Proceedings of the 33rd European Safety and Reliability Conference (ESREL 2023)
Edited by Mário P. Brito, Terje Aven, Piero Baraldi, Marko Čepin and Enrico Zio
 Published by Research Publishing, Singapore.
doi: 10.3850/978-981-18-8071-1_P463-cd

Comparison of flight safety between different aircraft modifications

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This paper discusses the relationship between the next aircraft modifications on the number and consequences of accidents or incidents. The problem is discussed on the example of selected models of the Boeing brand. The first part of the paper discusses the impact of introducing new designs on flight safety. The differences between modifications of selected Boeing aircraft are briefly presented. Definitions of an accident and an aircraft incident are quoted and the sources of data used for the analysis are presented. In the next part of the study, the number of aircraft of a given type in service at a given time was estimated based on delivery reports. The numbers of aircraft in service were compared with aircraft accident and incident reports. The number of adverse occurrences per aircraft of a given type in the sequential years following the introduction of a new model was presented in tables and graphs. In the following part of the study, the probability of occurrence of different loss categories in the first two years of operation after the launch of the new aircraft models was calculated. Finally, the results obtained are summarised and discussed as well as interpreted.

Keywords: Aviation, Boeing, aircraft evolution, cause of accidents, machine learning.

1. Introduction

The civil aviation industry is characterised by a high level of safety Ingraham (2015); Dabrowska and Soszynska-Budny (2018); Valis et al. (2019). This is the result of stringent procedures for the design, maintenance and operation of aircraft and all surrounding infrastructure. It is not possible to achieve a 100 per cent level of reliability. However, it is possible to strive to improve it.

The purpose of this research is to examine differences in safety levels for newly introduced aircraft designs over successive years of operation. The analysis is based on the example of Boeing aircraft and accidents and incidents in the United States of America.

2. Risk aspects in the introduction of new aircraft designs

The aviation industry is constantly evolving and, with advances in technology and widespread computerisation, seeks to optimise operating costs and improve travel safety. Aviation is characterised by a high level of safety compared to other forms of transport Ingraham (2015); Kuben et al. (2019); Kolowrocki et al. (2017). This is due to the numerous requirements that both aeronautical structures and crew training programmes and operating processes must meet. Certification procedures are developed, among other things, on the basis of accident and incident investigation experience Organizacja Miedzynarodowego Lotnictwa Cywilnego (2010); Tloczynski (2017); Kolowrocki and Kuligowska (2018).

The introduction of a design to the market involves the deployment of new technological solutions both in terms of operation and in maintaining continuous airworthiness. These new developments require training of the operators both during normal operation and in abnormal situations. Training is time-consuming and the programme is designed to minimise the risk of hazardous situations during operation.

2.1. *Impact of the introduction of new designs on flight safety*

The majority of available articles on the safety of next-generation commercial jets detail individual cases. A lot of attention is paid to the 737 MAX model due to two crashes caused by the introduction of new aircraft trim solutions Gelles (2021); Valis et al. (2019); Grzejda (2014).

Another issue, widely discussed when comparing successive generations of aircraft, is the reduction of unit costs and environmental impact MWL (2021); Grabowski et al. (2021); Hasilova and Valis (2018).

Literature sources dealing with commercial flight safety over the years do not make the number of aircraft accidents dependent on the age of a particular design, but instead focus on the causes of accidents and the possible improvement in statistics from year to year Karen and Marais (2012); Oszczypala et al. (2022); Grzejda (2021).

2.2. *Aircraft used in the analyses conducted*

The study considered Boeing 737, 747, 757, 767, 777 aircraft in variants manufactured between 1959 and 2007. This allowed information to be collected on aircraft of selected types in service between 1982 and 2007. The average service life was assumed equal to 25.7 years (25 years, 8 months and 21 days) based on data from year 2015 Forsberg (2015); Cicmanec and Petrasek (2019).

3. Data sources

3.1. *NTSB — National Transportation Safety Board*

Accident data was taken from the National Transportation Safety Board (NTSB) NTBS - National Transportation Safety Board (2023); Palasz and Przysowa (2019); Grzejda and Parus (2021). The organisation was founded in 1967 to improve transport safety. The agency covers areas such as road, rail, sea and air transport, among others. The agency's main objective is to improve safety by conducting independent investigations into the causes of accidents. Based on the obtained findings, the NTSB makes recommendations to prevent or reduce similar incidents in the future NTBS - National Transportation Safety Board (2023); Ivchenko and Zhuzhukin (2020); Giel and Plewa (2016a).

The agency publishes detailed statistics on civil aviation accidents. The data collected is published on the NTSB website. The compilation includes data such as:

- Type of incident (incident, accident);
- The daily date of the incident;
- Approximate or exact location, including geographical coordinates;
- The code of the airport where the incident occurred (if applicable);
- Degree of injury and number of casualties;
- Total number of persons on board;
- Degree of damage to the aircraft;
- Registration number of the aircraft involved;
- Manufacturer and model of aircraft;
- Type and number of engines;
- Carrier operating the service;
- Weather conditions;
- Phase of flight.

3.2. *Boeing*

Data on delivered aircraft was obtained from the manufacturer's website Boeing (2023a); Giel et al. (2017); Wang and Pham (2020). Boeing is one of the largest manufacturers in the aerospace industry. Its product range includes commercial aircraft, systems and military aircraft, and is involved in the space industry Boeing (2023b); Oravec et al. (2021); Giel and Plewa (2016b). The corporation employs more than 140,000 people in more than 65 countries worldwide Boein (2023); Sun and Geng (2021); Rzadkowski et al. (2021). Aircraft delivery data published on the website includes parameters such as:

- Name of recipient;
- Country of delivery;
- Model and series of aircraft delivered;
- Engine type;
- Month and year of delivery;
- Number of aircraft delivered in a given delivery.

4. The methodology of calculation

The paper calculates the probability of accidents and incidents in the first years after the introduction of a particular aircraft type on a per-aircraft basis. The number of aircraft operating in the US was approximated by the percentage of passengers carried by US-registered aircraft relative to all commercial traffic worldwide The World Bank IBRD - IDA (2010); Bielawski et al. (2017); Hoskova-Mayerova et al. (2020). The resulting ratio is as follows:

$$p = \frac{\text{number of USC passengers}}{\text{number of passengers worldwide}} = \frac{926\ 737\ 000}{4\ 369\ 655\ 800} = 21.08\% \qquad (1)$$

$$eks = wyp \cdot p \qquad (2)$$

where:

p - percentage of passengers carried by aircraft of airlines registered in the USA,

wyp - the number of aircraft of a given type in service worldwide at any given time,

eks - the number of aircraft of a given type in service in the US at a given time.

The number of aircraft of a given type in service at any given time was approximated on the basis of the average service life of the aircraft and the delivery dates of the aircraft.

The following relationships were used to calculate the number of incidents by aircraft type:

$$N_{inc} = \frac{N_{inc12}}{N_{aver}} \qquad (3)$$

where:

N_{inc} - number of per aircraft,

N_{inc12} - number of incidents involving the type in the following 12 months afte release,

N_{aver} - average numbe of aircraft of a type in service over the following 12 months afte release.

The following equation was used to average the number of incidents and accidents:

$$N_{inc\,\&\,acc} = \frac{N_{all}}{N_{types}} \qquad (4)$$

where: $N_{inc\,\&\,acc}$ - average number of incidents per aircraft,

N_{all} - total number of incidents per aircraft of all types,

N_{types} - number of types of aircrafts under consideartion.

The following classification was used in calculating the probability of loss by category:

- u_0 - no damage to the aircraft;
- u_1 - light damage to the aircraft;
- u_2 - significant damage to the aircraft;
- u_3 - destruction of the aircraft;
- r_0 - no injuries to persons present on board;
- r_1 - slight injury to at least one person present on board;
- r_2 - serious injury to at least one person present on board;
- r_3 - fatal injuries to at least one person present on board.

The risk measure was calculated based on the following relationship Szopa (2016); Mogilski et al. (2020); Ameri et al. (2019):

$$\Lambda(c,t) = Q(t) \cdot Z(c) \qquad (5)$$

where:

- $\Lambda(c,t)$ - risk measure
- $Q(t)$ - probability of the adverse event occurring in period t
- $Z(c)$ - probability that the adverse event will cause

It was assumed in the calculations that the variable t represents the first 2 years from the introduction of the new model into service.

5. Analysis

Based on Boeing aircraft delivered data from 1959 to 2007 Boeing (2023b); Bekesiene and Hoskova-Mayerova (2018); Babiarz (2015) and assuming an average service life of 25.7 years Forsberg

(2015); Babiarz (2018), the number of aircraft of a given type in service at a given time was calculated. Up to 2007, eight main variants of the 737 were produced. The table 1 shows the delivery dates of the first units.

Table 1. Delivery dates for the first 737s

	Originals			
Date of	737-100	737-200		
first delivery	12.1967	12.1967		
	Classic			
Date of	737-300	737-400	737-500	
first delivery	11.1984	09.1988	02.1990	
	Next Generation			
Date of	737-600	737-700	737-800	737-900
first delivery	09.1998	12.1997	04.1998	05.2001

The figure 1 shows the number of examples of a particular series remaining in service at a given time.

5.1. *Number of incidents*

Using data downloaded from the NTSB website NTBS - National Transportation Safety Board (2023); Babiarz and Szymanski (2020), information was collected on the number of incidents of each series of Boeing aircraft. The data is from 1982-2007.

Figure 2 shows that the number of accidents involving Boeing aircraft of the series in discussion ranges from one to eleven per year.

Figure 3 shows the number of incidents by year involving aircraft of the Boeing 737s of each series. There were no incidents involving 600-series aircraft between 1982 and 2007.

5.2. *Comparison of the number of incidents with the release date*

The number of incidents involving aircraft of a particular series in the years following the launch of the variety was calculated. The data is presented per aircraft in service at the time.

The calculation for the 737 excludes the 100 and 200 series due to the launch date of these types prior to 1982, the first year for which US incident data is available.

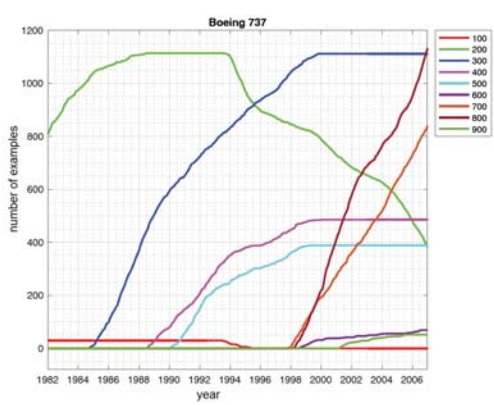

Fig. 1. Number of model 737s in service

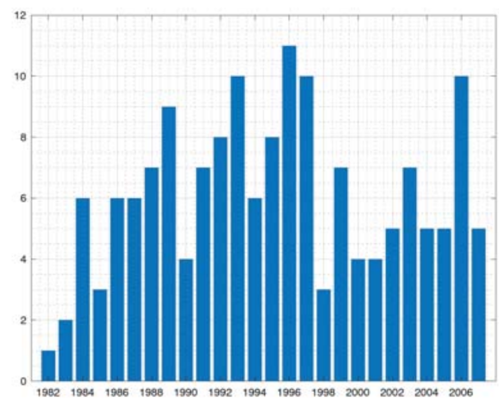

Fig. 2. Total incidents involving aircraft types 737, 747, 757, 767, 777

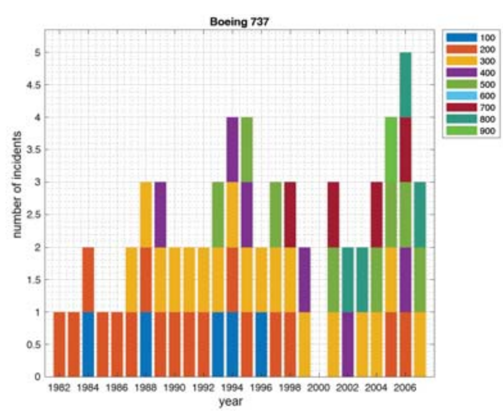

Fig. 3. Number of incidents involving Boeing 737s

The sum of the number of incidents by year is shown in the graph (Figure 4).

The most incidents are certainly in the first year of service.

5.3. *Average number of incidents*

Totals of incidents were averaged across aircraft types which allowed data to be obtained without a breakdown by type. The results are presented below.

The highest number of incidents per aircraft occurs in the first two years after the beginning of service for an aircraft of a given type. The probability of an incident in the first two years is on average almost five times (4.84) higher than in the following eight years. In the following years, the calculated values are significantly lower and fluctuate within a small range.

5.4. *Number of accidents*

Figure 6 shows that the number of accidents involving Boeing aircraft of the series in discussion varies from one to sixteen per year.

5.5. *Average number of accidents*

Total accidents were averaged across aircraft types, allowing data to be obtained without a division into a given type. The results are presented in Figure 7.

The highest number of accidents per aircraft occurs in the first two years after the beginning

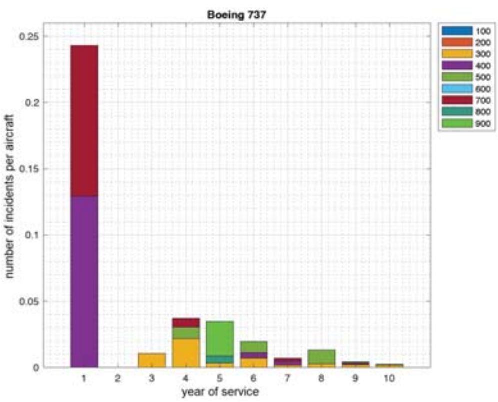

Fig. 4. Number of incidents per 737 aircraft in service

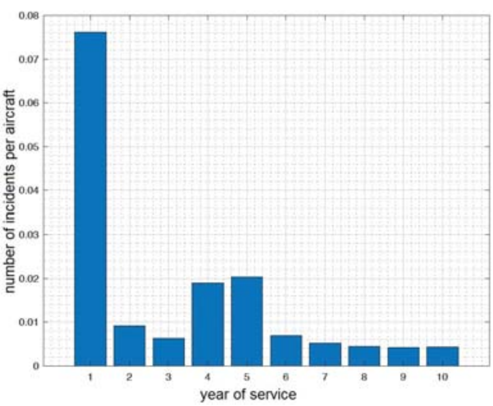

Fig. 5. Average number of incidents per type of aircraft in subsequent years of service

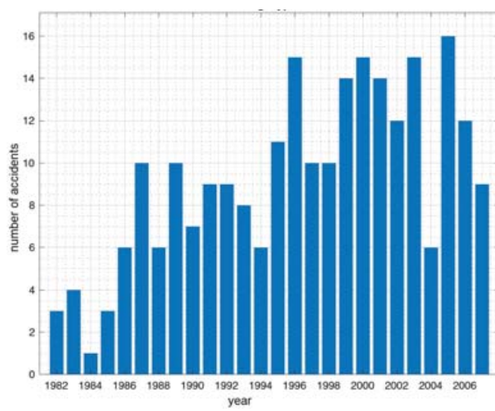

Fig. 6. Total accidents for aircraft types 737, 747, 757, 767, 777

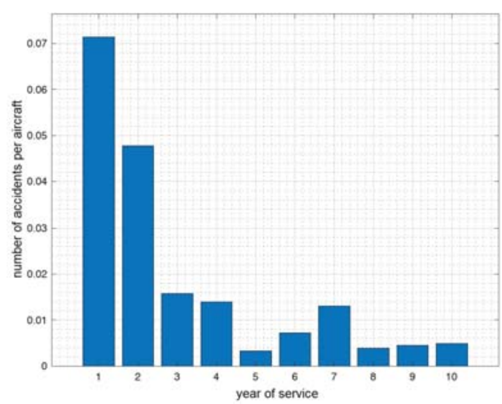

Fig. 7. Average number of accidents per type of aircraft in consecutive years of operation

of service for an aircraft of a given type. The probability of an accident in the first two years is on average more than seven times (7.16) higher than in the following eight years. In the following years, the calculated values are significantly lower and fluctuate within a small range.

5.6. *Probability of loss*

The highest number of incidents occurs during the first two years of aircraft operation. To illustrate the risks involved, the probability of loss by category was calculated.

The calculated values are shown in the table 2.

Table 2. Probability of loss in the first two years of service

Category of loss	Probability
u_0	0.042
u_1	0.085
u_2	0.051
u_3	0.026
r_0	0.127
r_1	0.009
r_2	0.042
r_3	0.026

The results from the table 2 are shown in the graph 8.

Most accidents and incidents result in no injuries to persons on board. The lowest probability

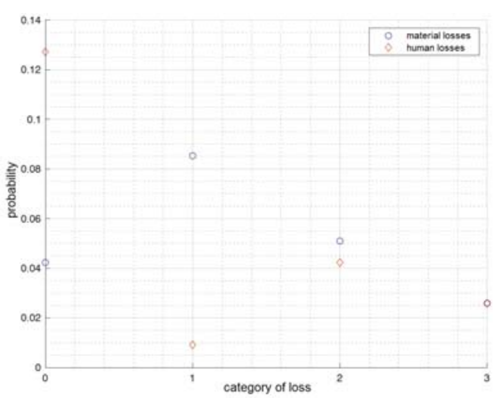

Fig. 8. Probability of loss in the first two years of service

is for minor injuries during an incident and accident. The highest probability level in the damage category is for minor damage. The lowest probability level occurs for damage resulting in the destruction of the aircraft.

The calculated probability values are relatively high, this is influenced by the calculation method or methodology, in which only aircraft in service in the first two years after introduction to the commercial sector are considered. The real probability of loss during regular aircraft travel is much lower.

6. Summary

The calculations show that the highest probability of adverse events, i.e. incidents and accidents, occurs within the first two years after the launch of a given aircraft model. The distribution of adverse events is analogous to the typical course of malfunctions of a technical object. In the calculations, no increase in the failure rate, characteristic during Phase III, was observed. One reason for this may be that the calculations were carried out for the first ten years after the launch, which may be a non-exhaustive period for the occurrence of Phase III.

The safest period is Phase II, which is dominant over time. During this period, the number of adverse events is relatively low. From the results obtained, it can be concluded that it occurs from the third year of operation. This is the time when most of the defects resulting from the design and operating procedures have been eliminated and the undesirable phenomena characteristic of Phase III are prevented by not allowing excessive wear and tear and continuous aircraft modernizations. In Phase II, crew training programmes are revised and improved over Phase I. This allows for a significant reduction in human error causing accidents and incidents.

Acknowledgement

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