



NLR-TP-2007-153

Analysis of aircraft weight and balance related safety occurrences

G.W.H. van Es



EXECUTIVE SUMMARY

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Problem area

Each year there are a number of aircraft accidents related to weight and balance issues. Such accidents have occurred due to for instance incorrect loading of the aircraft and the use of wrong takeoff weight for performance calculations amongst others.

Description of work

Weight and balance related accidents are analysed that have occurred with commercial aircraft worldwide since 1970. Furthermore weight and balance related incidents as reported by airlines are analysed for the period 1997-2004. Factual information, causal factors, and trends of weight and balance related accidents and incidents are analysed using the data sample. Finally the influence of technologies such as onboard weight and balance systems is discussed.

Results and conclusions

The important findings of the study are that the risk of having a weight and balance related accident with cargo flights is 8.5 times higher than with passenger flights; that there are various factors involved in weight and balance accidents/incidents such as errors in the load sheet, shifting of cargo, incorrect loading etc.; and that automatic onboard aircraft weight and balance systems could resolve most of the weight and balance problems identified in the present study. However the accuracy and reliability of such systems is currently insufficient to enforce the use of these systems on commercial aircraft as primary means for determining the weight and balance.

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Summary

Each year there are a number of aircraft accidents related to weight and balance issues. Such accidents have occurred due to for instance incorrect loading of the aircraft and the use of wrong takeoff weight for performance calculations amongst others. The present paper gives a review of weight and balance related accidents that have occurred with commercial aircraft worldwide since 1970. Furthermore weight and balance related incidents as reported by airlines are analysed for the period 1997-2004. Factual information, causal factors, and trends of weight and balance related accidents and incidents are analysed using the data sample. Finally the influence of technologies such as onboard weight and balance systems is discussed.

The conclusions made in the present study are:

- The risk of having a weight and balance related accident with cargo flights is 8.5 times higher than with passenger flights;
- There are various factors involved in weight and balance accidents/incidents such as errors in the load sheet, shifting of cargo, incorrect loading etc. No single factor could be identified in the present study that had a very dominant influence;
- Large regional differences in the weight and balance related accident rate are identified. The African region showed the highest accident rate and the North American region the lowest;
- Worldwide the weight and balance related accident rate shows a slow improvement since 1970. Nevertheless the accident rate has reduced by all most 50% in 35 years;
- The amount of time spent on training of weight and balance related items are often limited both for flight crew as well as with ground agents;
- Automatic onboard aircraft weight and balance systems could resolve most of the weight and balance problems identified in the present study. However the accuracy and reliability of such systems is currently insufficient to enforce the use of these systems on commercial aircraft as primary means for determining the weight and balance.



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1 Introduction

1.1 Background

“On March 12, 1950, an Avro 689 Tudor V was on a charter flight carrying rugby fans home from Dublin, Ireland. The aircraft was approaching runway 28 at Llandow Airport located near Cardiff at an abnormally low altitude from the North-East with the air-carriage down. This rapid loss of height was evidently of concern to the pilot, who at one-third of a mile from the runway and approximately 150-200 feet above the ground, slightly increased the engine power to maintain height. This was followed by a sudden application of full power and the aircraft pitching up. Climbing to about 300 ft. the aircraft finally stalled and the aircraft fell sharply to starboard and plunged into the ground, narrowly missing a farm and a couple of young boys playing football, some 2,500 ft. from the runway threshold. Only 3 out of the 83 persons onboard survived the crash. The investigation revealed that the aircraft was not loaded correctly resulting in a centre of gravity which was at least 9 ft. aft of the aft limit. After selecting landing flaps the aircraft became unstable, pitched up and stalled. The investigation showed that the loading instructions pertaining to the aircraft were unsatisfactory as it did not contain adequate directions in determining how passengers and their luggage should be distributed. For this particular trip there was an alteration in the seating arrangement to allow six more passengers than the maximum permissible. This change required an amendment of the certification status of the aircraft. The loading of the aircraft was not in accordance with the provisions of this amendment.” (Source: NLR Air Safety Database)

The accident described above took place more than 55 years ago. Still today accidents with exactly similar causes related to weight and balance as found in the above described accident occur. Weight and balance refer to the weight of an aircraft and the location of the centre of gravity. Aircraft are designed and certified to operate within certain weight and balance limits. Exceeding these limits can be dangerous. Unfortunately each year a number of accidents and serious incidents take place in which the aircraft involved exceeded the weight and balance limits or in which weight and balance issues affected the flight adversely. In this research paper such occurrences are studied in more detail.

1.2 Objectives and scope

The objective of this research paper is to provide insight into the safety factors that are related to aircraft involved in exceeding their weight and balance limits. The study is limited to commercial civil transport aircraft with a maximum take off mass exceeding 5,500 kg.

2 Certification and flight operational issues

It is not the objective of this paper to provide a complete overview of all certification and flight operational issues regarding weight and balance. However, some background information could help in a better understanding of some of the safety factors to be discussed later in this paper. Therefore a brief summary of some of the important issues on certification and flight operations are discussed next.

Regulations such as provided in FAR 25, EASA CS 25 specify the design criteria that shall be conformed to in determining the allowable centre of gravity and weight limits (see e.g. FAR 25.27 and EASA CS 25.27). These criteria determine the stability, controllability, and strength requirements at all allowable centre of gravity positions and corresponding weights. The forward centre of gravity limit is typically determined by control requirements and the aft position by stability requirements. These requirements are discussed in more detail next.

Normally, the condition which typically determines the forward centre of gravity limit is that the aircraft shall be controllable in landing. This means that the aircraft shall be able to be trimmed at the high lift values required for the desired landing speeds (including the abuse case of $V_{ref}-5$ knots). Other flight control cases that can influence the forward limit of the centre of gravity are the capability to make a prompt avoidance pitch-up manoeuvre, the capability to make a prompt nose-down recovery at low speed and adequate pitch control in abnormal configurations (failure cases). The above mentioned conditions all apply to the case in the free air. On the ground the forward centre of gravity limit is basically determined by the maximum loads on the nose landing gear.

Static longitudinal stability is the most important factor in determining the aft centre of gravity limit. At the aft centre of gravity limit position the aircraft should demonstrate that a positive natural stability exists, that the aircraft is capable of pitch control at low speeds and high thrust (e.g. during a go-around), and that an adequate control is possible in abnormal configurations (failure cases such as fuel that is trapped in the trim tank). On the ground the aft centre of gravity limit is determined by the minimum loads on the nose landing gear required for good nose wheel steering, the maximum loads on the main landing gears, the tipping tendency of the aircraft and adequate directional control during the take off run after an engine failure.

In the end all these requirements (which are only briefly discussed here) determine the envelope of allowable centre of gravity and weights during take off, landing and in flight. An example of such an envelope is shown in Figure 1 and can be found in the certified aircraft flight manual.

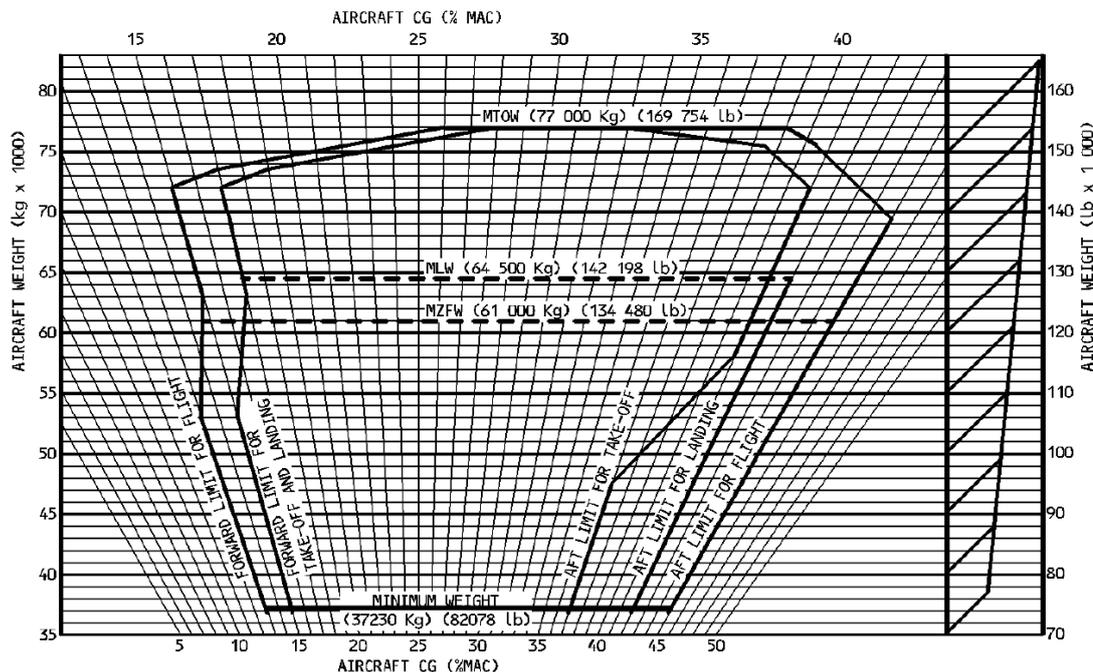


Figure 1: Example of a centre of gravity envelope

During certification special attention is given to the take off trim setting and the so-called green band during certification. In this case the take off trim setting is limited in order to cover required abuse cases at take off. It has to be shown that the aircraft remains controllable throughout the take off run at the aft centre of gravity limit for take off and with the trim at the nose-up limit of the green band. Furthermore it should be possible to rotate the aircraft with no significant increase in the take off distance at the forward limit of the centre of gravity limit for take off and with the trim at the nose-down limit of the green band.

The centre of gravity envelope used during the operation of an aircraft is not necessarily the same as the certified envelope. For a passenger aircraft operation it is not practical to determine the weight of each individual passenger including their hand luggage before departure. Regulations give standard values of the mass of a passenger that can be used instead of weighing each passenger. This approach however implies that operational margins have to be applied to the certified centre of gravity envelope. In determining the centre of gravity possible deviations from the assumed load distribution must be considered. As a result the operational centre of gravity envelope shows a more restrictive range in aft and forward centre of gravity. If free seating is applied (which is popular amongst many of the so-called low cost carriers), procedures must be introduced to ensure corrective action by the crew if extreme longitudinal seating selection occurs. For instance if in a half full aircraft all the passengers are seated at the last rows or at the front rows the crew should correct this seating.

What happens if the certified limits as defined in the centre of gravity envelope are exceeded? From design the aircraft flight characteristics will be adversely affected whenever the certified limits are exceeded. For instance as centre gravity limit moves aft, the aircraft will become less stable as the centre of gravity approaches the neutral point¹⁾. If the centre of gravity lies aft of the neutral point the coordination and control motions required to maintain a stable flight condition will exceed the capability of the pilot and the aircraft will become uncontrollable. On the ground, a centre gravity aft of the aft limit can result in a tail strike due to the pitch up of the aircraft (even at low speeds during the take off roll when power is applied to the engines). The effect of a centre of gravity position forward of the forward limit is evidenced by a decrease in elevator control capability. Because of excessive stability, the elevator control required to manoeuvre the aircraft is increased. At some point, elevator control might become insufficient to perform required manoeuvres, such as the flare during landing and a go-around. During take off the centre of gravity position can be moved forward until it reaches the point where the aircraft is very stable but cannot be rotated or with great difficulty because the elevator has reached its maximum deflection. An adverse centre of gravity position can also have significant effects on the loads imposed on the aircraft's structural components and could cause structural failure. Exceeding the maximum weights as specified in the aircraft flight manual does not necessarily affect the flight characteristics adversely. For instance exceeding the maximum landing weight could result in a landing gear collapse. However, the landing gear structure is designed with a standard safety margin assuming a higher load than obtained during a normal landing at maximum landing weight. With this it could be possible to land the aircraft somewhat beyond the maximum landing weight. Overweight landings are often made during emergency or precautionary landings. Exceeding the maximum take off weight will affect the flight performance characteristics. The take off ground roll distance increases and the climb performance reduces. As long as the overweight is not significant the aircraft should be able take off safely. However, the margins reduce rapidly when an engine failure occurs during an overweight take off, if the runway is short for the aircraft, or if there are high obstacles along the take off flight path that the aircraft has to clear.

¹⁾ The neutral point is the boundary between stable and unstable conditions around the pitch axis.

3 Analysis of occurrence data

3.1 Accident data

Searches were conducted in the NLR Air Safety database for accidents (as defined by ICAO Annex 13) that were directly related to weight and balance issues. The query was focused on those cases in which the certified weight and balance limits were exceeded. The search covered the time period 1970-2005 and encompassed civil transport aircraft with a take off mass of 5,500 kg or higher, equipped with turbo jet/fan or turbo prop engines. Included were passenger and cargo flights. Excluded from the data sample were test flights, ferry flights, emergency/precautionary landings and occurrences related to sabotage or any other criminal act.

The query resulted in 82 accidents that met the above mentioned criteria. There were 34 (41%) accidents with one or more onboard fatalities. The data sample comprises of 50 (61%) passenger flights and 32 (39%) cargo flights. These frequencies of flight types are not very meaningful unless they are related to the flight exposure of each flight type as many more passenger flights are conducted than cargo flights. With the NLR Air Safety database it is possible to calculate the exposure of civil passenger or cargo transport aircraft from 1970 and onwards. For the period 1970-2005 it is calculated that 7% of all revenue flights are full cargo flights and 93% of all revenue flights are full passenger²⁾ flights. This means that the risk of having a weight and balance related accident is about **8.5** times higher with a cargo flight than with a passenger flight.

The distribution of the flight phase in the data sample is shown in Figure 2. Clearly the take off phase is by far the most critical in weight and balance related accidents for both passenger and cargo flights accounting for more than half of all accidents.

²⁾ So-called combi flights in which the aircraft transports both passengers and cargo are considered here as full passenger flights as the same operational rules for real full passenger flights rules applies to these combi flights.

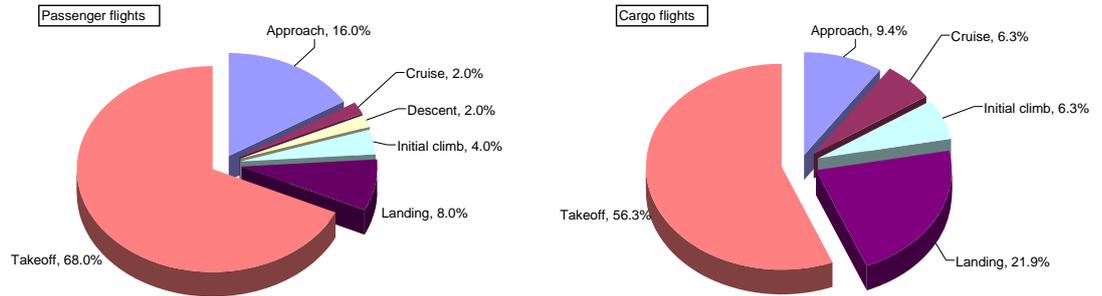
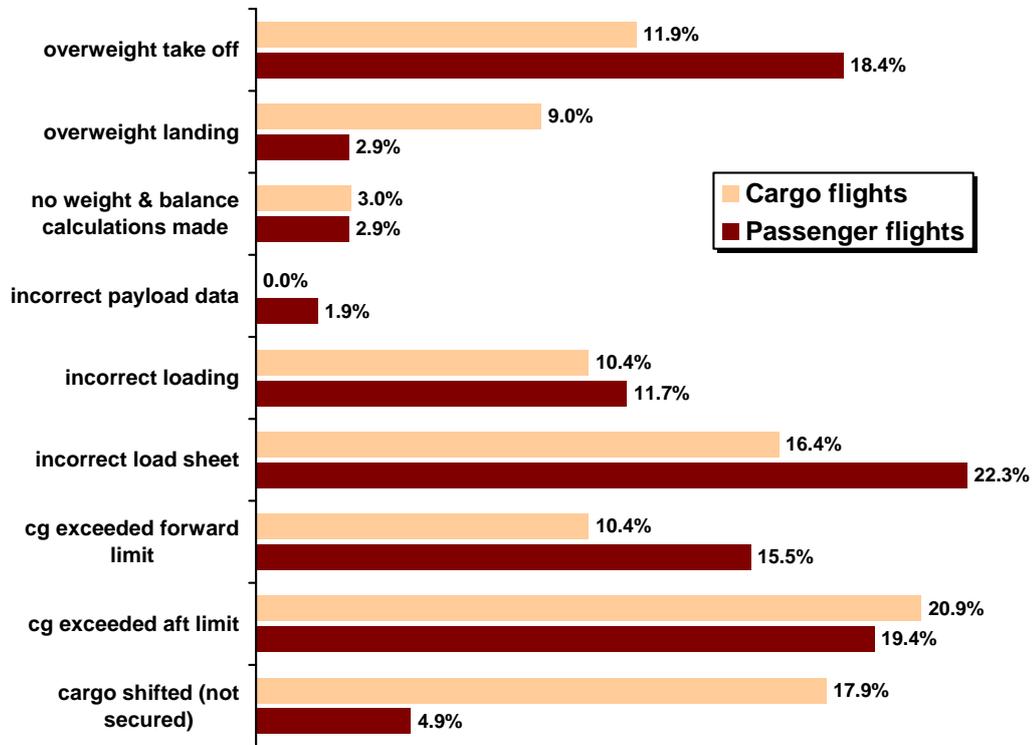


Figure 2: Flight phase distribution in weight and balance related accidents



More than one factor can be assigned to a single accident

Figure 3: Distribution of factors in weight and balance related accidents (percent of all factors per flight type)

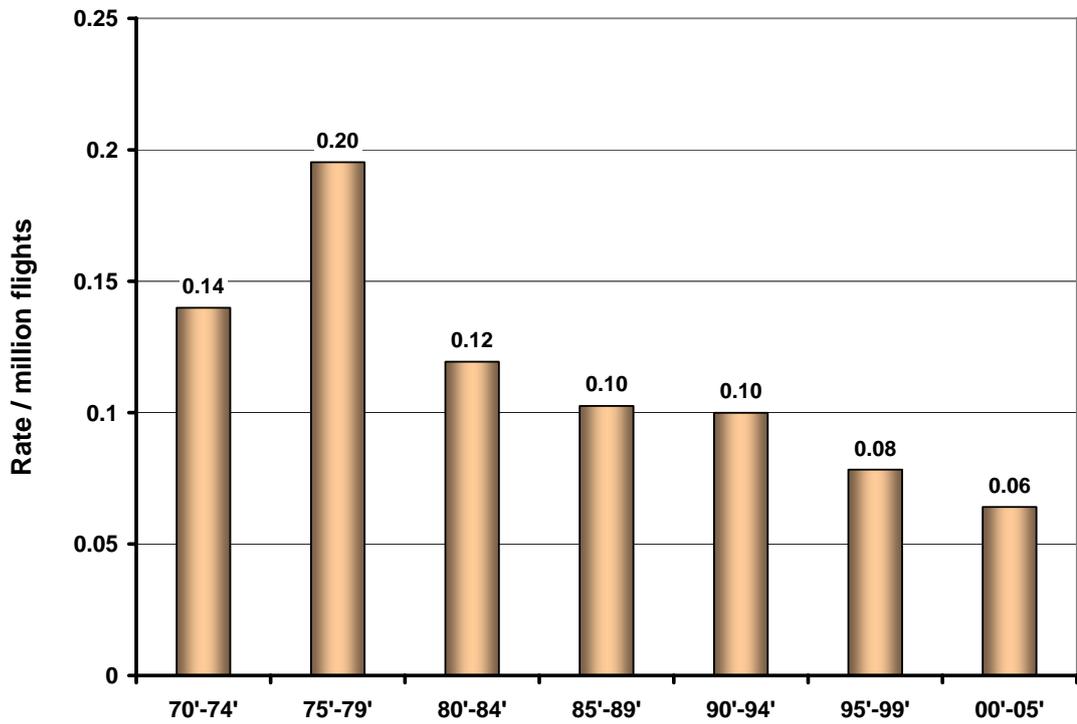


Figure 4: Trend in the accident rate (passenger and cargo flights combined)

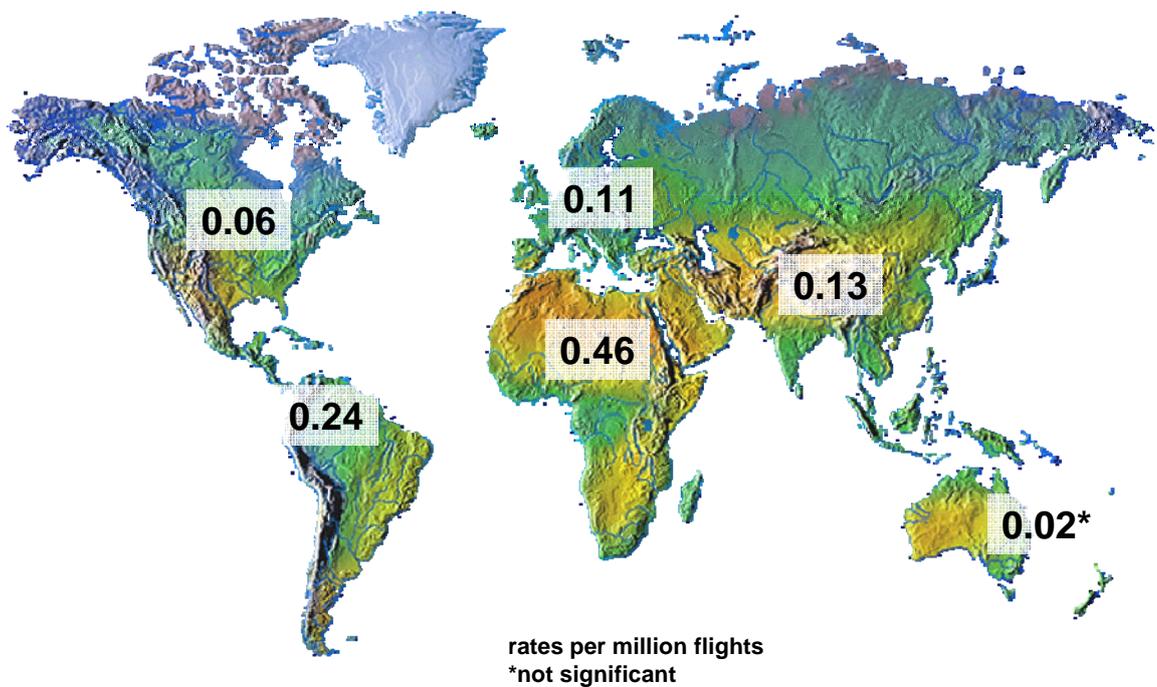


Figure 5: Accident rate by region (1970-2005)

Figure 3 shows the factors that are involved in accidents related to weight and balance. A distinction is made between passenger and cargo flights in this figure. Although there are some

differences in the frequency of factors between passenger and cargo flights, some care should be taken when drawing conclusions from this as the data sample of factors is not always sufficiently large to do so. However still some observations can be made with confidence. Shifted (not secured) cargo is a factor that is often present in cargo flights and is much less observed in passenger flights. Exceedance of the aft centre of gravity limits occurs more often than exceedances of the forward limit. This applies to both passenger and cargo flights. Overweight take offs occur more often than overweight landings³⁾. However there is no systematic difference between passenger and cargo flights when looking at overweight take offs and landings.

In Figure 4 the trend in the accident rate is shown for the study period. Data from both passenger and cargo flights are combined to obtain a sufficient high statistical accuracy in the calculated rates. The data show that over the years the accident rate of weight and balance related occurrences has reduced by a factor two.

In Figure 5 the distribution of the accident rate by world region is shown. It is clear from this figure that there exist large differences amongst the different regions regarding the accident rate. For reasons of statistical accuracy the whole study period studied is used to estimate the region rates.

3.2 Incident data

The NLR Air Safety Database contains a large set of airline safety reports obtained from more than 40 operators for the period 1998-2004. This database was also queried for weight and balance related incidents for the complete period covered in this database. Only the operational flight phases were considered (e.g. incidents when the aircraft was parked were excluded). It was not possible to distinguish between passenger and cargo flights in this set of data of the NLR Air Safety database. Some 1,200 weight and balance related incidents were found and analysed. Figure 6 shows the distribution of factors in the analysed incidents.

³⁾ Emergency and precautionary landings in which the aircraft was overweighted are excluded in the present analysis.

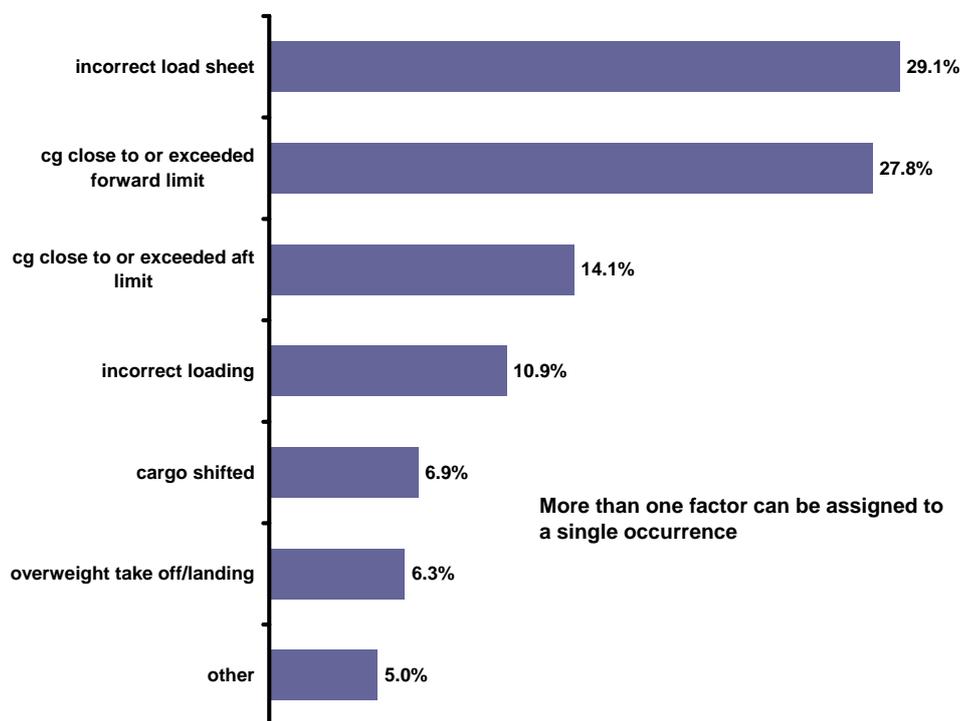


Figure 6: Distribution of factors in incidents (percent of all factors)

3.3 Discussion of results

The results presented in section 3.2 clearly show that are number of basic factors involved in weight and balance related occurrences. Both the accident and incident data show similar factors. The standard method used for aircraft weight and balance control is based on the use of the load sheet. Before each departure a load manifest has to be prepared. This manifest has to be accepted and approved by the captain. The items that have to be considered in the load manifest are numerous and many different people are involved in setting it up. This leaves plenty of room for errors. When looking deeper into the data some interesting root causal factors are observed⁴⁾. Typically causal factors are poor communication, time pressure, poor quality assurance within the ground agents' organisation, lack of training of flight/cabin crew, lack of training of ground agents' personnel and poor loading procedures. Communication in this case refers to the exchange of information on weight and balance issues between the flight crew and the ground agents, and within the ground agents' organisation itself. For instance important information regarding the last minute changes to the cargo is not communicated correctly to the pilots, or changes to the cargo are communicated by phone only which can easily be misheard. The analysed data shows that there is a higher likelihood of making errors when an unfamiliar aircraft is loaded by the ground agent. Often the ground agent had no written procedures for

⁴⁾ Unfortunately, not all analysed accident/incident reports contain such detailed information. However, it is believed that the underlying causal factors found apply to the majority of weight and balance related occurrences.

loading such an unfamiliar aircraft. The availability of unambiguous loading procedures is an important factor in avoiding loading errors. The amount of time spent on training of weight and balance related items are often limited both for flight crew as well as with ground agents. The data shows that better and more frequent training could help in avoiding weight and balance problems.

The presented data in this study show that the risk of a weight and balance related occurrence is much higher for a cargo flight than for a passenger flight. This observation would not come as a surprise to many. The results from Figure 3 suggest that this is mainly the result of accidents in which shifted cargo, that was not secured properly, was a factor. This was the case in 40% of all cargo accident flights and only in 10% of the passenger flights. Furthermore many of the accidents related with cargo flights analysed here involved smaller airlines that operated in regions with a low safety performance in general⁵⁾. These small cargo airlines were often found to have low standards and did not have a quality control system in place. Also the oversight by the regulators in some countries of these smaller cargo airlines and the ground agents was often found to be insufficient.

In 7 accidents from the data sample the control was lost during the approach after selecting landing flaps followed by the initiation of power increase and/or a go-around. The aircraft involved were all turbo prop aircraft and had a centre of gravity very close to or aft of the aft limit for landing. The 7 accidents all show a very similar pattern which is briefly discussed in more detail. Lowering the flap will move the neutral point forward and changes the pitching moment (this effect is not limited to propeller aircraft only). The pilot feels this as a tendency for the aircraft to pitch up and needs to push forward on the control column to hold a steady flight path by lowering the elevator. The pilot will re-trim the aircraft by winding the trim wheel forward which moves the trim tab to keep the elevator in the new position without the pilot having to maintain a push force on the control column. One feature of propeller driven aircraft is that when the engines accelerate from idle power to full power, the neutral point moves forward (up to 10% of the mean aerodynamic chord!). When due to incorrect loading the actual centre of gravity position is close to or slightly aft of the certified aft limit, the aircraft may be just stable during take off and cruise. However this situation can change during landing in which the aircraft may become unstable after lowering the flaps to landing position and may show a very strong pitch up tendency. The normal reaction to increase power to recover from the pitch up or to make a go-around will make things even worse as the neutral point moves forward significantly with the increase in power on turbo prop aircraft.

⁵⁾ Note that the (fleet) size of the operator itself was not identified as factor.



The change in the accident rate since 1970 shown in Figure 4 shows an optimistic trend. However the actual progress made in safety is rather small. For instance in the period running from 1980 to 1995, the accident rate remained nearly constant. Towards the end of the nineties rate started to drop again. It is difficult to say what has caused to this improvement. Most likely it is a combination of a number of factors.

The differences in accident rates for the different world regions as shown Figure 5 are not a surprise. These differences in rates can also be observed when considering overall accident rates for these regions. Clearly, the African region is the most vulnerable regarding weight and balance accidents. Surprisingly this is not caused by cargo flights. Passenger flights are more often involved in weight and balance related accidents in the Africa region.

3.4 Examples of some typically weight and balance related accidents

In this section a number of examples of typical weight and balance related accidents are presented and discussed.

Example 1: Overweight take off

B727-200 (PP-LBY), Fly Linesas Aereas, Quito airport, Ecuador, 01/05/1996. (source: NLR Air Safety Database)

During take off from runway 35 at Quito, the crew felt that the aircraft was not accelerating quickly enough and was not reaching the calculated V speeds. Therefore the crew elected to abort the take off at 120 knots ($V_1=143$ knots). The runway was wet and the available runway length left to stop the aircraft was only 900 meters (3000 ft.). The aircraft could not be stopped on the runway and overran the end. It came to rest some 130 meters from the runway end after having struck an ILS antenna and the airport perimeter fence. The maximum take off weight was exceeded by some 9,729 kg (+16%) for the conditions at Quito. It was determined after the accident that the crew had not calculated the weight and balance for the flight. Instead they had used the load sheet from a previous flight.

Example 2: Exceedance of aft centre of gravity limit during landing

F27-600 (G-CHNL), Channel Express (Air Services) Ltd, Guernsey, Channel Islands, United Kingdom, 12/01/1999. (Source: AAIB UK)

The aircraft was destroyed when it went out of control and crashed during the final stage of the approach to Runway 27 at Guernsey. After an uneventful flight, during the final stage of the approach, the pilot called for 'flaps forty' (the full down position) and the flaps were extended to this position. Moments after the wing flaps were lowered to their fully down position, the nose of the aircraft rose and the crew were unable to prevent it rising further. The nose continued to rise until the aircraft's pitch attitude was near vertical. Although the crew applied nose down



pitch trim and high engine power, the aircraft lost flying speed, stalled and entered an incipient spin. Returning the flaps to the intermediate approach setting of 26.5° and raising the landing gear did not restore controllability. It descended in a shallow nose down pitch attitude with little forward speed and crashed at the rear of a private house, striking the house with its port wing. Both the house and the aircraft caught fire. The two pilots were killed but the sole occupant of the house escaped without physical injury.

The aircraft was operating a flight from Luton with a cargo of three tonnes of newspapers. Prior to departure, the cargo had to be hand loaded. However, neither the load team leader nor the dispatcher had loaded an F.27 before nor did they have a load plan to assist them. They therefore asked the captain how to proceed. The captain reportedly replied along the lines 'from the back' or 'put it all in the rear.' Subsequently the loading team stacked the papers in even piles, some 2ft. 6in. high, across the width of the cabin, working from a point in line with the rear doors forward. The papers eventually extended forward for an estimated distance of between one quarter and one third of the length of the cabin. As a result, the aircraft's centre of gravity ended up significantly aft of its approved limit and it became uncontrollable once full flap had been selected for landing.

The crew of the aircraft appeared to have taken only limited interest in the loading. The comments made by the investigators was that 'this behaviour contrasts strongly with the commander's careful manner and thorough attitude whilst actually flying' and suggests that 'either he was not aware of the importance of load positioning and restraint or that he was not sure how to direct and supervise the loading operation.' No official 'load planning' tables were provided for the flight crew to use. Crews were apparently expected to devise a load plan by 'trial and error' using the balance chart on the load sheet. The investigators commented that this could be time consuming and not as error resistant as pre-planned tables. Additionally, it was noted that loading procedures were not a structured element of the command training syllabus and there was therefore an element of chance that new commanders might not be properly trained in this area. This accident was provoked by operating the aircraft outside the cleared load and balance limitations. This error went undetected because nobody ensured that the cargo distribution in the aircraft was the same as that shown on the load and balance sheet.

Example 3: Exceedance of forward centre of gravity limit during take off

Convair 880, N5865, Air Trine, Miami International Airport, USA, 16/12/1976 (source: NLR Air Safety Database/NTSB)

The Convair 880 was loaded with a cargo of cows. Following an apparently normal take off run on Runway 09L reaching the rotation speed, the aircraft would not rotate despite repeated efforts by the crew including re-trimming the aircraft to the 'full nose-up' position. The pilot

subsequently elected to abort the take off but was unable to bring the aircraft to a stop before the end of the runway. After leaving the runway, the aircraft passed over an area of soft ground, where its nose undercarriage collapsed, before falling into a wide drainage canal. The investigation determined that on take off the aircraft's centre of gravity was some 2.2% of the mean aerodynamic chord in front of the maximum forward limit, due to the way the aircraft had been loaded, and that the crew's weight and balance calculations bore no resemblance to the way the weight was actually distributed.

Example 4: Overweight take off with an exceedance of forward centre of gravity limit B727-200, 3X-GDO, Union des Transports Africains, Cotonou, Bénin, 25-12-2003 (source: BEA Bureau d'Enquêtes et d'Analyses pour la Sécurité de l'Aviation Civile, report translation 3x-o031225a)

On December 25th, 2003, a Boeing 727 operated by the Union des Transports Africains (UTA) crashed during take off from Cotonou. There were at least 160 people on board and only 22 survived. Passenger boarding and baggage loading was carried out in great confusion. For flight preparation, incomplete information on the loading was provided to the Captain. He had determined the configuration for take off on the basis of this information. The investigation showed that, after the brakes were released, the aircraft accelerated up to rotation speed. As the forward hold had been filled, the aircraft had a significant forward centre of gravity that the crew had not compensated for with the stabiliser because they had not been informed of the loading of this hold. The pilot's nose-up input thus did not have an immediate effect and it took seven seconds for the aircraft to leave the ground, with a very low slope angle. The aircraft hit a building located on the extended runway centreline, crashed onto the beach and ended up in the ocean. The investigation also showed that, without the uncompensated forward centre of gravity, the aircraft would have taken off despite its excess weight. The investigation concluded that the accident was due to the crew's difficulties in performing the rotation with an overloaded aircraft with a forward centre of gravity that they were unaware of.



4 Onboard Aircraft Weight and balance Systems

The majority (more than 90%) of weight and balance problems identified in this paper could be eliminated if there was a system available to the flight crew that would do an automatic onboard weight and balance assessment. In the past accident investigation boards have often recommended the development of such *primary*⁶ onboard weight and balance systems. For instance the NTSB recommended to conduct or sponsor research to develop systems that are capable of delivering actual aircraft weight and balance data before flight dispatch after the accident with a Beech 1900D that occurred on January 8, 2003. Another example is the recommendation made by the French BEA after the accident with a B727-200 operated by UTA (Union des Transports Africains) on 25 December 2003. The BEA stated that *“knowing the true weight and balance of the airplane would most likely have enabled the crew to avoid the accident. In addition, erroneous estimates of these parameters are quite likely during operations. Onboard autonomous systems are, however, available and they give an indication of the airplane's weight and balance that is sufficient to attract the crew's attention in case of an abnormal situation. Consequently, the BEA recommends that: the civil aviation authorities, in particular the FAA in the United States and the EASA in Europe, modify the certification requirements so as to ensure the presence, on new generation airplanes to be used for commercial flights, of onboard systems to determine weight and balance, as well as recording of the parameters supplied by these systems; the civil aviation authorities put in place the necessary regulatory measures to require, where technically possible, retrofitting on airplanes used for commercial flights of such systems and the recording of the parameters supplied.”*

Attempts to develop an onboard weight and balance system go back to the 1940's. Unfortunately, many of those attempts failed to deliver a system that was accurate and reliable enough to be used as a primary system. Therefore implementation of onboard weight and balance systems has been limited. In 1998, an evaluation of the reliability of onboard weight and balance systems conducted by the FAA showed that (cargo) operators had concerns with onboard weight and balance systems. Operators noted reliability problems resulting in unnecessary delays and maintenance burden. However, their biggest concern was with the accuracy of the system. Large differences were noted between the centre of gravity position determined by the onboard systems and the centre of gravity position determined by the operator's primary weight and balance method. These large differences and the reliability problems resulted in a lack of confidence in the system by the flight crew. These issues generally result from the wide range of the operating environment the onboard systems have to deal with. In many cases the system was deactivated by the operators due to these reliability and

⁶ This means that this system is used by the operator as its primary means of calculating weight and balance.



accuracy problems. Therefore the FAA stated (in 1998) that the results of its evaluation did not support imposing a requirement to install a system that displays airplane weight and balance and gross weight in the cockpit of transport-category cargo airplanes.

Specifications drafted for onboard weight and balance systems state that the system shall be capable of measuring the gross weight within an accuracy of 1% and the aircraft centre of gravity within 1% of the mean aerodynamic chord (see FAA AC-120-27E). For a large jumbo jet with a mean aerodynamic chord of 8.3 meter this would mean that the system shall be accurate within 83 mm. The system must also self-detect any fault which would significantly degrade the accuracy, so that the probability of an undetected catastrophic fault is less than 1 in a **billion** flight hours. It is clear that these requirements are very tough demands for a *primary* onboard weight and balance system. Also maintainability of the system is often a problem. This is something that cannot be ignored if an onboard weight and balance system is to become successful.

The most typical onboard weighing system consist of a set of strain sensing transducers in each main wheel and nose wheel axle, a weight and balance computer, and an indicator of the ground attitude of the aircraft. The strain sensors measure the amount each axle deflects and send these data into the computer, where signals from all of the transducers and the ground attitude sensor are integrated. The technical aspects of onboard aircraft weighing systems are too complex to discuss here in great detail. However, it can be easily understood that designing a certifiable primary onboard weight and balance system that works with high a reliability and accuracy under various harsh conditions (high and low temperatures for instance) is very difficult. Despite these difficulties, systems (not primary) for onboard aircraft weighing are available for a number of (mainly) large transport aircraft such as the Boeing B747-400, the MD-11 and the Airbus A300, A320, A330/340. In the NLR Air Safety Database there are a number of examples of incidents in which onboard weight and balance systems saved the day. Indeed an accurate onboard weight and balance system can help in mitigating most weight and balance related occurrences. However, some example incidents also showed their weakness if they are not properly used. New patents are filled regularly for onboard weight and balance assessment systems showing that the ideal system has not been developed yet. Still these systems are often too expensive to be introduced on all aircraft types and for now they are mostly used on large aircraft. However a secondary weight and balance systems could still be of some value in preventing weight and balance related accidents. On some civil transport aircraft such secondary systems are standard.

The advances of a primary onboard weighing system go further than safety only. In fact the operator can gain more operational flexibility and reduce cost. In theory a primary onboard

weight and balance system should measure the actual weight and centre of gravity location of an aircraft. As a result an operator may not need to include certain curtailments to the loading envelope to account for variables such as passenger seating variation or variation in passenger weight giving more flexibility. However, an operator still needs to curtail the loading envelope for any system tolerances that may result in centre of gravity or weight errors.

As an alternative to onboard systems there are efforts to develop systems to rapidly weigh and automatically track passenger and baggage weight and location data as passengers board aircraft. The rapid development in different technological advances such as hand-held devices and wireless bar code scanners indicate that it may be feasible to compile actual weight data and account for the weight location, which can result in a reliable calculation of actual aircraft weight and balance.

5 Conclusions

The following conclusions are made:

- The risk of having a weight and balance related accident with cargo flights is 8.5 times higher than with passenger flights;
- There are various factors involved in weight and balance accidents/incidents such as errors in the load sheet, shifting of cargo, incorrect loading etc. No single factor could be identified in the present study that had a very dominant influence. However, load sheet errors, incorrect loading, and shifting of cargo seem to be the most important factors. Typically root causes to weight and balance related occurrences are poor communication, time pressure, poor quality assurance within the ground agents' organisation, lack of training of flight/cabin crew, lack of training of ground agents' personnel and poor loading procedures.
- Large regional differences in the weight and balance related accident rate are identified. The African region showed the highest accident rate and the North American region the lowest;
- Worldwide the weight and balance related accident rate shows a slow improvement since 1970. Nevertheless the accident rate has reduced by all most 50% in 35 years;

- The amount of time spent on training of weight and balance related items are often limited both for flight crew as well as with ground agents. The analysed occurrence data show that better and more frequent training could help in avoiding weight and balance problems;
- Primary onboard aircraft weight and balance systems could resolve most of the weight and balance problems identified in the present study. However the accuracy and reliability of such systems is currently insufficient to enforce the use of these systems on commercial aircraft as primary means for determining the weight and balance. However secondary weight and balance systems could still be of some value in preventing weight and balance related accidents.

Recommended reading material

The following documents are recommended to anybody how wants to get more background information on aircraft weight and balance issues:

- Getting to grips with weight and balance, Flight Operations Support & Line Assistance, Airbus, 2004.
- Aircraft Weight and Balance Handbook, FAA, FAA-H-8083-1, 1999.
- Aircraft weight and balance control, FAA advisory circular, AC-120-27D, 2004.

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