, and unfamiliarity with the procedures all were present and interacting factors. Superimposed on these, in several cases, were flight crew fatigue or weather factors that were not directly related to the profile descent procedures but exacerbated those adverse conditions that were.

These findings not only supported the hypothesis convincingly but identified the most serious of the factors causing the errors. This was a predisposing condition--the complex and cluttered design of the charts available to the flight crews. This condition was rectified and shortly afterwards a notable decrease in profile descent error reports at the pertinent terminals was observed at ASRS.

Distraction--A Human Factor in Air Carrier Hazard Events

An ASRS study of flight crew distraction, observed to be the most frequently cited factor in air carrier reports, began in the fall of 1978 as a part of a series of human factor investigations. The purpose of the study was to discover the kinds of distractions that affect flight crew performance, their sources, the seriousness of their effects, and to comment on possible remedies. The epidemiological method was used in the study to associate the cause and effect chain.

In terms of the model, the starting point for this study, in contrast to the one previously described, was the arbitrary identification of distraction as a predisposing condition for errors. Epidemiology was used descriptively to classify distractions by generic type and then to associate those types with the environmental factors cited as causing them and the types of errors and outcomes described as resulting from them. Statistical techniques were not employed; the ingredient used in making the classifications and confirming the cause-effect associations was the expertise of the investigator, an experienced airline pilot and safety researcher.

Analysis of the dataset of 169 reports resulted in the following classifications and associations among factors:

- o Flight crew distractions fall into two generic classes: (1) Those arising from non-flight operations activities (public address announcements, on/off block messages, logbook paper-

work, handling flight-service/passenger problems, and untimely cockpit conversations) and (2) those imposed by flight operations tasks internal to crew functioning and frequently cited in reports as "excessive workload" (running checklists, looking for traffic, communicating with ATC, coping with minor malfunctions, avoiding weather buildups, and monitoring radar).

- o The sources of distraction as a predisposing condition were traced to operational environment factors. The two most significant were (1) company rules and procedures directed to maximizing passenger comfort and service and (2) the inherent complexity of the flight crew's job mandated by the technology of the modern jet airplane and the ATC system in which it functions.
- o Two kinds of human errors arose from distractions: failures on the part of individuals to perform an essential task such as traffic watch and, even more critical, breakdowns in crew coordination or crew management. Both are failures in operating technique involving controlling, communicating and monitoring behaviors.
- o Overwhelmingly, in the dataset used in this study, the outcomes of the distraction occurrences were system perturbations in the form of altitude deviations, many of which led into conflict situations. Other outcomes consisted of failures to see traffic -- also productive of conflicts -- unauthorized penetrations of airspace, landings or takeoffs without clearance, and, in a few cases, successful correction of an error.

The average quality of the reports in this dataset was excellent; many of them depicted associations among distractions, errors, and outcomes with precision and detail. The study results not only served to delineate the problems involved with distraction but suggested considerations important to remedial action. The causes of nonoperational distractions, for example, may be minimized by continued emphasis on cockpit priorities through both written procedures as in flight operations manuals, and constant command attention to optimum use of cockpit resources. Trends in cockpit design are aimed at simplification of the tasks involved and many of the reports indicate that this, if achieved, would significantly reduce the distraction burden. It is noteworthy that regulatory measures aimed at reducing non-operational activity distractions in air carrier cockpits are being actively considered (ref. 7). ASRS data indicate that there is a considerable opportunity for safety improvement in controlling distractions and they are acknowledged to have pointed the way toward achieving that control.

Fatigue and Associated Performance Decrements in Air Transport Operations

Although relatively few reports about fatigue in aviation operations have been received, public and Congressional concern prompted the conduct of an ASRS study on the topic during the summer of 1980. The purpose was to assess the effects of fatigue on air crew performance by examining the hypothesis that skill fatigue and associated performance decrements occur and are associated with some combination of such factors as sleep deficit, work schedules, circadian desynchronosis (effects of jet lag), and the like.

The reader will discern the outline of the epidemiological model in the preceding statement of purpose. Fatigue was hypothesized to be the predisposing condition arising from a variety of operational environmental factors having to do with trans-meridian flights and various scheduling issues. Further, the hypothesis assumed that fatigue was capable of producing performance decrements -- human errors -- leading to potentially hazardous outcomes.

The epidemiological method was used somewhat more rigorously in this study than in the two described previously since some statistical analysis entered the study procedure as well as descriptive analysis to establish associations. The fatigue-related dataset of 77 occurrences was compared in several respects with a similarly retrieved set of reported performance errors where fatigue was not present. These comparisons showed that the fatigue-related occurrences involved patterns of error and outcome significantly different from the non-fatigue-related ones. The descriptive analysis coupled with the statistical comparisons supported seven conclusions regarding fatigue.

- o Fatigue-associated performance decrements occur;
- o Fatigue-associated performance decrements can produce potentially hazardous conditions;
- o Only a small fraction of performance decrements reported to ASRS are associated with fatigue by their reporters;
- o The performance decrements associated with fatigue differ in frequency, but not in kind, from those occurring in its absence;
- o Failures in monitoring tasks are described frequently in fatigue-associated performance decrements reports;
- o Long duty periods, large numbers of flight segments, and disturbed sleep are frequently reported as the reasons for fatigue associated with performance decrements;
- o The ASRS data do not permit a conclusion as to the effect of circadian desynchronosis on flying performance.

In this study, the practice of epidemiological analysis in conjunction with ASRS data may be said to have reached some degree of maturity since the classic case history comparison procedure (comparison of a population having a phenomenon with a similar one not having it) was employed for the first time. It is of course, not yet known whether ASRS data will consistently be capable of supporting analysis in this somewhat more rigorous way but it is indicative that, at the time of preparation of this paper, two other ASRS research investigations are proceeding using case history comparison procedures.

CONCLUSIONS

The ASRS program has developed successfully along the lines originally envisioned. It has secured and retained the confidence of the members of the aviation community so that submission of the voluntary reports has not only continued but has increased in volume since the beginning of the program. The average quality of the reports is high and they are primarily concerned with human error in operations. It has proved feasible to analyze the reports, to abstract pertinent information from them, and to store it in highly retrievable form in a computerized database. The design of the database has provided an effective means for arranging the data in ways that facilitate the application of the epidemiological method.

Epidemiology has been an effective tool in the conduct of research investigations using ASRS information. It has been present either implicitly or explicitly in all of the studies performed to date and has provided the principal strategic approach in many. The results obtained validate fully the design of the ASRS. Information and new knowledge about aviation safety matters gleaned from these studies are flowing to the aviation community in the form of published technical reports. Sixteen such reports have been published -- all but two in NASA Quarterlies. All have contained information useful to the operating community and in several cases, as exemplified in Reference 7, ASRS research results are being used in bringing about changes to increase aviation safety.

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TABLE 1. - SOURCES OF REPORTS

Reporter	Percent of total reports
Controllers	48.1
Pilots	40.7
Air Force	5.0
Crew members	4.0
Navy	1.3
Observers	.7
Passengers	.2
Unknown	neg.

TABLE 2. - PRIMARY PROBLEMS

Problem description	Percent of total reports
Human error -- flight crew	45.4
Human error -- ATC	39.8
Ground navigation or communication equipment failure	4.5
Airport physical or institutional problem	3.4
Aircraft or aircraft equipment failure	3.1
Publications problems	1.6
Other (including weather related)	2.2

TABLE 3. - OCCURRENCE OUTCOMES

Outcome	Percent of total reports
Aircraft/Aircraft Separation Anomaly	51.1
Flight crew errors	14.3
Controller errors	10.1
Aircraft out of position	7.9
Situations	7.9
Ground equipment failures	3.6
Airborne equipment failures	2.4
Controlled flight toward terrain	.5
Aircraft out of control	.4
Other	1.8

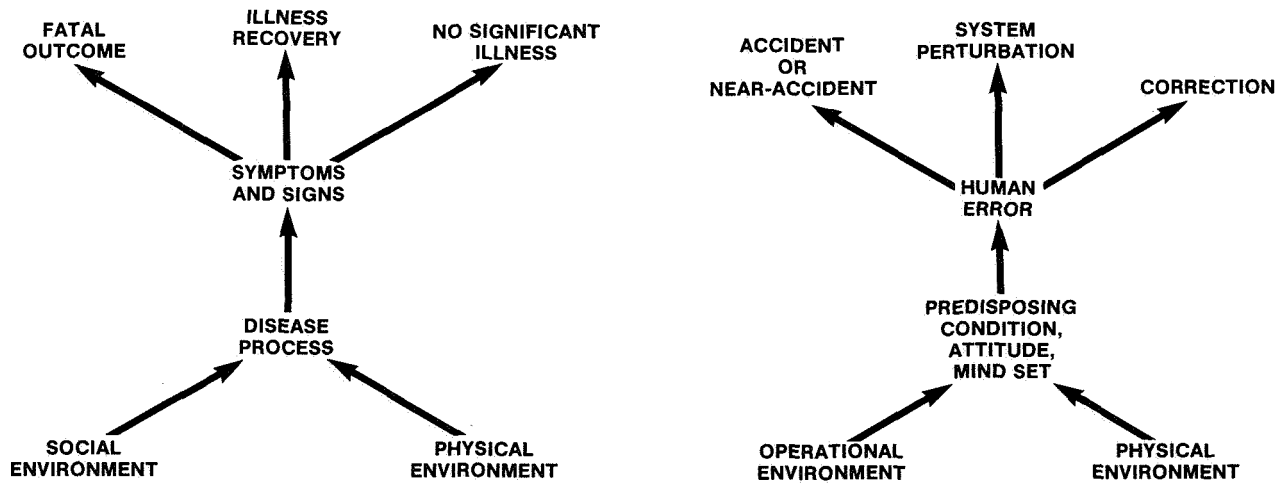


Figure 1.- The epidemiological model and its aviation system analogy.

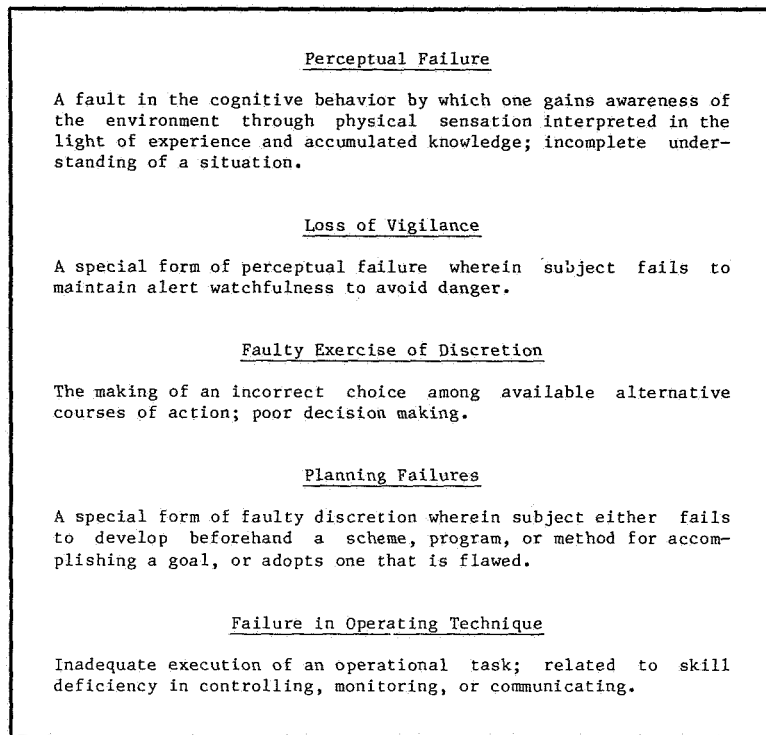


Figure 2.- Human error listing.

AN OCCURRENCE AS AN EVENT CHAIN

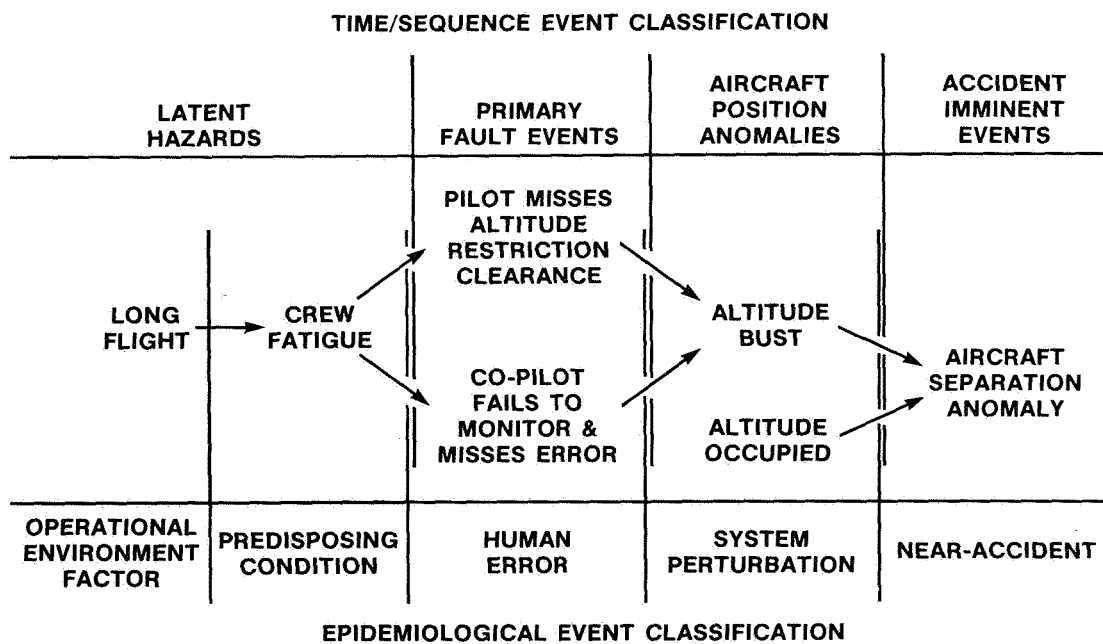


Figure 3.- Event classifications.

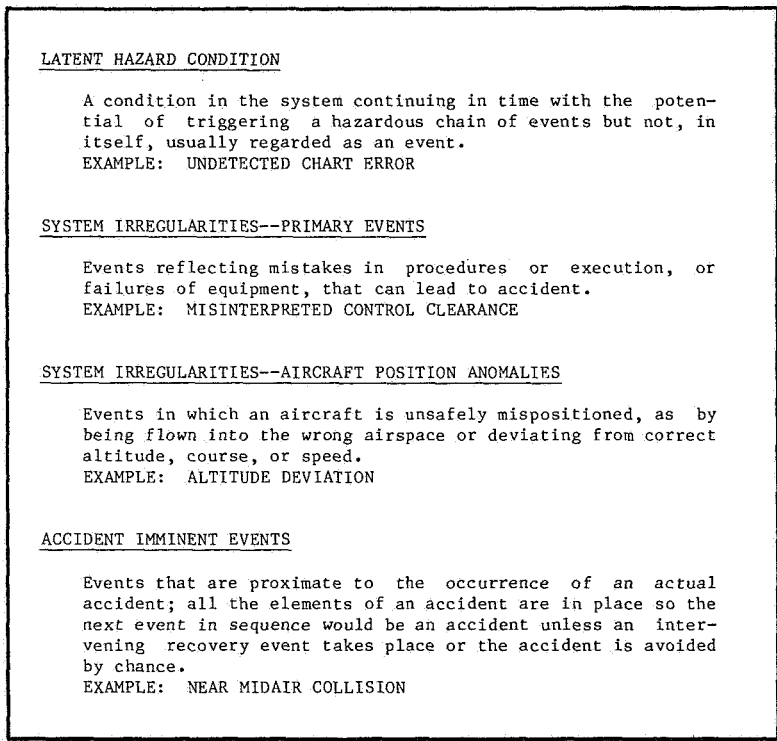


Figure 4.- Time/sequence event classification.

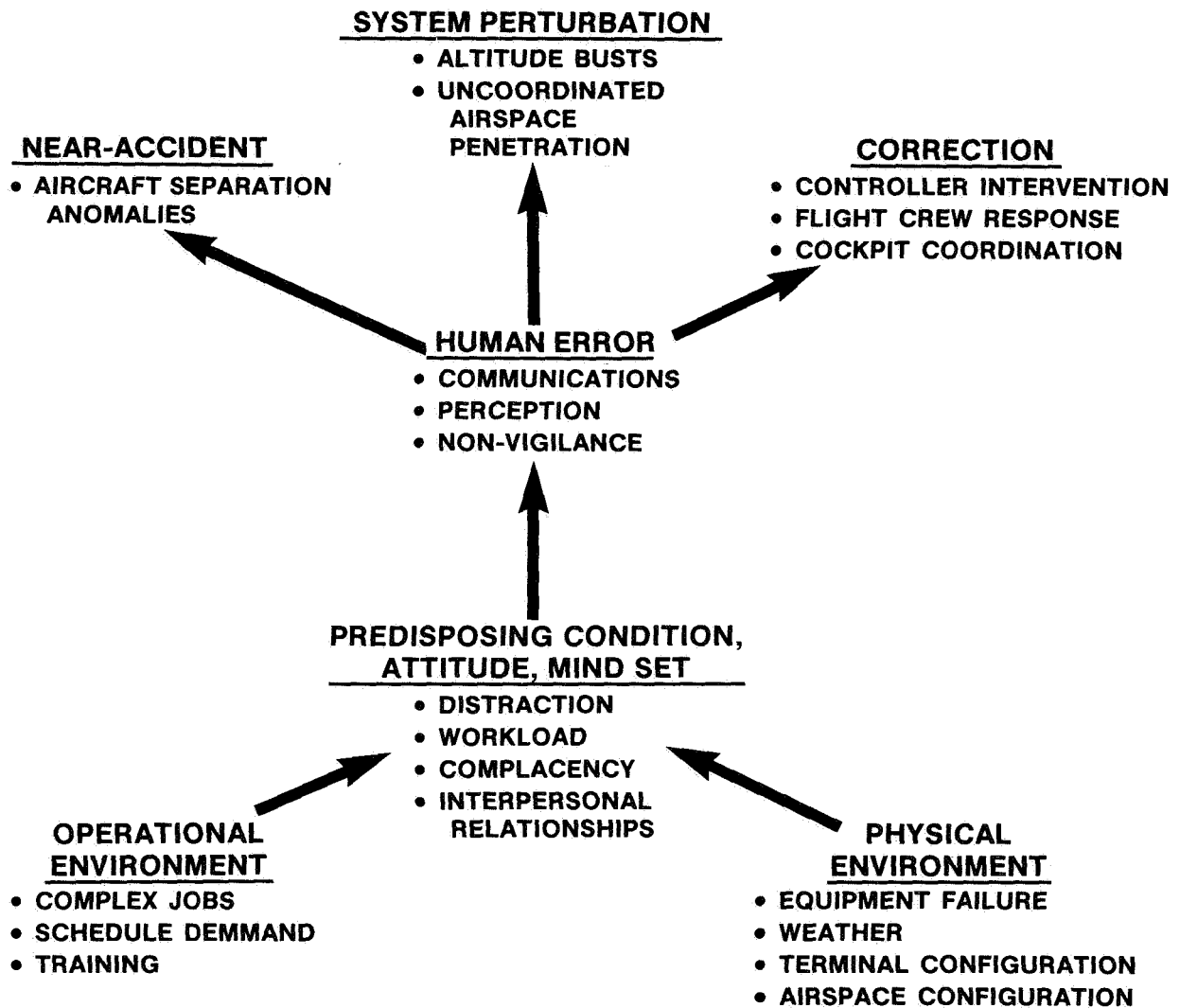


Figure 5.- Prevalent factors in the ASRS database.