Trends in Aviation Accidents: a time series analysis approach

AGRADECIMIENTOS

SUMMARY

The aviation industry plays a pivotal role in global transportation, facilitating connectivity and economic growth. As aviation continues to evolve, ensuring safety remains a paramount concern. Understanding accident trends and patterns is crucial for enhancing safety measures and regulatory frameworks within the industry. In this context, this study aims to analyze historical fatal and total accident within the United States civil aviation sector, specifically examining and differentiating regulations which involve commercial (air carriers) and general aviation.

The primary objectives of this study are to analyze the temporal trends in air accidents within the US, examining fluctuations in occurrence over time. Additionally, the study aims to assess the influence of parts various regulatory frameworks on accident rates across different sectors of the aviation industry. Furthermore, the research seeks to evaluate the evolution of aviation safety in the US by examining historical data on total and fatal accidents, with a focus on comparing trends across different regulatory domains. Special attention will be given to evaluating differences between total and fatal accident rates to determine not only if there has been a reduction in accident but also in the fatality of accidents over time. Ultimately, the study aims to draw conclusions regarding effective strategies for accident prevention and safety enhancement in US. Aviation, informed by a comprehensive analysis of regulatory impacts, historical trends, and safety performance metrics.

First, before starting the analysis procedure, a brief explanation is needed to understand the basic concepts of this study.

The Federal Aviation Administration (FAA) is the agency of the United States Department of Transportation responsible for the regulation and oversight of civil aviation within the U.S., as well as operation and development of the National Airspace System. Its primary mission is to ensure safety of civil aviation (FAA, Federal Aviation Administration, 2016).

On the other hand, the Code of Federal Regulations (CFR) is the codification of the general and permanent rules published in the Federal Register by the departments and agencies of the Federal Government. It is divided into 50 titles that represent broad areas subject to Federal regulation. The 50 subject matter titles contain one or more individual volumes, which are updated once each calendar year, on a staggered basis (GovInfo, 2023). Within these 50 titles, the one that will be refered to throughout this paper will be Title 14: Aeronautics and Space (14 CFR). This Title will be constituted by the Federal Aviation Regulations (FARs), which are rules prescribed by the Federal Aviation Administration (FAA) that govern all aviation activities in the United States. Moreover, it will be divided into Parts, which refers to a specific section of the CFR that address a particular area of aviation.

As a summary for clarification and continuation, the FAA publishes the Title 14 of the Code of Federal Regulations (14 CFR) to make readily available to the aviation community the regulatory requirements placed upon them. These regulations are sold as individual parts which will be constituted by FARs (FAA, Code of Federal Regulations and Advisory Circulars, 2024).

The two main blocks that will be addressed and differentiated in this project are commercial aviation and general aviation. Thus, referring to the distribution in different parts of the 14 CFR, the former will correspond to part 91 while the latter will be divided into parts 121 and 135, the characteristics of which will be detailed below.

After this introductory part, in the first phase of the project, the data collection was carried out. The National Transportation Safety Board (NTSB) has been used as the main source for this data. The NTSB is an independent Federal agency charged by Congress with investigating every civil aviation accident in the United States and significant accidents in the other modes of transportation. It investigates aviation accidents, records the findings, and maintains a publicly available accident database. For the case of this project, the number of total and fatal accidents per CFR Part, as well as their flight hours will be needed to extract the indicators and reach the conclusions aimed.

Note that, according to 49 CFR 830.2 – Definitions, an aircraft accident means an occurrence associated with the operation of an aircraft which takes place between the time any person boards the aircraft with the intention of flight and all such persons have disembarked, and in which any person suffers death or serious injury, or in which the aircraft receives substantial damage. On the other hand, a fatal injury means any injury which results in death within 30 days of the accident and, therefore, a fatal accident is the one in which there have been one or more fatal injuries (Cornell Law School, 2022).

Once data is collected, the rates of total and fatal accidents in commercial (Part 121 and 135) and general aviation (Part 91) are estimated against their corresponding aircrafts flight hours. By this way, the indicators in question would be defined: total and fatal accidents per 100,000 flight hours. Therefore, six datasets are created, consisting of total and fatal accidents rates for both general and commercial aviation since 1990. The main objective of this analysis is to obtain a stochastic model that adequately assigns the contributions and variabilities for the accident rates. In order to carry out the study, two possible approaches are differentiated, the Frequentist and the Bayesian, which differ in their first phase by the way in which the accidents rates are estimated.

In the Frequency approach, the rates are estimated in a simple way by the maximum likelihood method, while in the Bayesian approach, a Hierarchical Bayes smoothing is implemented in order to increase the quality of the rates and thus increase the reliability of the model results.

This second approach is adopted as more appropriate, so it is developed in greater depth and its rates are used to perform the subsequent dynamic factor analysis. The code implemented in the Rstudio tool is also included. After obtaining the smoothed data for both series, visual information of interest for the analysis is provided, such as the time evolution of the smoothed rates or the comparison between the rates obtained with the classical approach and with the Bayesian approach.

Finally, using the rates obtained through the Bayesian method, the dynamic factorial model is carried out. This model is implemented by reducing the dimension of the series vector, obtaining a series of unobserved common factors that allow us to interpret the behaviour of the accident rates considering temporal evolution. The document shows the calculation procedure using Rstudio and the results obtained for both series, including graphs for each factor with the weights per CFR Part.

As conclusion, it is obtained that…

Overall, this study contributes to the broader discourse on aviation safety by providing empirical insights into accident trends within the United States civil aviation sector. Through rigorous analysis and modelling techniques, we aim to enhance understanding and promote continuous improvement in safety standards and practices.

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# INTRODUCTION

## JUSTIFICATION

The rationale behind this thesis lies in the paramount importance of aviation safety and the ongoing need for comprehensive analysis and improvement strategies within the industry. Aviation safety is not only a critical concern for the well-being of passengers and crew but also a significant factor in the sustainability and growth of the aviation sector as a whole. Therefore, it is imperative to delve into the factors influencing accident rates, particularly in the context of general aviation versus commercial aviation, as well as their correlation with regulatory measures and flight hours.

By undertaking this research, we aim to provide valuable insights into the patterns, trends, and potential causative factors affecting aviation accidents. Understanding these dynamics is essential for policymakers, regulatory bodies, aviation stakeholders, and safety professionals to formulate effective strategies and interventions aimed at reducing accident rates and enhancing overall safety performance.

This thesis seeks to contribute to the existing body of knowledge by conducting a rigorous analysis of accident data and exploring innovative methodologies, such as Bayesian methods and dynamic factorial models, to gain deeper insights into the underlying dynamics of aviation safety. By employing such advanced analytical techniques, we aim to uncover nuanced relationships and trends that may not be immediately apparent through traditional approaches.

Ultimately, the findings and recommendations generated through this research endeavor have the potential to inform evidence-based decision-making processes, shape regulatory frameworks, and drive continuous improvement initiatives within the aviation industry. By enhancing our understanding of aviation safety dynamics and identifying areas for targeted intervention, we can strive towards achieving the overarching goal of a safer and more resilient aviation system for all stakeholders involved.

## BACKGROUND

Drawing upon trends identified in civil aviation incidents (Peng He and Ruishan Sun, 2023) and general aviation (Kamala I. Shetty and R. John Hansman, 2012), as well as the state-based modeling approach proposed for general aviation accidents (Arjun H.Rao and Karen Marais, 2020), offers a nuanced perspective on the dynamics influencing safety outcomes. Additionally, insights into human factors (Alan Hobbs, 2009) and statistical analysis of commercial aviation accidents (AIRBUS, 2023) provide valuable context regarding the underlying factors contributing to aviation safety incidents.

Examining the findings of these articles more closely, He and Sun's analysis of civil aviation incidents highlights the importance of employing both causal and statistical inference techniques to identify underlying patterns and causal relationships. This approach is particularly relevant to the current research as it provides a methodological framework for analyzing the relationship between accident rates, flight hours, and regulatory measures. Similarly, Shetty and Hansman's exploration of general aviation trends in the United States offers insights into the historical evolution and unique challenges of the sector. By comparing these trends with those observed in commercial aviation, researchers can identify potential areas for targeted intervention and regulatory improvement. Furthermore, Rao and Marais' state-based modeling approach provides a structured framework for analyzing general aviation accidents, facilitating the identification of recurrent patterns and contributing factors. Integrating this methodology into the current research enables a more nuanced understanding of the underlying dynamics influencing general aviation safety outcomes.

Hobbs' examination of human factors in aviation safety underscores the critical role of human behavior and decision-making processes in accident prevention. Understanding these factors is essential for developing targeted interventions aimed at mitigating human-related vulnerabilities and enhancing safety culture within the industry. Additionally, Airbus' statistical analysis of commercial aviation accidents offers insights into the trends and patterns observed within the sector, providing valuable context for identifying common risk factors and regulatory gaps across the aviation industry.

By synthesizing the insights from these articles, the background section of the thesis provides a robust foundation for the current research. It not only offers a comprehensive overview of aviation safety dynamics but also identifies gaps and opportunities for further investigation. Ultimately, this synthesis serves to inform the research objectives, methodology selection, and data analysis strategies, thereby advancing knowledge and contributing to the enhancement of aviation safety practices.

## RESEARCH MOTIVATION

In the realm of aviation, safety stands as an indispensable cornerstone, shaping the trajectory of the industry and underpinning public trust in air travel. Within the intricate fabric of civil aviation, understanding the nuances of safety trends and regulatory frameworks is paramount to fostering a culture of continuous improvement and resilience.

Against this backdrop, this master’s Thesis embarks on a journey to delve into the depths of the U.S. civil aviation landscape, unraveling the threads that weave together the tapestry of safety outcomes. Through a meticulous examination of historical accident data provided by authoritative sources such as the Federal Aviation Administration (FAA) and the NTSB, this study attempts to shed light on the evolution of safety performance over time.

Beyond mere observation, this research endeavor sets its sights on comparative analysis, traversing the diverse terrain of civil aviation sectors. From the sprawling expanses of general aviation to the structured pathways of air carriers operating under Part 121 and Part 135 regulations, this study seeks to discern patterns, disparities, and opportunities for improvement in safety practices and regulatory oversight in each of them.

Moreover, this thesis aspires to scrutinize the efficacy of existing safety measures and regulatory frameworks, probing beneath the surface to evaluate their impact on safety outcomes. Armed with insights gleaned from rigorous analysis, this research aims to chart a course towards enhancing air safety practices, offering evidence-based recommendations poised to fortify the foundations of the aviation industry.

# PREVIOUS TECHNICAL KNOWLEDGE

Firstly, an explanation of the problem and the technical aspects involved will be provided to facilitate the subsequent comprehension of the procedures.

When it comes to which distinction must be made between the part under which an operation falls and the aircraft it uses, we need to take the following into account. A charter company, for example, may be able to fly their turbo-propeller aircraft under Part 91 for a repositioning flight with no passengers, allowing fewer restrictions on that specific flight. Then, when an aspect of Part 135 or Part 121 is met (such as a paying passenger onboard), their operations specifications for the corresponding part is enforced.

Now, the most relevant characteristics of each part of the regulations that will be studied in this project will be explained.

## GENERAL AVIATION

The term general aviation is a catch-all phrase for all aviation activities that does not fall under commercial aviation, major cargo or military operations, and covers a broad spectrum of airborne activities outside the realm of commercial airlines, serving as a vital component of the nation’s aviation ecosystem and. It is regulated under 14 CFR part 91.

In fact, Part 91 concerns the general rules under which *all* aircraft operate unless trumped by more restrictive laws that apply to their respective operation. For example, all part 91 restrictions apply to a part 121 or 135 operator, but the more restrictive part 121 and 135 rules trump their part 91 counterparts.

Part 91 effectively prohibits compensation for air transportation by only allowing it in a minimal set of circumstances, even then limiting the amount paid. This constraint upholds the safety standards of air travel by ensuring that paying passengers are only flying on more restrictive (and in effect, safer) part 121 and part 135 operators. This sector encompasses private flights, flight instruction, aerial surveying, agricultural spraying, and emergency medical transport.

From an operational standpoint, these GA activities can be categorized as either local or itinerant operations, whereas commercial aviation is almost exclusively itinerant. Operations are defined as either an arrival or departure of local or itinerant nature. Local operations, are defined as operations performed by aircrafts that are operating within the local traffic pattern of the airport or within sight of the airport, are going to designated local practice areas within 20 miles of the airport or are performing simulated instrument approaches or low passes at the airport. For instance, many operations that fall within the personal or instructional use category are categorized as local. Itinerant operations are defined as the compliment of local operations, i.e. aircraft coming from or going to a different airport. Most business or corporate transportation uses would call under itinerant operations.

Regarding aircraft type, it encompasses a wide array of them, ranging from single-engine piston airplanes and light sport aircraft to turboprops and small business jets. These aircrafts typically seat fewer passengers and are utilized for diverse purposes, including personal and recreational flying, flight training, aerial photography, and business travel. Aircrafts are often characterized by their versatility, affordability, and accessibility. They are frequently employed for short to medium-distance flights, offering individuals and businesses the flexibility to travel to locations not served by commercial airlines.

While general aviation is subject to regulatory oversight by the FAA, the safety regulations governing these operations are typically less stringent than those imposed on commercial carriers. Pilots are required to adhere to basic licensing and medical certification requirements, undergo recurrent training, and comply with aircraft maintenance standards outlined by the FAA. Moreover, they have no legally required rest periods, meaning they can fly their aircraft for days on end without ever taking a break.

Part 91 is also more relaxed when it comes to security. Passenger identification is not required for domestic flights under part 91.

## COMMERCIAL AVIATION (AIR CARRIERS)

Commercial aviation activities in the US are easily defined as all operations that are regulated by part 121 and part 135 of the Federal Aviation Regulations put forth by the FAA, which encompasses all scheduled and non-scheduled air carrier service. Air carriers are commercial airline companies that provide passenger and/or cargo air transportation services for compensation. Part 121 and part 135 are the two operation specifications that an air carrier can choose from when deciding how they will conduct their business. Air carriers are subject to stringent regulations concerning safety, maintenance, operation, and certification as they transport passengers and cargo commercially.

The most noticeable difference between both parts is regarding restrictions. Part 121 is the most restrictive of the three parts and is considered the highest commercial air travel safety standard., therefore it has much more rigid rules and regulations than Part 135 and, thus, Part 91. For example, the requirement for two pilots on a part 121 operation vs. the allowance for one pilot on a part 135 operation. The Pilot in Command (PIC) on a part 121 operation also shares operational control with a flight dispatcher. In contrast, the PIC on a part 135 operation can assume complete operational control of the flight.

However as both parts are included under commercial aviation they have some similarities. Under parts 121 and 135, there are mandated crew rest periods and maximum duty times (per day and month), pilots must adhere to strict rest schedules to ensure that they are not fatigued during their operations.

Another similarity is regarding weather minimums. A part 121 or 135 crew cannot legally initiate an approach if the weather is below minimums. Under part 91, however, they are free to do so. These weather minimums are also applied for takeoff. Moreover, for part 121 or 135 operations, passenger identities need to be verified by the operator, and passengers who are at least 18 years old will be required to provide photo identification.

In addition to those rules, there are minimum experience requirements. To be the Pilot-in-Command (PIC) of a Part 121 or 135 flight, you must possess an ATP (Airline Transport Pilot) certificate. To be Second-in-Command, you must possess at least a Restricted ATP. Parts 121 and 135 require that the operator designate a chief pilot in charge of flight operations. That person must meet experience requirements to be eligible. Larger operators might also have assistant chiefs or check airmen. Pilots in these positions must pass an FAA check ride.

### U.S. AIR CARRIERS PART 121

Part 121 operations represent major commercial airlines engaged primarily in scheduled passenger and cargo transportation. However, though less common, there can also exist non-scheduled commercial flights in specific occasions. Aircraft types are synonymous with large, scheduled commercial airlines operating a diverse fleet of aircraft, including narrow-body and wide-body jets. The FAA’s definition of PART 121 operations is at least “5 round trips per week on at least one route between two or more points according to the published flight schedule.”

They transport passengers and cargo on mostly scheduled routes across domestic and international destinations and are characterized by their scale, professionalism, and adherence to rigorous safety and operational standards. Airlines operate under the strictest regulatory oversight, employing highly trained flight crews, maintenance personnel, and support staff to ensure the safety and efficiency of their operations. These operations are governed by comprehensive safety protocols outlined by the FAA, including pre-flight inspections, standardized operating procedures, and emergency response protocols to mitigate risks and ensure the safety of passengers and crew. Safety regulations expand to aircraft certification, maintenance programs, crew training, operational procedures, and emergency preparedness. These carriers undergo regular inspections and audits to verify compliance with regulatory requirements and industry best practices.

### U.S. AIR CARRIERS PART 135

Part 135 operations encompass a diverse fleet of aircraft, including small jets, turboprops, and helicopters. These aircraft are utilized for on-demand charter flights, air taxi services, aerial tours, medical transport, and other non-scheduled air transport operations. Small private charter companies will typically opt for a Part 135 license as it is less expensive and time-consuming to obtain.

Part 135 only applies to aircraft with 9 or fewer seats (since 20 Mar 1997) or a maximum payload capacity of 7,500 pounds, including commercial helicopter operations (other than external loading (i.e., a helicopter sling), which is covered by part 133).

Operators offer flexible and personalized air travel solutions tailored to the needs of individual passengers and businesses. These operators cater to a wide range of clientele, from corporate executives and leisure travelers to medical patients requiring urgent transport. These operations are characterized by their flexibility and responsiveness to customer demands. Operators conduct on-demand charter flights, responding to client requests for point-to-point transportation, aerial sightseeing tours, and specialized air services. These operations require meticulous planning, coordination, and adherence to safety protocols to ensure the safety and satisfaction of passengers. Part 135 operators are also subject to safety regulations established by the FAA, tailored to the specific requirements of on-demand air transport operations. These regulations encompass aircraft maintenance, pilot training and qualification, operational procedures, and safety management systems. They also undergo regular inspections and audits to validate compliance with regulatory standards and industry best practices.

Part 135 operations conduct charter flights and other non-scheduled air transport services. They can be differentiated into:

* Commuter Operations: These operations typically involve regular flights between two or more points, often between nearby or regional cities. Passenger flights are conducted on a scheduled and regular basis, similar to the operations of a commercial airline, but on a smaller scale.
* On-Demand Operations: These operations are more flexible and designed to meet specific customer needs. Flights are conducted on-demand, without a fixed schedule, and may include charter flights, air taxi services, sightseeing flights, medical evacuations, among other unscheduled air services.

The main distinction from "Commuter Operations" is the flexibility and adaptability of flights according to the needs and preferences of the customers.

The differences between the operation types within Part 135 have been explained as an expansion of knowledge; however, they will be treated as a whole within Part 135 from now on.

### What are OPS SPECS?

One fundamental difference between part 91 and part 121 or 135 operators is the requirement of operations specifications (commonly referred to as “ops specs”) for part 121 and part 135 operators. It is a document that an operator puts together when applying for their Part 121 or 135 certificate. Ops specs are essentially an FAA-approved framework for how an air carrier will operate. They can be more restrictive than the laws detailed in parts 121 and 135, but never less. The Ops Specs are what allows companies to deviate from certain CFRs

It lays out which aircraft can be used and which airports they can fly out of, who the chief pilots is (and other key staff positions), what types of IFR approaches the pilots can use, and what other procedures and checklists the airline will use.

The FAA goes through the Ops Specs document and approves each item. The operator cannot deviate from their approved Ops Specs without getting new approval.

Where a Part 91 operator could purchase a new airplane, hire a new pilot, or land at a new airport, a Part 121 or 135 operator must add these to their Ops Specs and get the changes approved.

How an airline is allowed to operate in their ops specs are determined by an FAA Principal Operations Inspector (POI). The POI is the head of a division within the FAA tasked with determining how an air carrier is allowed to operate. It is assigned to each certificate holder by the FAA to help each operator with all the details and approvals.

Ops specs detail essentially every aspect of an airline’s operation, from the approval of Electronic Flight Bags (EFBs) to what airports an airline is allowed to use. Some airports, for example, can be used for refueling or diversions, but not for regular use. Another example would be the ability to use CAT II Instrument Landing System (ILS) approaches, allowing less visibility during landing than CAT I ILS approaches.

How much freedom an air carrier receives is determined by many different factors. If the POI feels that the air carrier is inexperienced or has a poor safety record, they may restrict certain aspects of their operation to improve safety. Conversely, if the POI feels that the air carrier demonstrates good safety standards, they may allow for more operational capability.

Two air carriers operating the same aircraft may have vastly different operational capabilities according to their respective ops specs. One air carrier may have better-trained pilots and upgraded equipment, allowing them to perform procedures that another air carrier will not be able to, for example.

# DATA PRESENTATION

The data sample used for the study is going to be presented. Then, the following phases for the analysis of the time series of the indicators and the modeling of the trends in accident rates will be elucidated.

The Table 3.1 provides a detailed breakdown of total and fatal accidents occurring in both general and commercial aviation (Part 121 and 135). This data offers a quantitative perspective on the safety performance of these aviation sectors, allowing for comparative analysis and identification of key trends. By examining these figures, we can gain valuable insights into the overall safety landscape of general aviation and air carrier operations.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | General Aviation | | U.S. Air Carriers Part 121 | | U.S. Air Carriers Part 135 | |
|  | Total | Fatal | Total | Fatal | Total | Fatal |
| 1990 | 2,242 | 444 | 24 | 6 | 122 | 32 |
| 1991 | 2,197 | 439 | 26 | 4 | 111 | 36 |
| 1992 | 2,110 | 450 | 18 | 4 | 99 | 31 |
| 1993 | 2,064 | 401 | 23 | 1 | 85 | 23 |
| 1994 | 2,021 | 404 | 23 | 4 | 95 | 29 |
| 1995 | 2,056 | 412 | 36 | 3 | 87 | 26 |
| 1996 | 1,908 | 361 | 37 | 5 | 101 | 30 |
| 1997 | 1,840 | 350 | 49 | 4 | 98 | 20 |
| 1998 | 1,902 | 364 | 50 | 1 | 85 | 17 |
| 1999 | 1,905 | 340 | 51 | 2 | 87 | 17 |
| 2000 | 1,837 | 345 | 56 | 3 | 92 | 23 |
| 2001 | 1,728 | 326 | 46 | 6 | 79 | 20 |
| 2002 | 1,716 | 345 | 41 | 0 | 67 | 18 |
| 2003 | 1,741 | 352 | 54 | 2 | 75 | 19 |
| 2004 | 1,619 | 314 | 30 | 2 | 70 | 23 |
| 2005 | 1,671 | 321 | 40 | 3 | 71 | 11 |
| 2006 | 1,523 | 308 | 33 | 2 | 55 | 11 |
| 2007 | 1,654 | 288 | 28 | 1 | 64 | 14 |
| 2008 | 1,569 | 277 | 27 | 2 | 65 | 20 |
| 2009 | 1,481 | 276 | 30 | 2 | 49 | 2 |
| 2010 | 1,441 | 271 | 30 | 1 | 36 | 6 |
| 2011 | 1,471 | 270 | 33 | 0 | 54 | 16 |
| 2012 | 1,471 | 273 | 27 | 0 | 42 | 8 |
| 2013 | 1,223 | 221 | 22 | 2 | 51 | 12 |
| 2014 | 1,222 | 255 | 31 | 0 | 38 | 8 |
| 2015 | 1,211 | 230 | 28 | 0 | 43 | 8 |
| 2016 | 1,269 | 213 | 30 | 0 | 38 | 9 |
| 2017 | 1,234 | 203 | 33 | 0 | 50 | 8 |
| 2018 | 1,275 | 224 | 31 | 1 | 42 | 7 |
| 2019 | 1,221 | 235 | 40 | 2 | 42 | 13 |
| 2020 | 1,086 | 205 | 14 | 0 | 44 | 7 |
| 2021 | 1,157 | 210 | 24 | 0 | 43 | 9 |
| 2022(d) | 1,205 | 214 | 20 | 1 | 52 | 5 |

Table 3.1: Number of total and fatal accidents per aviation part

Some notes should be mentioned about these data. As mentioned above, General Aviation encompasses U.S. registered civil aircraft not operated under 14 CFR 121 or 14 CFR 135 and accidents on foreign soil and in foreign waters are excluded. Moreover, suicide, sabotage, and stolen/unauthorized cases included in accidents, fatalities and rate computation in this table are: 1985 (11 accidents, 6 fatal accidents); 1990 (4, 1); 1991 (8, 5); 1992 (2, 1); 1993 (5, 4); 1994 (3, 2); 1995 (10, 6); 1996 (4, 0); 1997 (5, 2); 1998 (6, 4); 1999 (3, 1); 2000 (7, 7); 2001 (3, 1); 2002 (7, 6); 2003 (4, 3); 2004 (3, 0); 2005 (2, 1); 2006 (2, 1); 2007 (2, 2); 2008 (2, 0); 2009 (3, 0); 2010 (3, 2); 2011 (1, 0); 2012 (1, 1); 2013(3, 3); 2014(0, 0); 2015(7, 4); 2016 (2, 2); 2017(U); 2018(U); 2019(U); 2020(U) (National Transportation Safety Board(a), 2022) (National Transportation Safety Board(d), Apr. 2011, Jul. 2012, Aug. 2013, Sept. 25, 2014, April 2, 2015, Mar. 22, 2016, Sept. 26, 2016, Apr. 20, 2018, Aug. 8, 2019, Nov. 25, 2019, Oct. 28, 2020,).

Since April 1995, the National Transportation Safety Board has been required by law to investigate all public-use accidents, increasing the number of NTSB reported general aviation accidents by approximately 1.75%. In view of obtaining results, those first 5 years could be slightly altered and should be considered.

On the other hand, there are presented the Air carriers, operating under 14 CFR 121, scheduled and nonscheduled service. Data includes all scheduled and nonscheduled service accidents involving all-cargo carriers and commercial operators of large aircraft when those accidents occurred during 14 CFR 121 operations. It is important to mention that since Mar. 20, 1997, 14 CFR 121 includes aircraft with 10 or more seats formerly operated under 14 CFR 135. This change makes it difficult to compare pre-1997 accident data for 14 CFR 121 and 14 CFR 135 with more recent data. However, it does not affect accident rates due to the way they are computed so the regression will not be disturbed.

Illegal acts, such as suicide, sabotage, and terrorism, are included in the totals for accidents, fatalities, and rate computation. 1991 data do not include the 12 persons killed aboard a SkyWest commuter aircraft when it and a U.S. Air aircraft collided. For 2001, fatalities resulting from the September 11 terrorist acts are excluded, other than the persons aboard the aircraft who were killed (National Transportation Safety Board(c), 2022) (National Transportation Safety Board(d), Apr. 2011, Jul. 2012, Aug. 2013, Sept. 25, 2014, April 2, 2015, Mar. 22, 2016, Sept. 26, 2016, Apr. 20, 2018, Aug. 8, 2019, Nov. 25, 2019, Oct. 28, 2020,).

Eventually, Air carriers operating under 14 CFR 135, scheduled and non-scheduled service, includes accidents involving all-cargo air carriers when those accidents occurred during scheduled 14 CFR 135 operations. Before Mar. 20, 1997, 14 CFR 135 applied to aircraft with 30 or fewer seats but, as mentioned before, since Mar. 20, 1997, 14 CFR 135 includes only aircraft with fewer than 10 seats. Accidents on foreign soil and in foreign waters are excluded from on-demand operations count. Total fatalities for 1991 on U.S. air carriers operating under 14 CFR 135, scheduled service do not include the 22 persons killed aboard a large-certificated aircraft when it collided with a commuter aircraft. An attempted suicide case in 1992 is included in accidents but excluded in accident rates in this table. Rates are based on all accidents, including some that involve operators not reporting mileage or other traffic data to the U.S. Department of Transportation. Illegal acts, such as suicide, sabotage and terrorism, are included in the totals for accidents, fatalities, and rate computation. (National Transportation Safety Board(c), 2022) (National Transportation Safety Board(d), Apr. 2011, Jul. 2012, Aug. 2013, Sept. 25, 2014, April 2, 2015, Mar. 22, 2016, Sept. 26, 2016, Apr. 20, 2018, Aug. 8, 2019, Nov. 25, 2019, Oct. 28, 2020,).

The Table 3.2 shows the amount of flight hours (in thousands) per FAR Part. Note that Flight hours are compiled by the U.S. Department of Transportation (NTSB) and estimated by the Federal Aviation Administration (FAA) (National Transportation Safety Board(c), 2022) (National Transportation Safety Board(d), Apr. 2011, Jul. 2012, Aug. 2013, Sept. 25, 2014, April 2, 2015, Mar. 22, 2016, Sept. 26, 2016, Apr. 20, 2018, Aug. 8, 2019, Nov. 25, 2019, Oct. 28, 2020,), according to 14 CFR 61.51 Pilot Logbooks definitions (FAA, Code of Federal Regulations, 2018). Moreover, 2011 estimates are not currently available regarding General and Part 135 aviation, Federal Aviation Administration is engaged in re-calibration efforts.

|  |  |  |  |
| --- | --- | --- | --- |
|  | **General Aviation** | U.S. Air Carriers Part 121 | U.S. Air Carriers Part 135 |
| 1990 | 28.510 | 12.150 | 4.591 |
| 1991 | 27.678 | 11.781 | 4.533 |
| 1992 | 24.780 | 12.360 | 5.179 |
| 1993 | 22.796 | 12.706 | 4.962 |
| 1994 | 22.235 | 13.124 | 5.249 |
| 1995 | 24.906 | 13.505 | 5.114 |
| 1996 | 24.881 | 13.746 | 5.977 |
| 1997 | 25.600 | 15.838 | 4.081 |
| 1998 | 25.517 | 16.817 | 4.156 |
| 1999 | 29.246 | 17.555 | 3.547 |
| 2000 | 27.838 | 18.299 | 4.300 |
| 2001 | 25.430 | 17.814 | 3.297 |
| 2002 | 25.545 | 17.290 | 3.185 |
| 2003 | 25.997 | 17.468 | 3.246 |
| 2004 | 24.888 | 18.883 | 3.540 |
| 2005 | 23.168 | 19.390 | 4.114 |
| 2006 | 23.963 | 19.263 | 4.044 |
| 2007 | 23.819 | 19.637 | 4.325 |
| 2008 | 22.805 | 19.127 | 3.502 |
| 2009 | 20.862 | 17.627 | 3.210 |
| 2010 | 21.688 | 17.751 | 3.428 |
| 2011 | - | 17.963 | - |
| 2012 | 20.881 | 17.722 | 3.844 |
| 2013 | 19.492 | 17.780 | 3.710 |
| 2014 | 19.617 | 17.743 | 3.989 |
| 2015 | 20.576 | 17.926 | 3.926 |
| 2016 | 21.334 | 18.294 | 3.876 |
| 2017 | 21.703 | 18.581 | 3.902 |
| 2018 | 21.663 | 19.288 | 4.264 |
| 2019 | 21.801 | 19.764 | 4.228 |
| 2020 | 19.454 | 11.951 | 3.349 |
| 2021 | 21.966 | 15.932 | 4.876 |
| 2022(d) | 22.543 | 17.872 | 4.836 |

Table 3.2: Number of flight hours (thousands)

Finally, in the Table 3.3 shows the total and fatal accident rates calculated per 100,000 flight hours. Rates are computed by dividing the number of total and fatal accidents by the number of flight hours, except for the particularities for each part mentioned above. Note that, as long as in 2011 there were not data available, rates are not able to be computed.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | General Aviation | | U.S. Air Carriers Part 121 | | U.S. Air Carriers Part 135 | |
|  | Total | Fatal | Total | Fatal | Total | Fatal |
| 1990 | 7.86 | 1.56 | 0.198 | 0.049 | 2.658 | 0.697 |
| 1991 | 7.94 | 1.59 | 0.221 | 0.034 | 2.449 | 0.794 |
| 1992 | 8.51 | 1.82 | 0.146 | 0.032 | 1.911 | 0.599 |
| 1993 | 9.05 | 1.76 | 0.181 | 0.007 | 1.713 | 0.463 |
| 1994 | 9.09 | 1.82 | 0.175 | 0.030 | 1.810 | 0.552 |
| 1995 | 8.26 | 1.65 | 0.267 | 0.022 | 1.701 | 0.508 |
| 1996 | 7.67 | 1.45 | 0.269 | 0.036 | 1.690 | 0.502 |
| 1997 | 7.19 | 1.37 | 0.309 | 0.025 | 2.402 | 0.490 |
| 1998 | 7.43 | 1.41 | 0.297 | 0.006 | 2.045 | 0.409 |
| 1999 | 6.50 | 1.16 | 0.291 | 0.011 | 2.453 | 0.479 |
| 2000 | 6.57 | 1.21 | 0.306 | 0.016 | 2.140 | 0.535 |
| 2001 | 6.78 | 1.27 | 0.258 | 0.034 | 2.396 | 0.607 |
| 2002 | 6.69 | 1.33 | 0.237 | 0.000 | 2.104 | 0.565 |
| 2003 | 6.68 | 1.34 | 0.309 | 0.011 | 2.310 | 0.585 |
| 2004 | 6.49 | 1.26 | 0.159 | 0.011 | 1.977 | 0.650 |
| 2005 | 7.20 | 1.38 | 0.206 | 0.015 | 1.726 | 0.267 |
| 2006 | 6.35 | 1.28 | 0.171 | 0.010 | 1.360 | 0.272 |
| 2007 | 6.94 | 1.20 | 0.143 | 0.005 | 1.480 | 0.324 |
| 2008 | 6.87 | 1.21 | 0.141 | 0.010 | 1.856 | 0.571 |
| 2009 | 7.08 | 1.32 | 0.170 | 0.011 | 1.526 | 0.062 |
| 2010 | 6.63 | 1.24 | 0.169 | 0.006 | 1.050 | 0.175 |
| 2011 | - | - | 0.184 | 0.000 | - | - |
| 2012 | 7.04 | 1.30 | 0.152 | 0.000 | 1.093 | 0.208 |
| 2013 | 6.26 | 1.12 | 0.124 | 0.011 | 1.375 | 0.323 |
| 2014 | 6.23 | 1.30 | 0.175 | 0.000 | 0.953 | 0.201 |
| 2015 | 5.85 | 1.10 | 0.156 | 0.000 | 1.095 | 0.204 |
| 2016 | 5.93 | 0.98 | 0.164 | 0.000 | 0.980 | 0.232 |
| 2017 | 5.68 | 0.94 | 0.178 | 0.000 | 1.282 | 0.205 |
| 2018 | 5.87 | 1.02 | 0.161 | 0.005 | 0.985 | 0.164 |
| 2019 | 5.59 | 1.07 | 0.202 | 0.010 | 0.993 | 0.307 |
| 2020 | 5.58 | 1.04 | 0.117 | 0.000 | 1.314 | 0.209 |
| 2021 | 5.24 | 0.96 | 0.151 | 0.000 | 0.882 | 0.185 |
| 2022 | 5.34 | 0.94 | 0.112 | 0.006 | 1.075 | 0.103 |

Table 3.3: Total and fatal accident rates per 100,000 flight hours

The objective is to estimate trends for the accident rates of the exposed FAR Parts over the period of time considered and to compare the specific ratios of total and fatal accidents with the common trend of each Part considered.

It is considered that the probability of there being an accident in a sufficiently small-time interval is proportional to the length of this interval and the probability of accidents in non-overlapping independent time intervals.

# TRENDS ANALYSIS

In the following, the multivariate approach for the analysis of indicator time series will be explained. First, estimates of accidents rates will be made following both the Frequentist and Bayesian approaches, obtaining with the latter a smoothing rate more suitable for further modelling. Then, since multivariate analysis is computationally very expensive, dimension reduction methods will be carried out to fit models in a more parsimonious way and without loss of information. This will be done by obtaining factors common to all plants and combining them with the factors specific to each plant. These common factors will be used to identify the plants with behavior that differs from the common behavior of the series of plants, with the aim of being able to fix them more closely.

## METHODOLOGY

The aim of the work is to find a stochastic model through which the trend and variability contributions for this Accidents rate are appropriately assigned to the data generating process.

On this basis, the simplest model to describe the variability of an indicator in a specific plant is the homogeneous Poisson process, which implies absence of trend, constant variability over time and stochastic independence of the behavior of non-overlapping time intervals.

But there is a more suitable model for modelling trends, in this case time-varying occurrence rates, which is the non-homogeneous Poisson process (NHPP), which maintains the independence hypothesis for non-overlapping intervals.

It should be noted that Poisson processes generally have the restriction that the trend and variability depend on the same parameter (they are linked by a linkage relationship), which implies some rigidity, but on the other hand, they have the advantage of being able to operate with a reduced number of parameters in the model, in accordance with the statistical principle of parsimony. The latter property is interesting given the small sample sizes for the plants despite the fact that they have been increased in several years.

Therefore, in order to carry out the trend analysis that allows us to estimate the accidents rates of nuclear power plants, from the methodological point of view, two approaches can be applied: the Frequency-based (1) or the Bayesian (2) approach.

1. MV estimation of the rates + Factor Analysis

2. Rate estimation by HB + Factor Analysis

The difference between the two is that the Frequentist approach is formulated through a parametric model using maximum likelihood estimators (MLE), while the Bayesian approach calculates the occurrence rates prior to factor analysis by means of Hierarchical Bayes (HB) smoothing. This smoothing generally results in a higher explained variability for the model and thus a more reliable interpretation.

After reviewing both models, the methodology developed by H. Martz (LosAlamos Laboratory), R. Parker (Intel Corporation) and D. Rasmuson (NRC) (1999), based on the second approach of Bayesian models for Posisson processes in the estimation of occurrence rates and dynamic factor analysis for their temporal evolution and study of trends, will be adopted as the most appropriate.

Therefore, starting from this premise, both approaches will be explained, although in greater detail for the Bayesian approach.

Prior to the explanations, the variables with which we are going to work are presented, which, although some of them have already been seen previously, it is important to clarify their notation:

- Nuclear Power Plants: N (1, ..., i)

- Years: M (1, ..., j)

- Number of events (Accidents): Xij

- Operating Times: Tij

- Trend of the occurrence rate of accidents in each plant: λij

- Trend of the rate of occurrence of accidents in the population: λj

## 4.2. FREQUENTIST APPROACH

For this approach, the random variable x will be taken as the number of years of the study described by a function f(x). On the other hand, the centers will be a set of n independent observations on x. Thus, it is possible to define a new sample space consisting of all possible values of the vector x = (x1, ..., xn). That is, the sample will be considered to consist of a single random mean, which will be characterized by the quantities (x1, ..., xn). In this way the n means will be independent, but the function is the same for each measure.

After this brief introduction and making use of the data collected in section 3 on hours and stops, we proceed to show the results of the accidents rates per 1000 critical hours by maximum likelihood.

TABLA

GRAFICA

TABLA

GRAFICA

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