Analysis of Impact of Aircraft Age on Safety for Air Transport Jet Airplanes

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October 2014

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Executive Summary

A historical analysis was conducted of aircraft accidents occurring between 1959 and 2012 for commercial jet transport aircraft with a MTOW greater that 60,000 lbs where aircraft age and operational histories were available. The analysis indicates that there is no correlation between the fatal accident rates and aircraft age up to 27 years of age. Above this age there was a slight increase in the fatal accident rate but the accident rate data is not statistically significant due to the limited number of operational years for these older aircraft cohorts. When all accidents are considered there is no correlation between accident rates and age up till 18 years and a weak trend of increased accident rate with age is observed for aircraft older than 20 years. This increase in the worldwide accident rate is driven mainly by Africa which exhibits a statistically significant increase in accident rate for aircraft older than 20 years. Other regions such as North America and Europe do not exhibit any correlation of accident rate with aircraft age. An analysis of the accidents in which the aircraft were older than 20 years of age indicates that that the observed increase in accident rate in Africa is not due to aging aircraft factors but due to other risk factors. The analysis does not support age-based import restrictions as an effective measure to increase aviation safety, providing Design Approval Holders and Type Certification Authorities support National Aviation Authorities in managing older fleets under their responsibility.

1. Background

Modern commercial air transport jet aircraft are significant economic assets that can have an effective economic useful life of decades. For the past two decades, the average age of the worldwide air transport jet fleet has been between 10 and 12 years old. However, the size of the fleet has grown substantially so that the population of airplanes with ages in excess of 20 years has continued to increase.

Concerns regarding the safety of aging air transport jet aircraft, due to corrosion, fatigue or Widespread Fatigue Damage (WFD) rose following the dramatic in-flight explosive decompression of Aloha Airlines Flight 243 in 1988. The pressurization vessel of the 19-year old, heavily-used Boeing 737-297 was compromised and one occupant was ejected. The aircraft was, however, able to land. At the time of the accident, the aircraft had 35,486 hours of flight time and 89,680 flight cycles. The number of flight cycles was unusually high due to the short stage lengths that Aloha Airlines flew in Hawaii.[1]

In the aftermath of this accident, a number of actions were taken to monitor and assure the airworthiness of older air transport aircraft. In the United States, the Federal Aviation Administration (FAA) initiated a major research program on aging aircraft. The Airworthiness Assurance Working Group (AAWG) which consists of international manufacturers, operators, maintenance organizations and regulatory groups, was formed to find ways to address ageing issues such as corrosion and WFD that were found in the Aloha accident and in other incidents with older aircraft.[2,3,4,5]

The areas of concern regarding ageing aircraft were expanded to include aircraft systems such as wiring systems in 1996 following the in-flight breakup a 25 year old Boeing 747 operated as TWA Flight 800.[6] After this accident, at the recommendation of the White House Commission on Aviation Safety and Security (WHCSS), the FAA expanded its Aging Aircraft Program, which focused on structures, to cover non-structural systems. The FAA developed the Aging Transport Nonstructural Systems Plan. While the plan's primary focus was on electrical wiring systems, there are other on-going research and development activities that address mechanical and avionics systems[7].

One of the key questions regarding aging aircraft was whether chronological age or operational exposure (e.g. flight cycles or flight hours) were the factors which created age-related risk such as corrosion or Widespread Fatigue Damage for the aircraft. The AAWG and the FAA ultimately concluded that chronological age was a better indicator of environmental damage, while operational exposure was a better indicator of fatigue damage, including WFD. Airworthiness could be assured with proper maintenance and identification of specific operational Limits of Validity (LOV) for aircraft structures where failure is potentially catastrophic. Once the LOV limits were reached the aircraft could remain airworthy if specific inspections, modifications or replacements were performed.

Depending on the particular component and the fatigue mechanism, the LOV could be defined in flight cycles or flight hours. In 2011 the FAA issued a number

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1 NTSB Accident Report Aloha Airlines, Flight 243 Boeing 737-200, N73711, Near Maui, Hawaii

2 National Aging Aircraft Research Program, DOT/FAA/CT-88/32-1, September 1991, Federal Register Volume 66, Number 56, March 22, 2001.

3 Federal Register Volume 66, Number 56, March 22, 2001.

4 "How Old is too Old? The Impact of Ageing Aircraft on Aviation Safety", Australian Transportation Safety Board Transport Safety Report B20050205, February 2007.

5 http://www.faa.gov/aircraft/air_cert/design_approvals/transport/aging_aircraft/.

6 NTSB Aircraft Accident Report, In-flight Breakup Over the Atlantic Ocean Trans World Airlines Flight 800, Boeing 747-131, N93119, Near East Moriches, New York, July 17, 1996 (PB2000-910403, NTSB/AAR-00/03, DCA96MA070) http://www.ntsb.gov/doclib/reports/2000/AAR0003.pdf.

7 Enhanced Airworthiness Program for Airplane Systems/Fuel Tank Safety (EAPAS/FTS) http://www.gpo.gov/fdsys/pkg/FR-2005-10-06/pdf/05-19419.pdf#page=1.

of regulatory amendments implementing WFD rules and the LOV approach. Similar rules are under development by EASA in Europe and are anticipated to be adopted by many other regulatory agencies around the world.[8] In the early 1990's, regulatory agencies (including the FAA) required that operators of air transport jet aircraft incorporate an approved Corrosion Prevention and Control Program (CPCP) into their maintenance program[9].

Some states took alternative approaches to managing the exposure risk of aging aircraft by imposing both conventional maintenance requirements and chronological age limits under the assumption that newer aircraft were safer than older aircraft. In general, these limits were imposed on aircraft importation, and vary from 10 to 25 years.[10] The wide variation in limits indicates that such age-based import restrictions do not necessarily have a specific technical basis. If chronological age is not a valid indicator of increased safety risk, then imposing conservative age based import restrictions reduce the population of available air transport aircraft and thereby increase the cost and reduce the access to air transportation for those states that impose such restrictions.

The objective of this study is to investigate if there is a valid basis for imposing operational or import restrictions on commercial air transport jet aircraft based on chronological age.

2. Approach and Data

In order to evaluate if aircraft chronological age is an indicator of safety in the commercial air transport jet fleet, a historical analysis was conducted of aircraft accidents occurring between 1959 and 2012 for commercial jet transport aircraft where accident records and aircraft age and operational histories were available.

2.1 Accident Rate Metric

Because of the broad scope of this analysis, covering the entire history of modern commercial jet aviation, it was not possible to obtain accurate flight hours or flight cycle data for every aircraft. When evaluating accident rates, it was, therefore, difficult to use traditional exposure criteria for accident rate metrics (e.g. accidents per departure or accidents per flight hour). It was, however, generally possible to determine the year when an aircraft was built and in operational service and the size of the in-service fleet for each year. Therefore, a simpler aircraft-year based accident rate metric was defined and used in this analysis. This metric effectively assumes that each aircraft year of operation has the same

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[8] Aging Airplane Program: Widespread Fatigue Damage Final Rules Federal Register Volume 75, Number 219, November, 2010.

[9] FAA Aviation Rulemaking Advisory Committee, Transport Airplane and Engine Issue Area, Airworthiness Assurance Working Group, Task 1 – Corrosion Prevention and Control Program http://www.faa.gov/regulations_policies/rulemaking/committees/documents/media/TAEaaT1-113092.pdf.

[10] Dissimilar Technical Regulatory Requirements Impacting Cross-Border Transfer of Aircraft (SGI Aviation, January 2011.

risk exposure. While this may not capture the risks of differences in aircraft annual utilization it is a reasonable assumption particularly given high level scope of this analysis.

The aircraft-year based accident rate was defined as number of accidents which occurred divided by the total number of aircraft-years of exposure of the fleet. For the annual accident rate, this is just the number of accidents which occurred in a given year divided by the number of aircraft in the in-service fleet. When evaluating age effects, this would be the total number of accidents of aircraft of a specific age divided by the total number of aircraft-years flown by aircraft of that age. The inverse of the aircraft-year based accident rate metric is the average number of years between accidents.

2.2 Data and Limitations

The principle data source was the Flightglobal Ascend Online Database. Fleet size, aircraft age, operational region and accident data were derived from the database. Accident data was sometimes supplemented or cross-referenced using data from the Boeing Statistical Summary of Commercial Jet Airplane Accidents or other sources.

The analysis was limited to commercial jet aircraft with a Maximum Takeoff Gross Weight (MTOW) of more than 60,000 lbs that were built and delivered by western manufacturers to commercial operators for commercial usage on the date of delivery. The analysis did not include aircraft types that had no recorded accidents. The analysis also did not include aircraft manufactured in the Soviet Union or the CIS due to lack of comprehensive operational or accident data.

The chronological age of an accident aircraft was defined as the difference between the year in which the accident occurred and the year in which the aircraft was built.

2.3 Fleet Data

The size of the in-service commercial jet fleet for the 45 aircraft types included in the analysis is shown in Figure 1. The fleet grew significantly from 141 aircraft in 1959 to 18,196 aircraft in 2012. The average age of the fleet increased from 1959 to 1989 where it stopped growing. It has remained constant at between 10 and 12 years since that time.

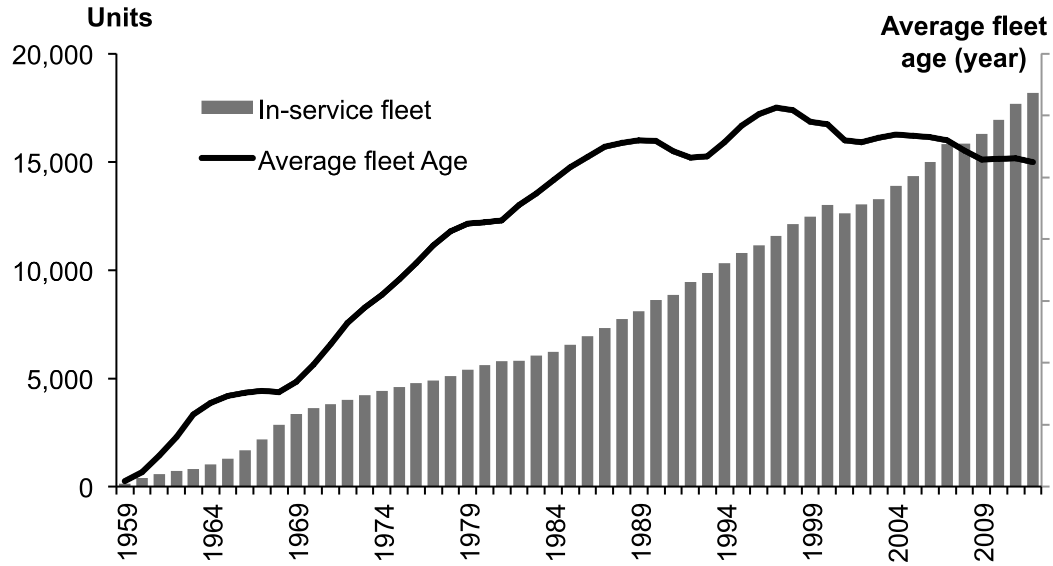

Figure 1: Growth of the in-service fleet and average fleet age.

The 45 aircraft types analyzed and the number of aircraft delivered of each type over the 53-year period from 1959 to 2012 are shown in Figure 2. A total of 28,825 aircraft were delivered. It is notable that a majority of the deliveries were single-aisle aircraft such as the Airbus A320 and Boeing B737 series aircraft.

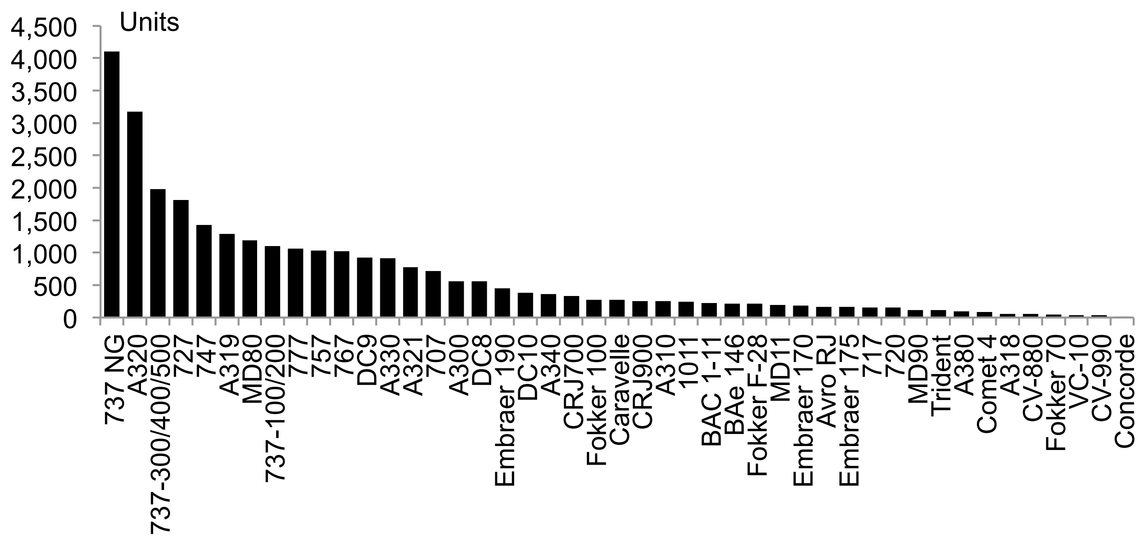

Figure 2: Distribution of commercial deliveries by aircraft type.

2.4 Accident Data

Accidents were defined as events where the aircraft sustained substantial damage, became missing or completely inaccessible as well as events where fatal or serious injury resulted from being in the airplane or direct contact with the airplane or its jet blast. Events resulting from hostile actions including sabotage, hijacking, terrorism, military action, stowaway events, and events with non-fatal injuries resulting from turbulence, loose objects or boarding were likewise not included. Fatal accidents were defined as accidents which resulted in a fatal injury.

The yearly number of total and fatal accidents is shown in Figure 3. Over the entire period a total of 1,573 accidents have been recorded in western commercial jet air transport aircraft, of which, 526 were fatal accidents. Discounting 1959 when there were only 141 commercial jet aircraft in operation, the number of total accidents has varied between 12 and 54 per year and the number of fatal accidents has varied between 2 and 19 per year. There has been a slight upward trend in the annual number of all accidents and a slight downward trend in the number of fatal accidents. Since the fleet has grown rapidly over this period there has been a general improving trend in both the total and fatal accident rates which will be discussed in more detail below.

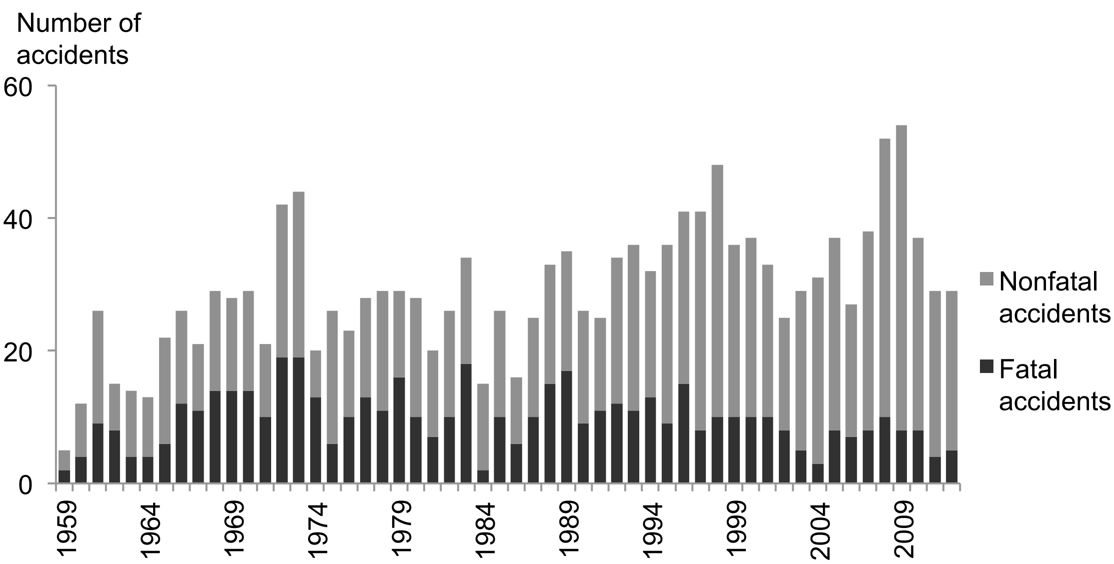

Figure 3: Annual number of accidents by year.

3. Historical Safety Trends

The historical trend in the total and fatal aircraft-year based aircraft accident rates are shown in Figure 4. Both accident rates have declined rapidly during the 1960s and have continued to decline over time to an average rate of one accident per 628 aircraft years of operation and one fatal accident per 3,645 years of operation in 2012.

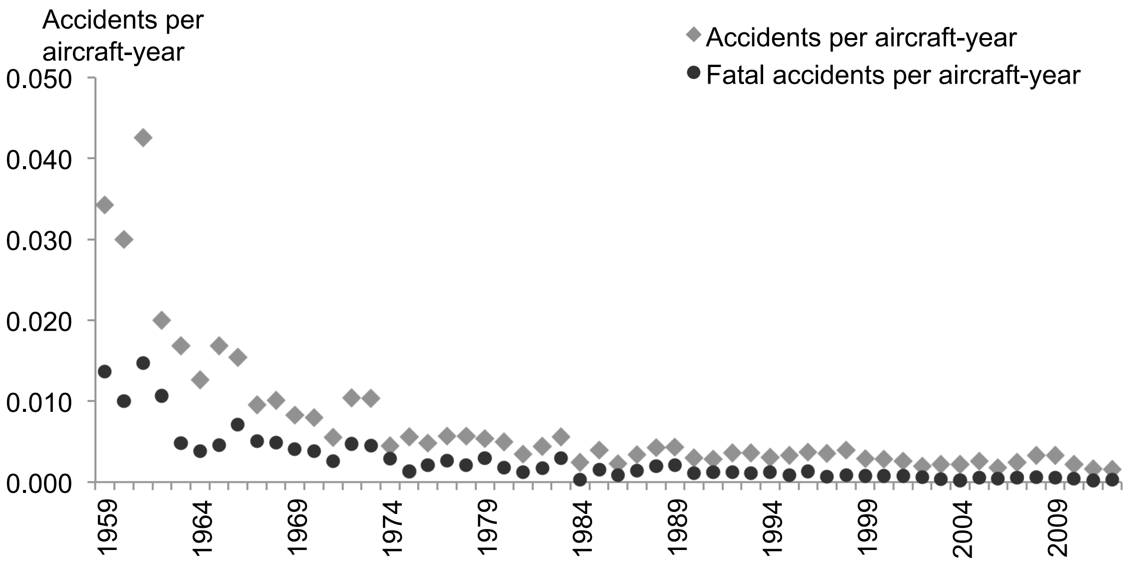

Figure 4: Accidents per aircraft-year as a function of time.

The significant improvement in the accident rates is attributed to a number of factors. These include: improved aircraft and aircraft systems, improved crew training, refined operating procedures, crew warning and alerting systems, stronger regulatory oversight, improved maintenance, better weather forecasting, improved enroute and approach navigation systems, improved airport infrastructure and a strong safety culture in the industry.

3.1 Regional Safety Trends

The level of safety and rate of safety improvement has not been uniform around the world. Figure 5 depicts the average number of years between all accidents and fatal accidents by world region over the 1959 to 2012 time period. Note that this metric is just the inverse of the aircraft-year based accident rate shown in Figure 4.

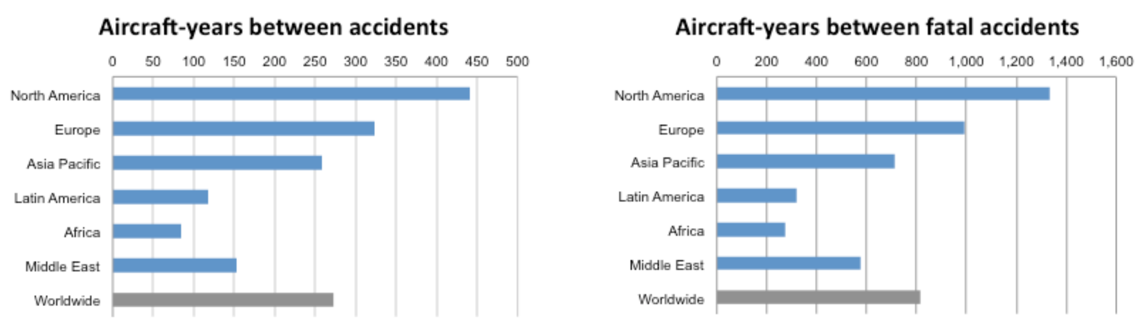

Figure 5: Total and fatal accident rates by world region.

Both the total and fatal accident rates exhibit similar regional differences. Both North America and Europe have experienced lower total and fatal accident rates than the Worldwide average. Africa, Latin America and the Middle East have experienced higher accident rates.

Even though the absolute levels of safety have varied, there has been significant improvement in all world regions as can be seen in Figure 6 which depicts the total accident rate trends by region.[11] The rate of accidents has declined in each region although there has been high variability in some regions such as Africa.

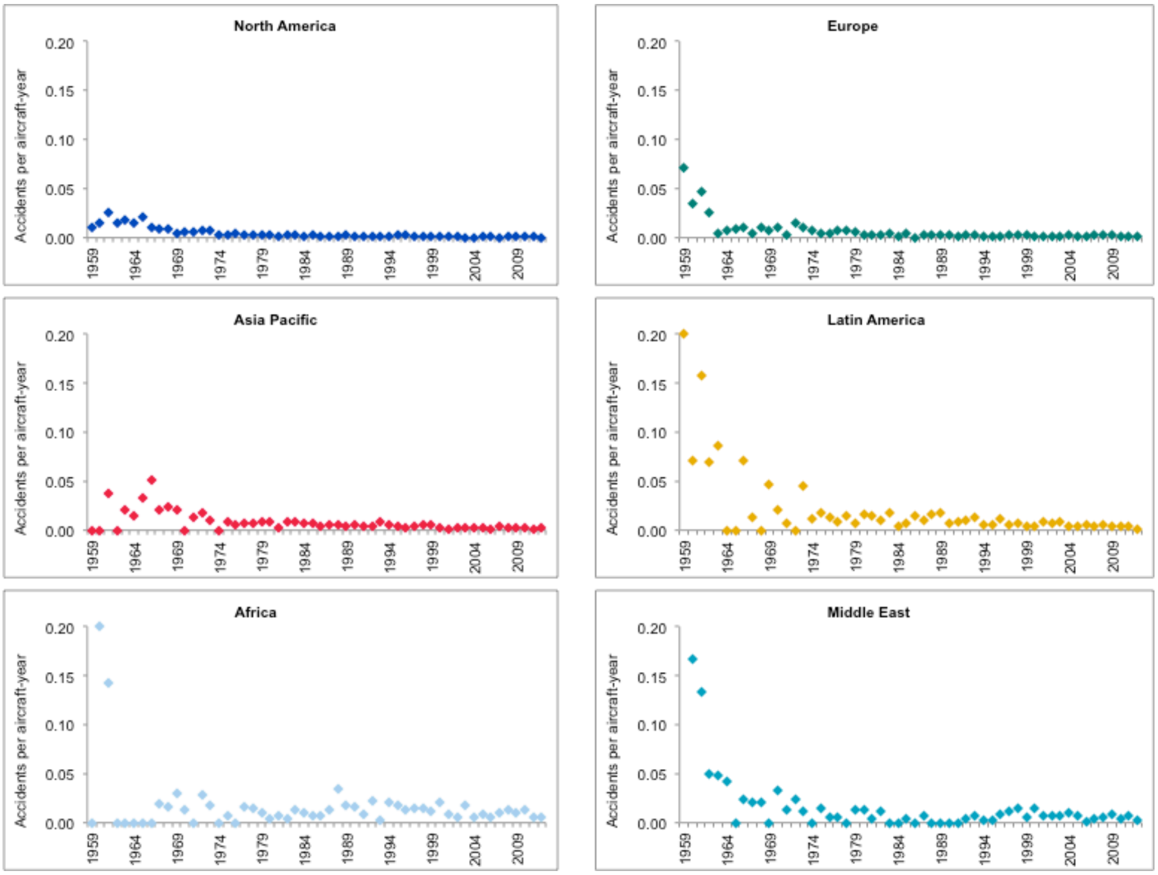

Figure 6: Aircraft-year based accident rate trends by world region.

3.2 Impact of Aircraft Technology Evolution

In order to investigate the impact of the evolution of aircraft technology the data was grouped by the Year of Build (YOB) of the aircraft. It should be noted that this analysis is confounded by the general decrease in accident rates, so it is not possible to determine the exact contribution, if any, of improved aircraft technology compared with other factors such as improved crew training, infrastructure and procedures. However, the data in Figure 7 do indicate that the accident rates have improved for each decade and are consistent with other studies which have found reduced accident rates with each generation of

[11] The fatal accident data was sparse and unreliable when disaggregated by region and year so it is not included in the disaggregated analysis.

aircraft.[12] The improvement is consistent with observations that modern commercial jet aircraft have improved performance and handling qualities, improved alerting systems such as Terrain Awareness and Warning System (TAWS) and faster engine spool-up times, which mitigate many of the accident causes observed in early generation commercial air transport jet aircraft.

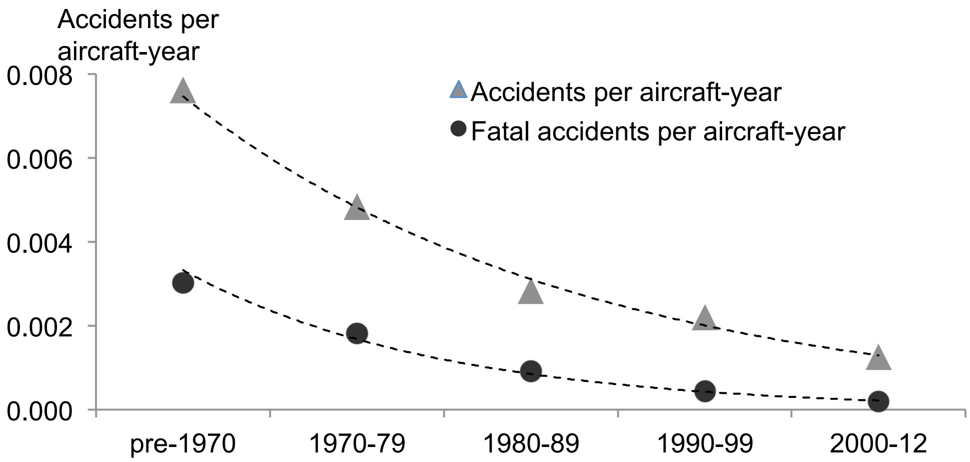

Figure 7: Accident rate by year-of-build group.

4. Impact of Aircraft Age

The aircraft age for each accident in Figure 3 was determined by subtracting the year that the aircraft was built from the age at which the accidents occurred. Figure 8 shows the distribution of accidents by age cohort. The data indicates that 53% of the fatal accidents and 47% of the total accidents occurred for aircraft 8 years old or younger. Aircraft 20 years old or older accounted for only 18% of the fatal accidents and 22% of the total accidents.

[12] Airbus study on “Commercial Aviation Accidents 1958-2013”.

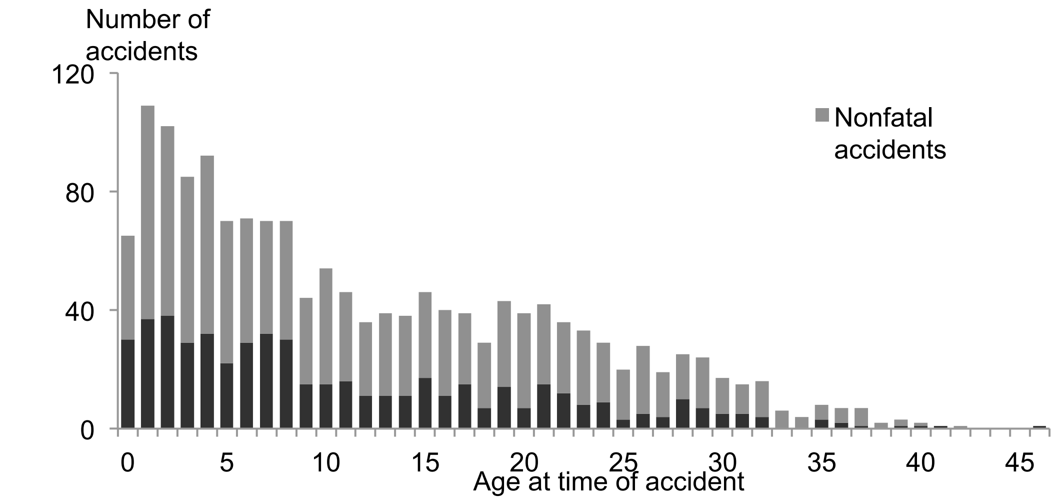

Figure 8: Accidents by aircraft age at the time of the accident.

The database was also evaluated to determine the operational fleet exposure in aircraft-years as a function of aircraft age. The fleet exposure results are shown in Figure 9. As would be expected, there is more exposure for younger aircraft. The exposure declines almost linearly until 25 years of age when there is a slight inflection and the decline is more gradual.

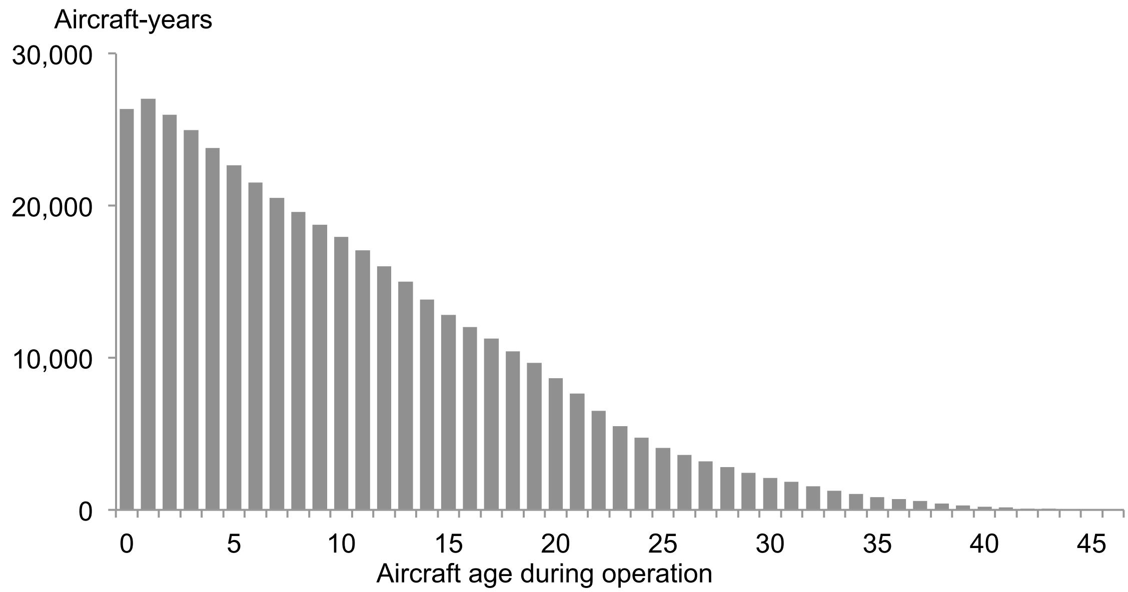

Figure 9: Fleet exposure (aircraft-years) by aircraft age.

By normalizing the number of accidents for each age cohort with the operational exposure, it is possible to determine the accident rate as a function of aircraft age. Because accidents are statistically rare events and the exposure decreases for each age cohort, the confidence in the accident rate data decreases for the older age cohorts.

Figure 10 presents the worldwide fatal accident rate data as a function of aircraft age. The error bars represent the 95% confidence intervals accounting for the different exposure levels by aircraft age.

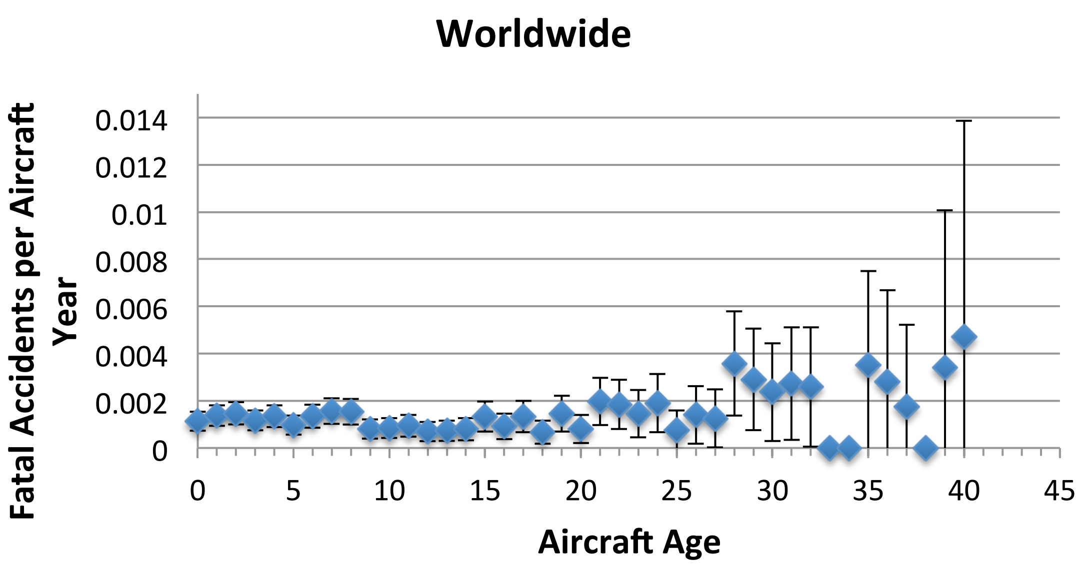

Figure 10: Fatal accident rate versus aircraft age for the worldwide dataset. Error bars indicate 95% confidence interval.

It can be seen that there is no impact of aircraft age up until 27 years of age. Between 28 and 32 years there is a rise in the accident rate but this rise is lower than the 95% confidence interval for the older aircraft cohorts and may be the result of sampling effects due to the low exposure for these older aircraft. No fatal accidents were observed for aircraft 33 or 34 years old but this is also likely due to the low exposure and there is relatively low confidence in the data for aircraft older than 33 years.

Figure 11 presents total accident rate data as a function of aircraft age for the worldwide dataset. It can be seen that for the all accidents there is no impact of aircraft age up until at least 18 years of age. There is a small increase in the 19 and 20 year old cohorts but again this is within the 95% confidence interval and may not be significant. Above 20 years of age the average accident rate for all accidents indicates a slightly increasing trend with age. The trend is generally consistent and by 26 years the accident rate has increased more than the 95% confidence interval indicating a statistically significant increase in the total accident rate from the 18 year and younger baseline.

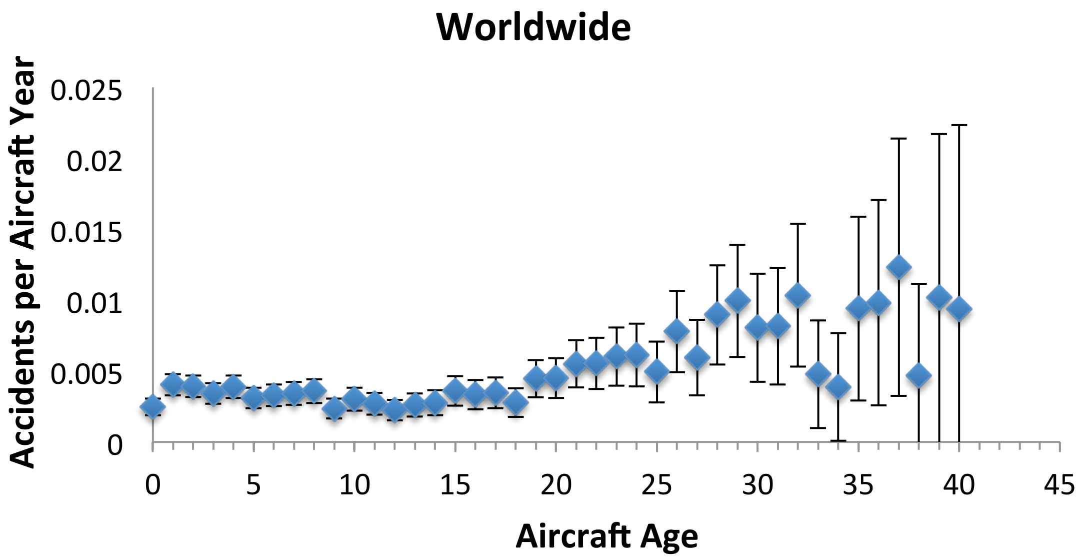

Figure 11: Accident rate versus aircraft age for the worldwide dataset. Error bars indicate 95% confidence interval.

Because the worldwide data includes regions with significantly different accident rates, it was useful to disaggregate the total accident rate analysis by world region of the domicile of the operator of the aircraft.[13] There are significant and striking differences between world regions as shown in Figure 12.

[13] The fatal accident data was sparse and unreliable when disaggregated by region and year so it is not included in the disaggregated analysis.

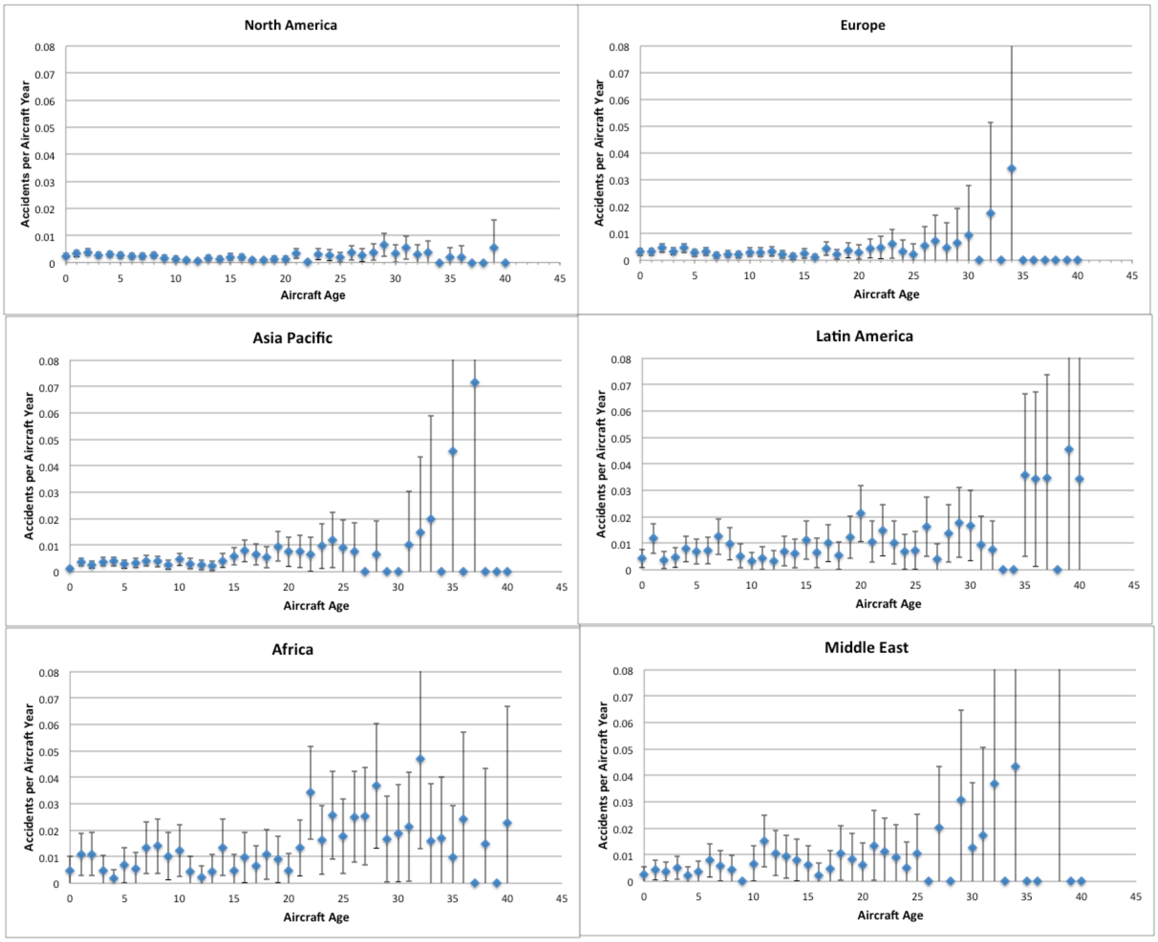

Figure 12: Accident rate versus aircraft age by world region.
Error bars indicate the 95% confidence interval.

In North America and Europe, the accident rates were low and there is no statistical correlation between aircraft age and the observed accident rate. This is seen most clearly in the North American data where there is a stronger statistical basis due to the higher exposure levels. The accident rate for North America is essentially flat up until 40 years of aircraft age. The European data is similar except for a few accidents for 32-year old and 34-year old aircraft cohorts which spike the accident rates at this years but these are not statistically significant due to the low exposure levels of these cohorts as indicated by the large 95% confidence intervals for these years.

By contrast, Africa and Latin America have higher accident rates even for the young aircraft cohorts. In Africa there does appear to be a statistically significant increase in the accident rates for aircraft over 20 years of age. This increase is what causes the worldwide total accident rate data in Figure 11 to increase after 20 years of age. The Latin America data shows increased volatility in accident rates after 20 years, but it is not clear if this is statistically significant.

The Asia Pacific data show lower baseline accident rates than Africa or Latin America, but do show a slight increase in accident rates between 10 and 20 years of age. The Middle East data are between Asia Pacific and Latin America in terms of their baseline accident rate, but the data are variable with large confidence intervals so it is difficult to make any strong conclusion from the Middle East data.

From these data it is not clear if the cause of the increase in accident rates after 20 years is due to aircraft aging issues or if the lower capital costs of older aircraft result in their being exposed to operational environments with weaker infrastructure, crew training and regulatory oversight. This will be investigated in more detail below.

5. Analysis of Accidents Involving 20+ Year Old Aircraft

In order to evaluate if the observed increase in accident rates in some regions was due to aircraft age or other factors, an analysis was conducted of the 385 accidents where the age of the aircraft at the time of the accident was 20 years of age or higher.

For each accident, the accident narrative was reviewed and evaluated to determine if an aircraft factor was related to the accident. The analysis used the ICAO Commercial Aviation Safety Team (CAST) Aviation Occurrence Category Taxonomy[14] with slight modifications to limit the classification to aircraft related factors.

The following events which were considered aircraft related:

Fire/Smoke (Non-Impact) F-NI Defined as fire or smoke in or on the aircraft, in flight, or on the ground, which is not the result of impact. This occurrence category was split into cargo and non-cargo related events. Cargo fires were not considered aircraft related occurrences.

System/Component Failure or Malfunction (Non-Powerplant) SCF-NP Defined as failure or malfunction of an aircraft system or component other than the powerplant. This occurrence category was split into failures or malfunctions which occurred before or after impact. Failures which occurred after impact or after a runway excursion were not considered aircraft related occurrences.

System/Component Failure or Malfunction (Powerplant) SCF-P Defined as Failure or malfunction of an aircraft system or component related to the powerplant.

Each of the 385 accidents were classified into one of the 3 *Aircraft* related categories described above or if none of these were present than the accident was classified as a *Non-Aircraft* occurrence. In some cases there was not

[14] Aviation Occurrence Categories – Definitions and Usage Notes, http://www.intlaviationstandards.org/Documents/OccurrenceCategoryDefinitions.pdf

sufficient information available to determine if the event was aircraft related or not. In these cases the event was classified as *Unknown UNK* consistent with the ICAO taxonomy.

The results of the analysis of aircraft and non-aircraft related occurrence categories for aircraft 20 years of age or older are shown in Figure 13 for the 104 fatal accidents and 14 for all accidents. For the most severe fatal accidents in Figure 13 only 18.2% (19 accidents) were determined to be aircraft related while 73.1% were non-aircraft related and 8.7% were unknown. For all accidents in Figure 14 a larger fraction of 29.6% (114 accidents) were determined to be aircraft related, 67.5% were non-aircraft related and 2.9% were unknown.

Since safety concerns regarding aircraft age such as WFD would manifest as aircraft related occurrences, the relatively low fraction of these occurrences in the accidents of 20+ year old aircraft indicates that aircraft age itself does not appear to be a key risk factor.

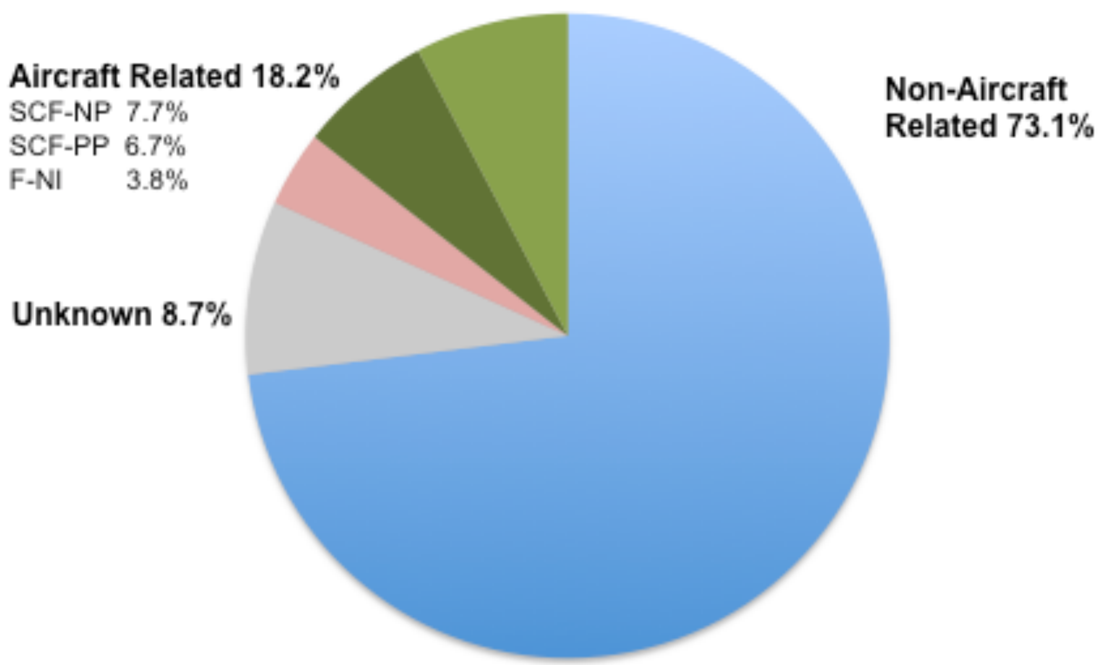

Figure 13: Occurrence categories for 104 fatal accidents of 20+ year old aircraft.

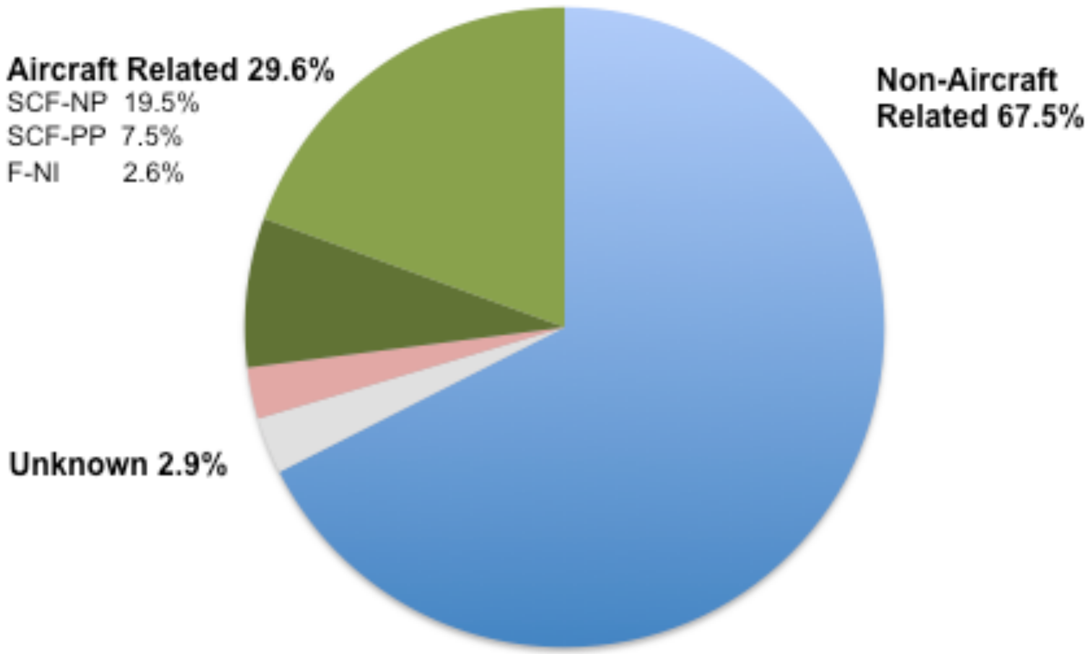

Figure 14: Occurrence categories for all 385 accidents of 20+ year old aircraft.

This hypothesis was further evaluated by considering the change of aircraft and non-aircraft related occurrence categories by world region of the domicile of the operator for all accidents.[15] If aircraft age is a significant risk factor for older aircraft, then those regions such as Africa where the accident rate increased for older aircraft should have a higher percentage of aircraft related occurrences than those regions such as North America where there is no increase in the accident rate with age. In Figure 15 it can be seen that the reverse is true. Only 22.9% of the accidents in Africa were caused by aircraft factors whereas 42.0% of the accidents in North America were caused by aircraft factors. This leads to the conclusion that the elevated risk observed by older aircraft is not due to direct age effects but with other risk factors which correlate with aircraft age in these regions. This is consistent with the higher percentage of non-aircraft occurrences observed in these regions.

[15] The fatal accident data was sparse and unreliable when disaggregated by region and year so it is not included in the disaggregated analysis.

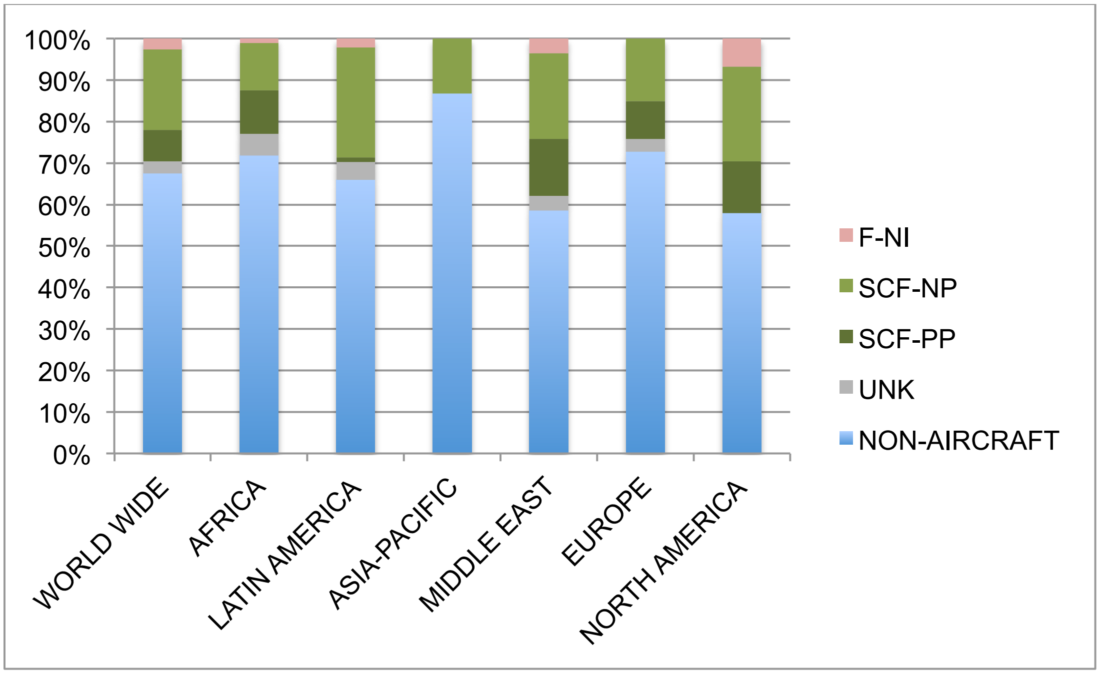

Figure 15: Distribution of causal factors by world region for 20+ year old aircraft.

6. Alternatives to Age Based Import Restrictions

The analysis of the impact of aircraft age on safety does not support simple age-based restrictions as the most effective mechanism to maintain aviation safety. As an alternative, many states have rigorous processes to assure the continued airworthiness of older aircraft.

The currently accepted practice in managing structural degradation effects is the Limit of Validity approach which is currently incorporated in the U.S. Federal Aviation Regulations[16] and is being incorporated in the European Aviation Safety Agency regulations.[17] The LOV approach is also supported by most manufacturers of commercial jet transport aircraft.

The Limit of Validity is the number of total accumulated flight cycles or flight hours or both, for which it has been demonstrated that Widespread Fatigue Damage is unlikely to occur in the aircraft structure; and that the inspections and

[16] Aging Airplane Program: Widespread Fatigue Damage Final Rules, U.S. Federal Register Volume 75, Number 219, November, 2010.
[17] Continuing Structural Integrity Program, EASA AMC 20-20, December 2007.

other maintenance actions and procedures resulting from this demonstration and other elements of the fatigue and damage tolerance evaluation are sufficient to prevent catastrophic failure of the aircraft structure. The LOV is commonly known as the limit of validity of the engineering data that support the maintenance program.

When an aircraft reaches the LOV specified in the Airworthiness Limitations Section (ALS) of the Instructions for Continued Airworthiness (ICA), in terms of either flight cycles or hours, it must be removed from service until the engineering data that support the structural maintenance programme are reviewed. If it is demonstrated that widespread fatigue damage will not occur in the aeroplane damage-tolerant structure the LOV can be extended. Although the LOV is established based on WFD considerations, it is intended that all maintenance actions required to address fatigue, corrosion, and accidental damage up to the LOV are identified in the structural-maintenance program. All inspections and other procedures (e.g. modifications or replacements, and the associated airworthiness limitations) that are necessary to prevent a catastrophic failure due to fatigue, up to the LOV, must be included in the Airworthiness Limitations Section of the Instructions for Continued Airworthiness.

7. Conclusions

The analysis indicates that there is no correlation between the fatal accident rates and aircraft age up to 27 years of age for commercial jet aircraft with a MTOW greater than 60,000 lbs. Above this age there was a slight increase in the fatal accident rate but the accident rate data is less reliable for these older aircraft cohorts due to the limited exposure. When all accidents are considered there is no correlation between accident rates and age up till 18 years and a weak trend of increased accident rate with age is observed for aircraft older than 20 years. This increase in the worldwide accident rate is driven mainly by Africa which exhibits a statistically significant increase in accident rate for aircraft older than 20 years. Other regions such as North America and Europe do not exhibit any correlation of accident rate with aircraft age.

A detailed analysis of the accidents in which the aircraft were older than 20 years of age indicates that the percentage of aircraft related accidents is significantly lower in Africa than in North America or the Worldwide average. This indicates that the observed increase in accident rate in Africa is due to other risk factors that correlate with aircraft age such as weaker crew training, regulatory oversight and procedures.

As a consequence, the evidence does not support age-based import restrictions as an effective measure to increase aviation safety, providing Design Approval Holders and Type Certification Authorities support National Aviation Authorities in managing older fleets under their responsibility.