An analysis of flight crew response to system failures

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Rombout Wever is a Research Scientist at NLR's Department of Safety and Flight Operations. He is involved in flight safety and flight operational research projects. Among the topics of his research are: civil and military aviation safety analysis, Operational Risk Management and Safety Management, Flight Data Monitoring, statistical analysis of flight data, development of aviation safety risk models, and flight testing. He is also an Aircraft Accident Investigator at NLR and involved in civil and military accident and incident investigations

Abstract

This exploratory study examined flight crew response to aircraft system malfunctions. The study sample consisted of 476 events of system malfunction for which good quality data was available. The data sample was limited to Western-built turboprop and jet aircraft operated by commercial operators. Only events that occurred between 1990 and 2000 were included in the sample. Failures of the following systems were included in the analysis: avionics and instruments, electrical systems, engine, flight controls, landing gear and hydraulic systems. The results show that in 19% of the sample, crew response to system failures was inappropriate. The percentage of inappropriate flight crew response decreases from 25% for earlier generation aircraft to 4% for the newest generation. The percentage of inappropriate response shows differences when various systems are compared, the lowest percentage of inappropriate responses occurs for flight control system malfunctions (8%), the highest percentage for instrument failures (48%). 11% of the investigated cases of inappropriate flight crew response involved wrong detection, 38% involved wrong diagnosis/decision and almost 51% involved wrong action. Annunciators have a pronounced effect on the probability of failure detection. Inherent cues play a relatively large role in decision failures. Inherent cues such as vibration, loud bangs etc., can be compelling, but are often not very conclusive or even misleading.

Introduction and objective

Inappropriate crew response to system failures often plays a role in aircraft accidents. Flight safety could be improved further if inappropriate crew response to system failures would be prevented. The objective of this exploratory study was to identify and analyse factors that are potentially associated with inappropriate crew response to system failures.

Research approach

The overall approach employed in this study was to:

1) Identify a sample of events involving aircraft system failures
2) Identify factors relevant for crew response using the accident narratives and literature
3) Analyse the information in the context of the central research question.

Data sample

Aircraft system categories

The scope and size of this study did not allow for an analysis of all accidents and incidents for which information was available. To obtain a set of relevant accidents and incidents a selection process had to be applied. For the sample to be as representative as possible, the selection was not restricted to a particular flight phase, type of aircraft or geographical region. Instead, it was decided to focus the analysis on a limited number of aircraft systems.

Aircraft systems are classified by the Air Transport Association of America (ATA) and this classification system is widely used. For the purpose of this study, six systems from this list were selected for further analysis. Only systems that are considered critical to flight safety were selected. The number of different systems was limited to six as this proved to generate a sample size that was large enough to generate robust results yet small enough to allow detailed analysis by the research team. Analysing accidents and incidents involving failures of particular systems had the additional advantage that it enabled a quicker search of incident databases.

Failures of the following systems were included in the analysis:

- Avionics and instruments
- Electrical systems
- Engine
- Flight controls
- Landing gear
- Hydraulic systems

Instrument failures

Instrument failures include failures of Instruments (ATA 31) and Navigation (ATA 34). Examples are failures and malfunctions of primary or backup flight instruments, such as a failure of the airspeed indicator. The selection may also include failures of the autoflight instruments (ATA chapter 22 Autoflight), such as the autopilot; however, in case the latter failure results in flight control problems (e.g. control upset), it is classified as a flight control failure.

Electrical failures

Electrical failures include failures of Electrical Power (ATA 24). Examples are failures or malfunctions of the electrical power supply and systems. Failures or malfunctions of the Auxiliary Power Unit are excluded since the APU is regarded as a separate system. Also excluded are incidents, in which the only observation is smoke, haze, sparks, or a fire without additional electrical malfunctions.

Engine related failures

Engine failures include failures of Propeller (ATA 61), Powerplant (ATA 71), Engine (ATA 72), Engine Fuel System (ATA 73), Ignition (ATA 74). Engine Air (ATA 75), Engine Controls (ATA 76), Engine Indicating (ATA 77), Exhaust (ATA 78), Oil (ATA 79) and Engine Starting (ATA 80). Engine Fire Protection and Extinguishing (ATA 2611 and 2621) are also included.

Engine failures include cases of mechanical damage to the engines, compressor stalls, and fuel contamination or fuel starvation. Engine fires are also included.

<u>Flight control failures</u>
Flight control failures include failures of Flight Controls (ATA 27), Stabilisers (ATA 55) and Wings (ATA 57). Also included are failures of the Auto Flight System (ATA 22) that directly affect control of the aircraft. Three types of a flight control failure were identified and included in the analysis:

- *Control Automation* failures include failures and malfunctions of the autoflight systems (e.g. autopilot, autothrottle), Flight Management System, Flight Control Computers and navigation systems for example.
- *Control Upset* includes failures and malfunctions of any system resulting in a (uncommanded) flight upset and a temporary or permanent loss of control.
- *Control Surface and System* failures include failures and malfunctions of the flight control surfaces or 'general' aircraft handling and control difficulties that are related to the flight control system.

Accidents or incidents which are a result of flight control problems that are caused by weather conditions (e.g. windshear, icing) or human error are excluded from the 'flight control failure' selection.

<u>Landing Gear failures</u>
Landing gear failures include failure of the Landing Gear (ATA 32), with the exception of failures of brakes (ATA 3240), tyres and wheels (ATA 3245) and nose wheel steering (ATA 3250). This includes problems with extending, raising, or locking the gear and gear doors, and unsafe gear warnings. Not included in this selection are incidents and accidents in which the gear failed, was torn off, or collapsed during take-off or landing. However, in some incidents the gear was damaged during take-off, while take-off was continued. In that case, the accident / incident is included since the crew might encounter problems with the gear in the subsequent approach. Incidents where the crew simply forgot to lower the landing gear before touch-down are excluded as well.

<u>Hydraulic system failures</u>
Hydraulic failures include failures of the hydraulic system (ATA 29) in the flight phase from take-off through landing.

Data sources

Multiple data sources have been used to develop a set of relevant accidents and incidents. The NLR Air Safety Database [Ref. 5 & 6] provided a large set of accidents and incidents, which have been reviewed in order to select those accidents or incidents that included a system failure as significant factor. The NLR Air Safety Database consists of accident data from a large number of sources including official international reporting systems (e.g. ICAO ADREP), Accident Investigation Agencies, and insurance companies (e.g. Airclaims). Full accident reports for selected cases were directly obtained through the accident investigation boards if such reports were available.

Accident/incident sample and inclusion criteria

The NLR Air Safety Database was searched for accidents and incidents in which a system failure was a significant factor. The search was limited to accidents and incidents that were reported through mandatory incident reporting systems. Voluntary reports such as those collected through the Aviation Safety Reporting System (ASRS) were not used because they can contain unverified and subjective information. The following selection criteria were applied to the database in order to obtain a first set of aircraft accidents and incidents:

1. The accidents or incidents involved aircraft operated by commercial operators, including:
   - Freight operators,
   - Air carriers involved in public transport,
   - Business jet flights (e.g. corporate jets),
   - Scheduled and non-scheduled flight,
   - International and domestic flights.

   But excluding:
   - Military and government flights,
   - Training and experimental/test flights.

2. Aircraft involved in an accident or incident include:
   - Western built aircraft, including manufacturers from North America, Europe, Israel and Brazil. ‘Eastern’ built aircraft were excluded because they were considered not to be representative of FAR 25 certified aircraft.
   - Fixed wing aircraft, excluding accidents with helicopters.
   - Turbojet and turboprop aircraft, excluding piston engine aircraft (piston engine aircraft are considered to be not representative of current and future designs).
   - Aircraft in the take-off weight category of 5700 kg (12,500 lbs) or higher.

3. The aircraft accidents and incidents occurred in the time span 1990 through 2000.

4. Accidents involving sabotage, terrorism and military action were excluded.

5. Accidents and incidents in the flight phases from take-off through landing, including the take-off roll and landing rollout, but excluding the taxi phase. The taxi-phase and standing at the gate were purposely excluded. Although system failures occur relatively frequent during those phases (especially immediately after 'powering up' the aircraft and after engine start) the response of the flight crew to system failures is considered to be not representative of the response to in-flight failures.

Application of these criteria to the database resulted in a data set containing over 5000 records of accidents and incidents. This dataset was further reduced by selecting failures of any one of the six selected systems only (i.e. avionics/instruments, engine, electrical systems, hydraulic systems, landing gear, flight controls). Selection was initially done by searching on key words, followed by individual reading of the accident synopsis by the research team to determine whether the case was actually relevant for the purpose of this study.

For example, an accident where the landing gear fails to extend and the crew has to cope with an ‘unsafe landing gear’ situation is more relevant for this study than a failure of the landing gear upon touchdown due to a hard landing.

Note: The selected systems are not stand-alone, but are in many cases interrelated or even integrated. The hydraulics system is used to power the landing gear and possibly flight control surfaces, instruments are driven by electrical power, and the engines generate electrical power and hydraulics power. The purpose of this study is not however to define system boundaries. In cases of doubt, it was left to the interpretation of the researchers to determine whether the case was relevant and which system was involved.

Because of the accident/incident inclusion criteria described above, the final sample cannot be considered a representative random sample of all (reported) incidents that include aircraft system malfunctions.

The final data sample that was used in the analysis consists of 476 accidents and incidents. For each of those cases, additional information was collected as described in the following section.

Further data collection and analysis

Aircraft generation

Since the development of certification regulations around 1970, much research has been conducted in the field of human factors, resulting in a better understanding of human behaviour. This is reflected in the design of current generation flight decks. To investigate whether this has also resulted in better crew response to system failures, the effect of aircraft generation was included in the analysis. Four generations of aircraft are distinguished:

First generation
These aircraft are typically designed in the fifties, when there was limited knowledge on, for instance, fatigue of metal structures. Certification was typically before 1965, based on, for example, old British Civil Airworthiness Requirements (BCAR). The engines are first production turbine engines. The aircraft have very limited cockpit automation, simple navigational aids, and no or limited approach equipment. Examples of this generation are Fokker F-27, De Havilland Comet and Boeing 707.

Second generation
Designed in the sixties and seventies, these aircraft have better and more reliable engines. Certification was between 1965 and 1980, not yet based on common JAR25/FAR25 rules. The cockpit is better equipped for instance with better auto-pilots, auto throttles, flight directors and better navigational aids. Examples of second generation aircraft are Fokker F 28, Boeing 737-200 and Airbus A-300.

Third generation
The aircraft design of the eighties and nineties typically shows consideration for human factors in the cockpit. The flightdeck contains Electronic Flight Instruments Systems (EFIS) and improved auto pilots. Furthermore, jet aircraft of this generation are equipped with engines of a high by-pass ratio. Aircraft are equipped with performance monitoring systems. Examples are Fokker 100, Boeing 737-400 and Airbus A-310.

Fourth generation
Aircraft are highly automated and equipped with fly-by-wire systems and flight envelope protection. Examples are Airbus A-330 and Boeing 777.

Type of failure manifestation

For the purpose of this analysis, in each of the cases the way in which the failure manifested itself to the flight crew was classified according to the following list:

- Annunciator. This includes warnings or cautions (lights or aural), stickshaker action, warning flags and system status lights that indicate a malfunction;
- Flight deck instrumentation. This includes abnormal status indications on instruments. An example is slowly rising EGT shown on the EGT gauge;
- Inherent cues. This includes unusual sound, vibrations, abnormal control forces, visible smoke or fire, etc.;
- Information from third parties. This includes cases where third parties, such as cabin crew or ATC, report malfunctions to the flight crew.
- No observation.
- Unknown.

Crew response

For each of the cases it was determined whether the response of the flight crew was appropriate or inappropriate.

Flight crew is defined as the combination of captain and co-pilot, or captain, copilot and flight engineer in earlier generation aircraft. For the purpose of this study, the 'appropriate' response is regarded from the perspective of the aircraft manufacturer. Appropriate response is defined as a correct execution of the correct procedure, where the correct procedure is the procedure as defined by the aircraft manufacturer. In some cases, the flight crew correctly followed procedures published by the airline, but the airline's procedures were not in accordance with those recommended by the manufacturer. These cases were classified as 'inappropriate response'.

Flight crew response to a system failure can be divided into three distinct components:

- Detection
- Decision or diagnosis
- Action

In the 'detection' step, the crew perceives the 'raw' information. This can be due to a fire warning going off in the cockpit, but also an unexpected motion of the aircraft, a strange noise, etc. In the decision step, the flight crew diagnoses the problem. Based on the result of this diagnoses, the flight crew decides on the corrective action to be taken, e.g. which procedure to follow.

For each of the sample cases it was determined whether each of these three steps had been accomplished correctly or incorrectly. Similar to the determination of appropriate and inappropriate response, a case where an airline provided the flight crew with incorrect procedures was classified as 'wrong action', regardless of whether the flight crew followed that procedure 'according to the book'.

Findings

Figure 1 shows the relative proportions of failed systems in the total study sample of 476 occurrences. Almost half of the cases are powerplant related malfunctions. The landing gear and flight control system each account for slightly less than 20% of the total sample. Failures of the hydraulic system, electrical system and flight instrumentation are relatively less frequent. Note that these figures do not represent the relative frequency of occurrence of failures of the different systems in day-to-day operations, it only represents the relative frequency *in the data sample*.

Percentages of appropriate and inappropriate crew response cases in the total sample of 476 are presented in Figure 2. Crew response was inappropriate in approximately one fifth of all cases.

A comparison of crew response for different aircraft generations (Figure 3) shows that the percentage of inappropriate response decreases for newer generations of aircraft.

Figure 4 presents a comparison of crew response to system failures for turboprop and jet powered aircraft. Perhaps surprisingly, there is no statistical significant difference between these two classes of aircraft.

When a comparison is made of flight crew response to system failures for the different aircraft systems that were included in the study, as shown in Figure 5, large differences can be observed.

In particular, the percentage of inappropriate responses to failures of instruments seems very high. It must be noted that this observation is based on a rather small sample of 23 cases.

Figure 6 shows a comparison between turboprop and jet aircraft of the percentage of ‘inappropriate response’ cases, for each of the types of aircraft systems.

Instrument failures show the largest difference between jets and turboprops, however, the total sample of instrument failures in turboprop aircraft consists of only 3 cases. The statistical reliability of this information is low. Similarly, the total sample of hydraulic failures in turboprop aircraft consists of only 5 cases. Again, the observed difference between jet and turboprop aircraft with respect to response to failures of the hydraulic system is statistically not very robust.

The sample sizes for the flight control system, the landing gear and the powerplant are large enough to provide statistically robust data. The percentage of inappropriate responses to flight control system malfunctions is lower for turboprop aircraft than for jet aircraft. This may be due to the fact that the flight control system of turboprop aircraft is in general much simpler than that of jet powered aircraft, reducing the possibility of e.g. autoflight mode confusion. The percentage of inappropriate responses to malfunctions of the landing gear system is similar for turboprop and jet powered aircraft. Because there are no basic differences between the landing gear system of a jet powered aircraft and that of a turboprop aircraft, this result is no surprise. When comparing the percentage of inappropriate responses to powerplant malfunctions, it is again not surprising that this percentage is higher for turboprop-powered aircraft. A failure of a turboprop engine results in a more complex situation because of the necessity to feather the associated propeller and the implications for the flight characteristics of the aircraft.

The way in which the system failures manifested themselves is shown in Figure 7 for each of the six different systems that were analysed and also for the total sample. Note that these categories are not mutually exclusive: a failure can manifest itself simultaneously in a number of ways. Therefore the percentages for each of the categories add up to more than 100%. For example, an engine fire can trigger engine fire warning light (annunciator), while simultaneously the pilots see flames coming from the engine (inherent cues) and they are advised by ATC of an engine fire (information from third parties).

Large differences can be observed among the different aircraft systems. For instruments and the hydraulic system, the primary source of information is the flight deck instrumentation. Failure manifestation to the flight crew from inherent cues, such as unfamiliar sounds, smoke, etc are relatively infrequent for those types of failures. For the landing gear, the most important manifestation is an annunciator system, in this case the gear indicator lights. A significant portion of information is also provided by 'information from third parties'. In this case that would primarily be ATC providing the flight crew with information on the status of the landing gear. It must be noted that in those cases the flight crew is already aware of problems with the landing gear and a fly-by is made for visual confirmation of the problems.

Electrical failures are perceived through annunciators (e.g. generator fail light), flight deck instrumentation (this can also be the popping of a circuit breaker) but also by inherent cues. This is in many cases the occurrence of smoke or a burning odour.

The vast majority of flight control failures are detected by the flight crew through uncommanded aircraft movements or unexpected control forces (inherent cues).

Propulsion failures are detected in the majority of cases by inherent cues. In this case the crew would observe loud bangs (in the case of compressor stalls or uncontained failures), vibration or aircraft yaw. Annunciator systems (engine fire warning) and flight deck instrumentation (EGT, N1, etc) are also important.

In conclusion, the importance of the 'inherent cues' group, i.e. unfamiliar noises, uncommanded aircraft movements, observation of smoke, unexpected control forces etc. must not be underestimated.

To investigate whether the type of failure manifestation would have an effect on the appropriateness of flight crew response, the failure manifestation of the 'appropriate' and 'inappropriate' flight crew response cases have been compared in Figure 8. The results show that in the case of inappropriate response, the detection by 'inherent cues' is relatively less frequent. The annunciators and flight deck instruments are relatively more prevalent for the inappropriate flight crew response cases. However, the differences are relatively small and may not be statistically significant.

As was explained in the previous section, flight crew response comprises three steps: detection, decision and action. The inappropriate flight crew response cases were analysed to determine which of these steps failed. The result is shown in Figure 9.

The majority of inappropriate responses (51%) involve cases where detection and diagnosis of the failure was correct, but the subsequent action was wrong. In 38% of the cases the crew failed to correctly diagnose the problem. In 11% of the cases was the failure not detected by the flight crew.

Combining failed response steps with the type of failure manifestation results in Figure 10.

Notice the pronounced effect of annunciator systems on the probability of failure detection. Also, it can be seen that inherent cues play a relatively large role in diagnosis/decision failures.

Inherent cues such as vibration, loud bangs etc can be compelling, but are often not very conclusive or even misleading.

Discussion

The study analysed 476 aircraft incidents and accidents that involved system malfunctions, using world-wide accident and incident data for 1990 to 2000. The aircraft involved were operated by commercial air carriers or charter operators.

The results show that in 17% of the cases the response by the flight crew to the system malfunction was inappropriate.

The frequency of inappropriate flight crew response to a system malfunction reduces for newer aircraft generations. To some extent this may be attributable to improvements in cockpit design. However, newer aircraft are generally operated by first tier airlines, and are in many cases flown by first tier pilots. To what extent the lower frequency of inappropriate responses can be attributed to improvements in flight deck design or to other factors such as crew training cannot be determined from this data.

According to the data sample, the frequency of inappropriate flight crew response is similar for turboprop and jet powered aircraft. Comparison of the results between turboprop and jet powered aircraft for each of the systems that where included in the analysis does show differences. Flight control malfunctions lead to relatively more inappropriate responses in jet aircraft, powerplant malfunctions lead to relatively more inappropriate responses in turboprop aircraft, while landing gear malfunctions do not show a difference between jet and propeller aircraft.

The difference for the flight control system may be explained by the fact that the flight control system of turboprop aircraft is in general much simpler than that of jet powered aircraft, reducing the possibility of e.g. mode confusion. Because there are no basic differences between the landing gear system of a jet powered aircraft and that of a turboprop aircraft, it is no surprise that no differences are observed with respect to the percentage of inappropriate responses. When comparing the percentage of inappropriate responses to powerplant malfunctions, it is again not surprising that this percentage is higher for turboprop powered aircraft. A failure of a turboprop engine results in a more complex situation because of the necessity to feather the associated propeller and the implications for the flight characteristics of the aircraft.

The results of this study also show that the frequency of inappropriate responses to system malfunctions decreases for newer generations of aircraft, reflecting the improved design of the flight deck crew interface in more modern aircraft. The importance of hardware design is underlined by the fact that the relative frequency of inappropriate crew responses shows large differences when various systems are compared. The lowest frequency of inappropriate responses occurs for flight control system malfunctions (8% inappropriate response), the highest frequency for instrument failures (48% inappropriate response). Because of the large differences that have been observed, it is recommended to include other flight critical systems, such as navigation and communication systems, in future research. It would also be useful to expand the dataset for those systems where the current sample size is very low (electrical system and instruments).

Flight crew response to system malfunctions comprises three steps: detection, diagnosis/decision and action. An analysis of 82 cases of inappropriate response shows that

11% of those cases involved failure of the flight crew to detect a problem, 38% involved wrong decision and almost 51% involved wrong action.

In many cases, a system failure manifests itself in different ways. The most frequent manifestation is by inherent cues, i.e. visible smoke, unexpected aircraft movements, unfamiliar sounds, etc. The second most frequent manifestation is from flight deck instrumentation or annunciators, such as a warning light. When comparing failure manifestations for cases of appropriate and inappropriate flight crew response the differences are small and may not necessarily be statistically significant. Comparison of failure manifestations across systems does show large differences however. For flight control system malfunctions the failure is manifested in more than 90% of the cases by inherent cues. For hydraulics and instrument malfunction, the failure manifestation in 80% of the cases is from the flight deck instrumentation, i.e. needles in the red region, volts going to zero etc. For landing gear malfunctions the most frequent (85%) manifestation by annunciators, in this case the unsafe gear light.

Annunciators have a pronounced effect on the probability of failure detection. Inherent cues play a relatively large role in decision failures. Inherent cues such as vibration, loud bangs etc can be compelling, but are often not very conclusive or even misleading on the nature of the failure.

While these results in itself provide insufficient information to draw firm conclusions, the large differences that have been observed among systems of the type of failure manifestation as well as the percentage of inappropriate response cases suggests that additional research would be useful.

Conclusions

For the data sample as described in this report, the following conclusions can be drawn:

- The percentage of inappropriate flight crew response to system failures decreases from 25% for earlier generation aircraft to 4% for the newest generation.
- The percentage of inappropriate crew responses shows large differences when various systems are compared. The lowest percentage of inappropriate responses occurs for flight control system malfunctions (8%) the highest percentage for instrument failures (48%).
- Inappropriate response to flight control system malfunction occurs relatively more frequent in jet aircraft. Inappropriate response to engine malfunction occurs relatively more frequent in turboprop aircraft.
- 11% of the investigated cases of inappropriate flight crew response involved wrong detection, 38% involved wrong diagnosis/decision and almost 51% involved wrong action.
- Annunciators have a pronounced effect on the probability of failure detection. Inherent cues play a relatively large role in decision failures. Inherent cues such as vibration, loud bangs etc., can be compelling, but are often not very conclusive or even misleading.

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Figures

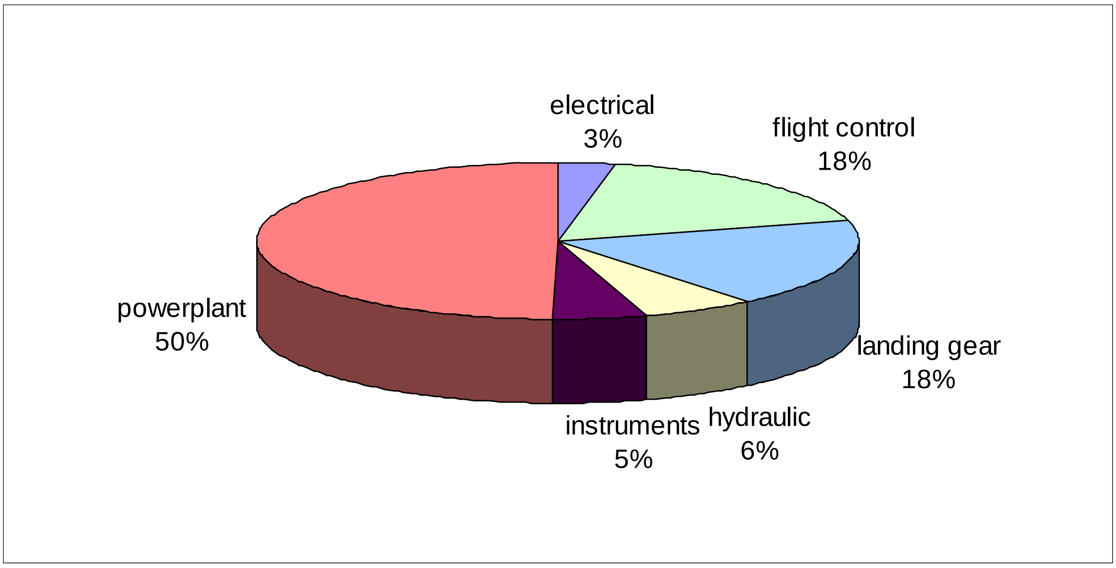

Figure 1: Distribution of system failures among total sample.

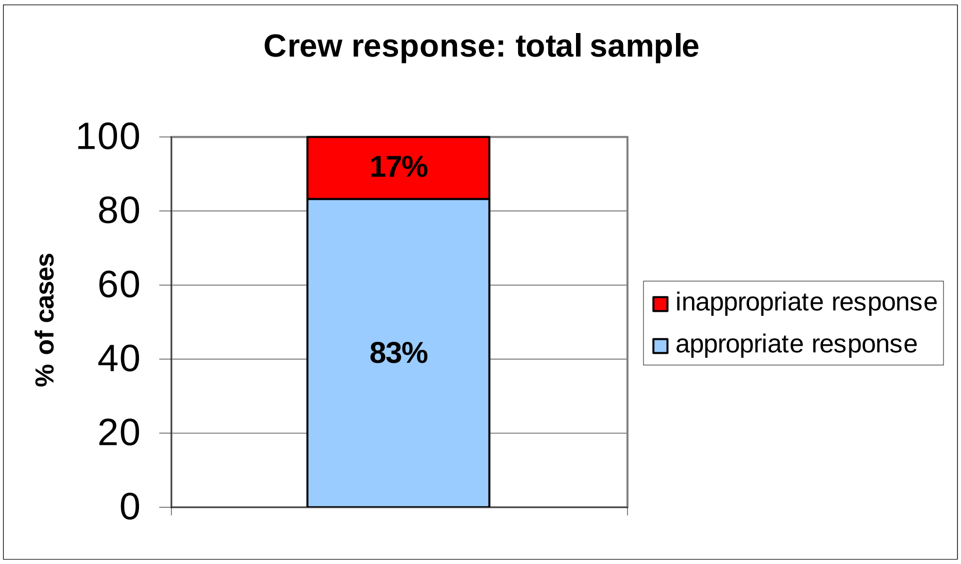

Figure 2: Crew response: total sample.

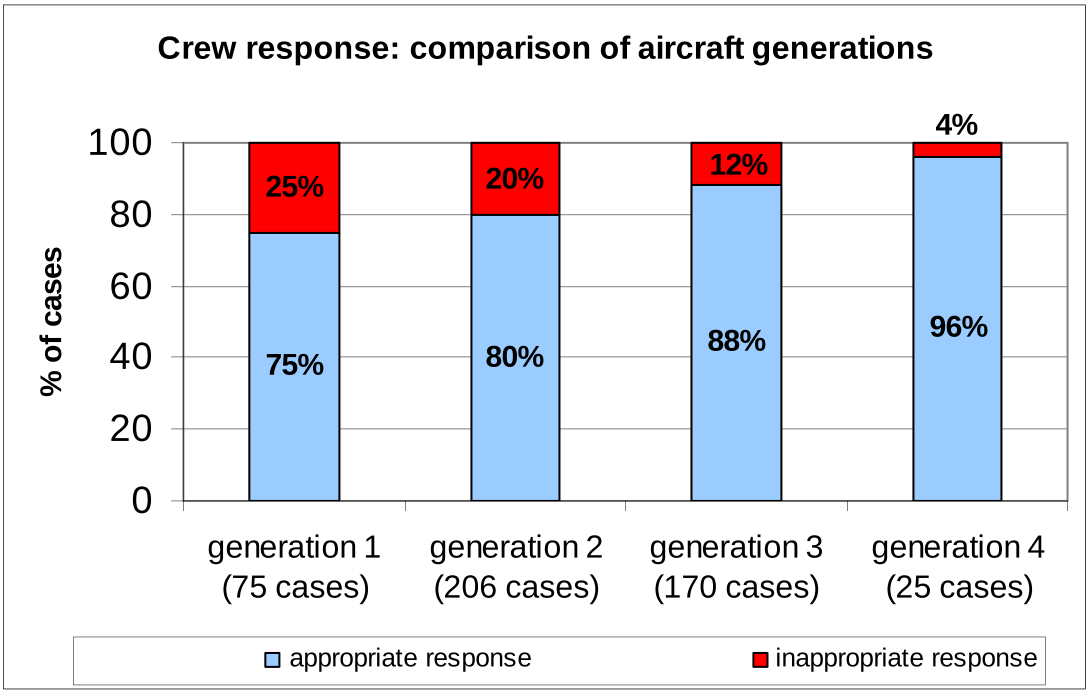

Figure 3: Crew response: comparison of aircraft generations.

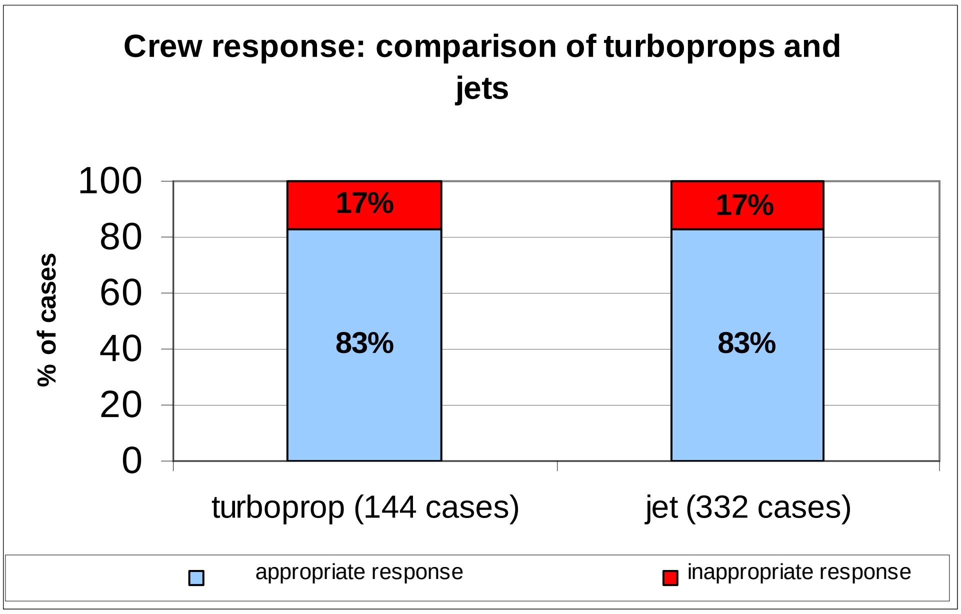

Figure 4: Crew response: comparison of turboprop and jet powered aircraft.

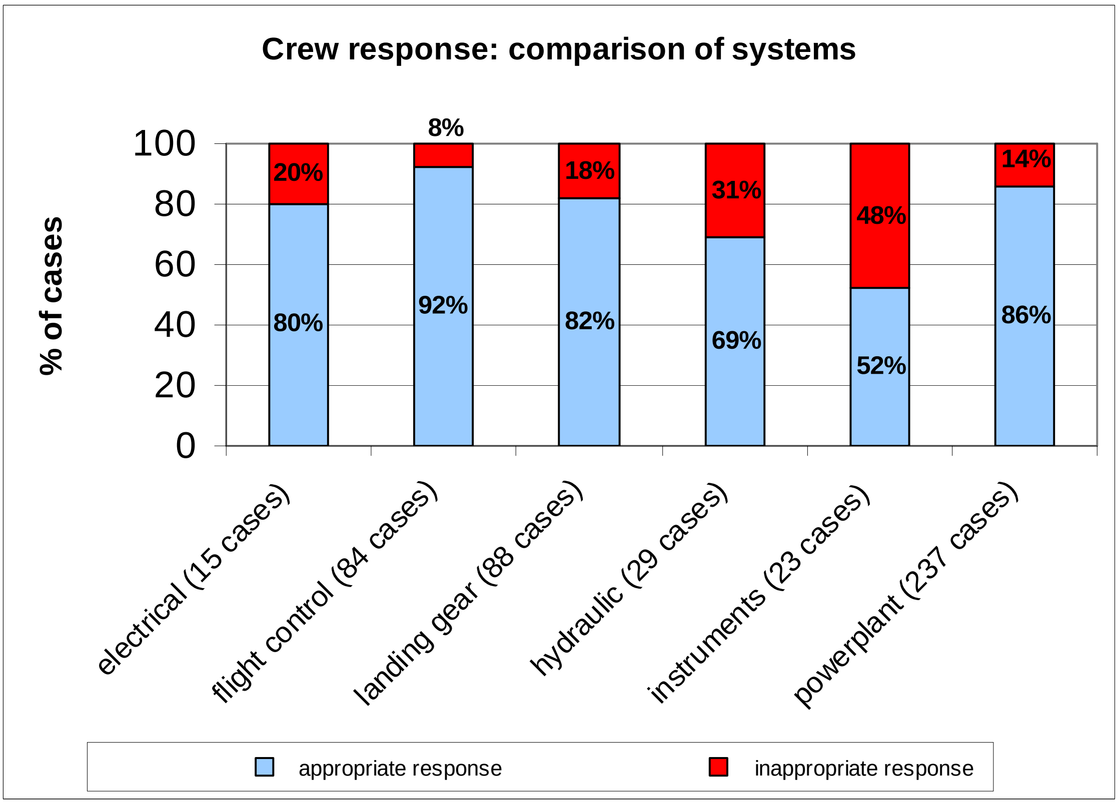

Figure 5: Crew response: comparison of systems

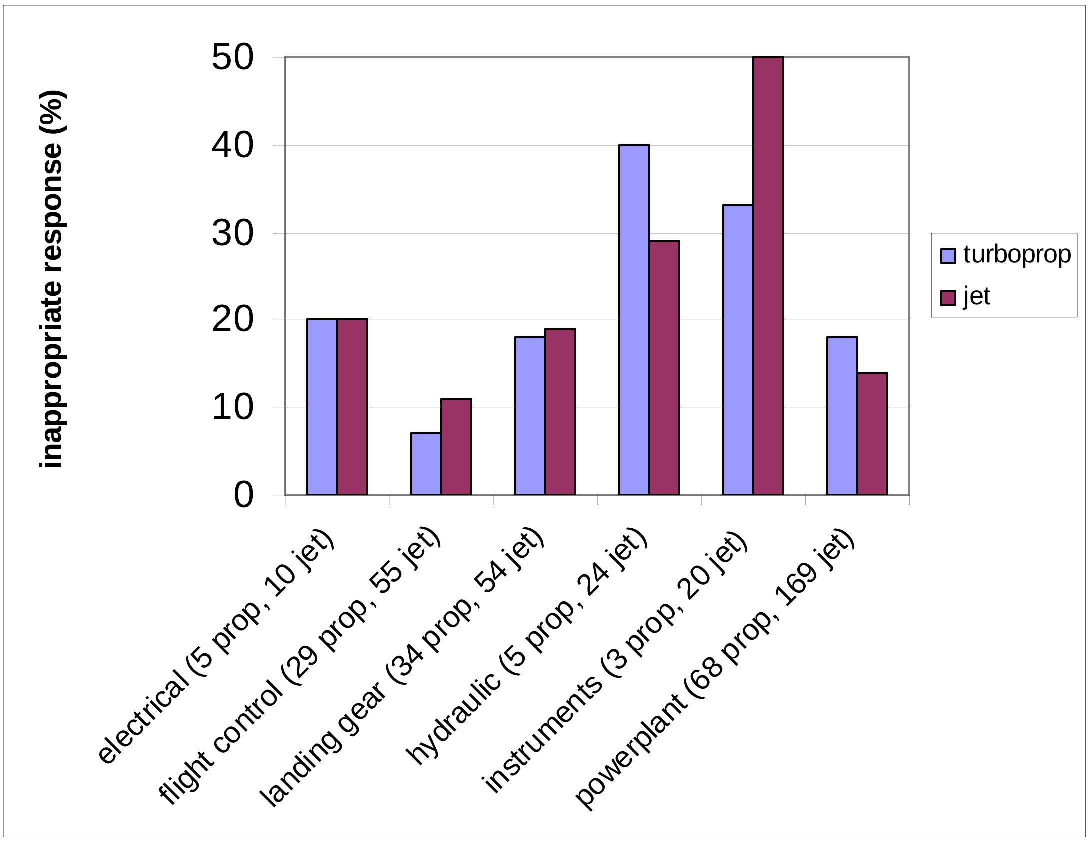

Figure 6: Comparison of inappropriate crew response for turboprop and jet aircraft for different systems. Numbers in brackets behind categories refer to total number of cases (appropriate and inappropriate response) of the study sample.

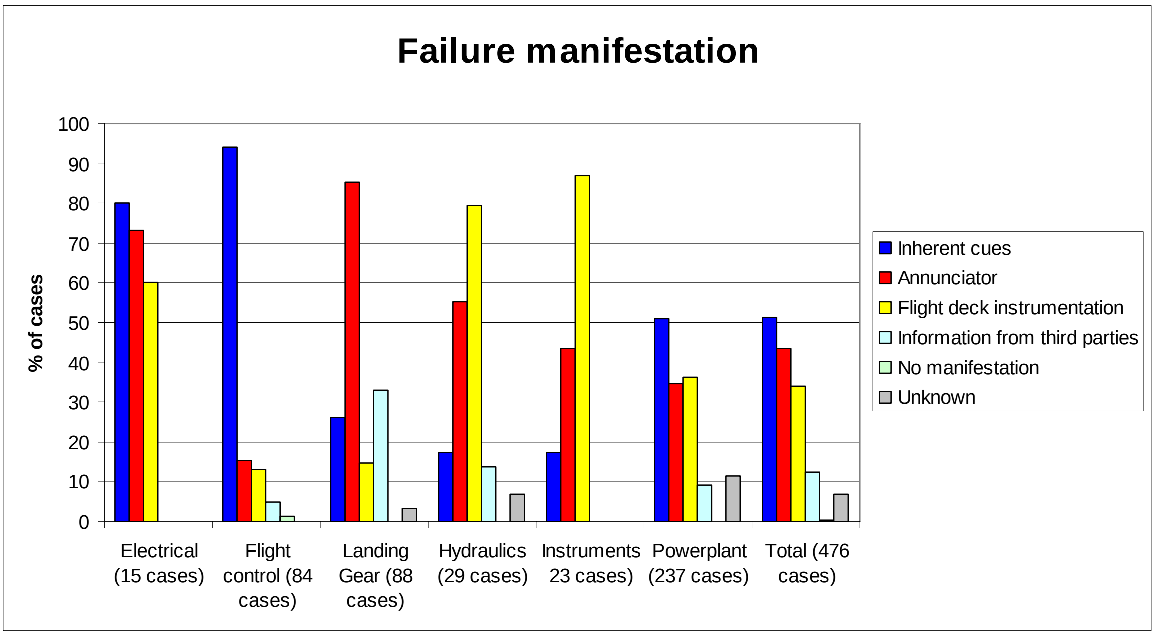

Figure 7: Failure manifestation

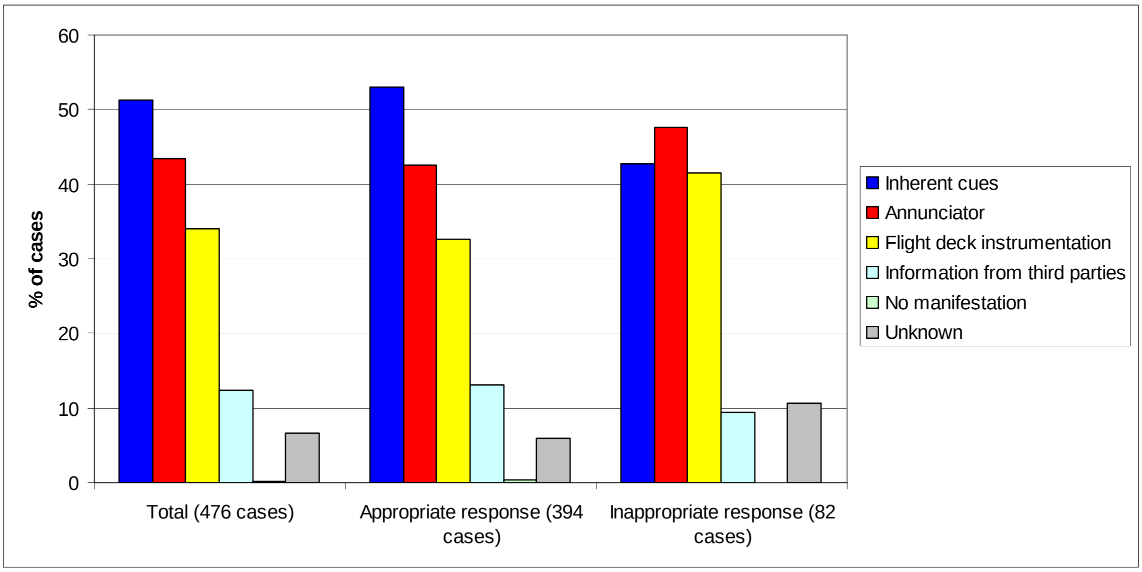

Figure 8: Comparison of failure manifestation for appropriate and inappropriate flight crew response.

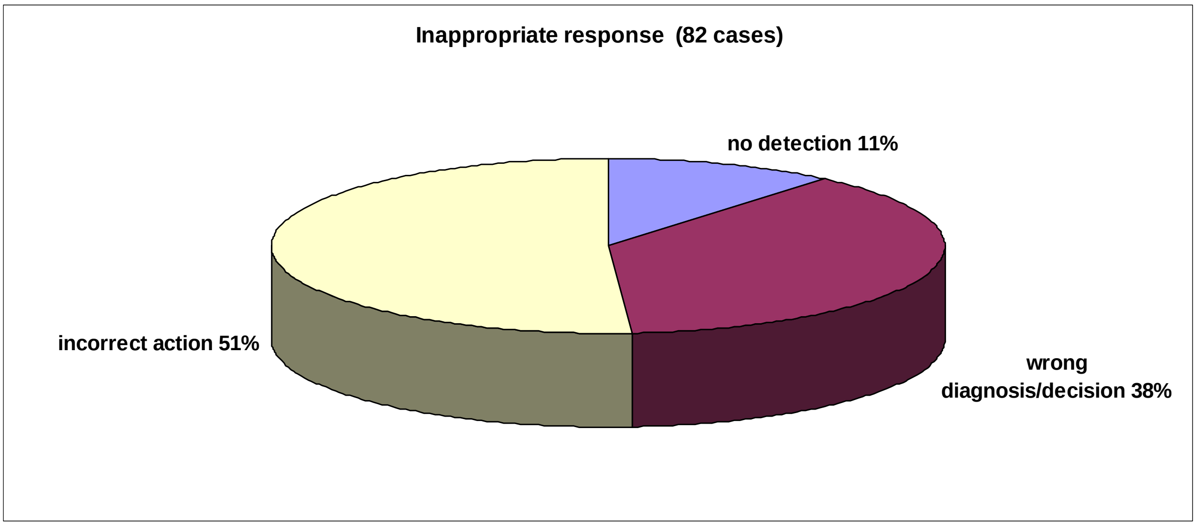

Figure 9: Failed response steps in cases of inappropriate response.

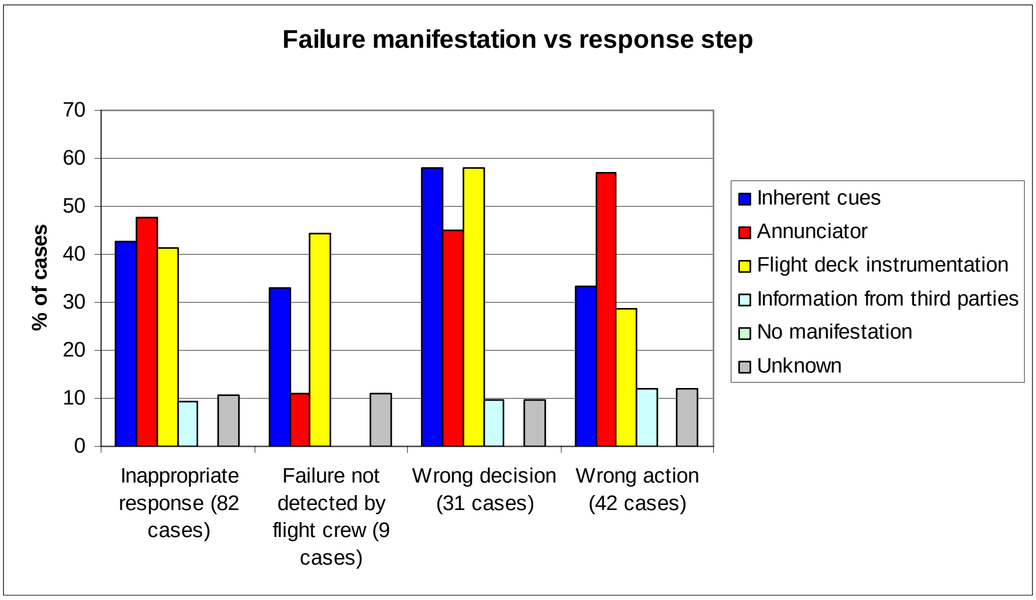

Figure 10: Failure manifestation for failed response steps.