Understanding the Contribution of Degraded Modes of Operation as a Cause of Incidents and Accidents in Air Traffic Management

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Abstract. This paper charts the role that 'degraded modes of operation' have played in a number of recent accidents and incidents in European Air Traffic Management. A central aim of this analysis is to identify and begin to understand why teams of co-workers continue to operate safety critical systems even when key elements of their technological infrastructure have been compromised, for example during routine maintenance. There is often a culture of 'making do' where managers and employees try their best to maintain services. The extent to which workers will adapt to degraded modes illustrates the flexibility and resilience of socio-technical systems. However, it can also endanger safety when infrastructure changes act to increase workload or remove necessary safety nets. It is, therefore, hoped that by studying previous incidents and accidents we can ultimately help operators and managers to understand the dangers of degraded modes of operation while at the same time supporting the flexible working practices that are necessary in many complex, safety-critical systems.

1. Introduction

From 1995 to 2000, the worldwide accident rate was 1 in every 1.25 million flights. This improved between 2001 and 2005 to 1 accident in every 2 million flights. However, there is a well-justified concern that the increasing numbers of departures in many regions of the world will act to offset this improvement in the accident rate. It is, therefore, critical that we learn as much as possible from the relatively small number of accidents that do occur.

'Degraded Modes of Operation' have been a common feature in the causes of many recent accidents and incidents within European Air Traffic Management (Johnson, 2006). As we shall see, the Linate runway incursion was in part caused by a gradual erosion of safety related systems including taxiway lighting and previous generations of ground movement radar; factors which contributed to a degraded working environment. The Überlingen mid-air collision occurred when Air Traffic Control Officers (ATCOs) had to perform the manual correlation of radar plots and flight plans during a planned upgrade.

1.1 Degraded Modes and Latent Causes

It can be difficult to derive precise definitions of what is meant by a 'degraded mode of operation'. Few safety-critical systems can provide continued services over long periods of time without suffering minor equipment failures. Hence most applications are routinely operated for short periods of time with some form of 'degraded' functionality. In general, these faults are rectified without significantly endangering safety. However, there is usually an understanding that the risks associated with minor faults will only be tolerated for limited periods of time and that they will not be allowed to affect core system functionality. Equally, however, there are faults that are not rectified over many months and years. Operators and managers find ways of 'making do' without some of the support systems that were originally developed to assist critical tasks. These long-term failures are often termed 'latent causes' because they may persist without necessarily causing any immediate safety concerns until a trigger event leads to an incident or accident. Degraded modes of operation and latent failures are obviously related. If a degraded mode is not addressed promptly then over time it will become a latent weakness that can eventually cause an adverse event.

Designers have sought to address the dangers of a gradual drift from degraded modes into latent failures by requiring that operations-managers develop corrective action plans that specify when and how faults will be addressed. There have also been attempts to develop *minimum equipment lists.* These enumerate the core systems that must be provided in order for operations to continue safely. If periodic failures remove these core functions then no exemptions should be granted and operations should be halted.

Minimum equipment lists do not provide the flexibility that is often necessary to support the operation of complex systems in dynamic environments. The importance of specific safety-related applications cannot be determined without some knowledge of existing environmental conditions. Operators will then draft a number of different minimum equipment lists; each of which is intended for use under different operating conditions. The Linate incident, reviewed in this paper, illustrates the impact of degraded modes of operation that culminated in a runway incursion. Linate is governed by ENAC procedures which state that operations must be changed in response to various environmental conditions and available equipment. In particular under low visibility conditions, ENAV DOP 2/97 specifies strict limits on the number of ground movements that can be performed should radio communications and ground movement radar systems be compromised (ANSV, 2004, p.53). The use of MELs is not confined to Air Traffic Service providers. A second case study in this paper involves an aircraft that began to flag a failure on the 'total temperature indicator' Ram Air Temperature (RAT). The airline's "Minimum Equipment List (MEL) authorizes the flight under acceptable deferred defect conditions, providing the Engine Pressure Ratio (EPR) limits are defined manually" (BEA, 2000, p.34). The operating company enforces this use of minimum equipment lists under circumstances where EPR limits cannot be calculated accurately. Under other conditions it remains acceptable to defer maintenance using corrective action plans or 'deferred defect conditions'.

The use of minimum equipment lists and corrective action plans are important elements within the best safety management systems (SMS). However, they require active support from middle and upper levels of management if they are to be preserved in the face of sustained commercial pressure to continue operations under adverse conditions. Hence there is a strong link between an organisation's 'safety culture' and the manner in which it preserves adequate safety margins in the face of latent failures and degraded mode operations. Conversely, accidents and incidents show that latent failures and the longer term acceptance of degraded mode operations is often strongly related to deeper issues around safety management within complex organisations.

1.2 The Case Study Incidents

We focus on three case studies. The Überlingen mid-air collision and Linate runway incursion are the most serious ATM-related accidents to have occurred in Europe over the last decade. The extreme consequences of these adverse events justify their inclusion in the study. However, the relatively low frequency of such adverse events also limits the insights that can be drawn from their 'pathological' combinations of latent causes and more immediate failures. The final case study focuses on an accident at Paris' Charles de Gaulle airport. Although this resulted in far fewer fatalities than the Linate and Überlingen accidents, there are strong similarities that justify the inclusion of this case study. Our selection was also motivated by the range of countries involved. The incidents provide insights into latent problems and degraded modes of operation across France, Italy and Switzerland.

The Überlingen accident occurred on the 1st July 2002 when a Boeing 757-200 was involved in a mid-air collision with a Tupolev TU164M (BFU, 2004). A total of 71 crew and passengers were killed on both aircraft. The immediate causes of the accident centred on the Air Traffic Control Officer's (ATCO) instruction to the Tupolev crew, which contradicted the Traffic Alert/Collision Avoidance System (TCAS) on-board warning system. The ATCO ordered them to descend in contradiction to the TCAS instruction causing them to collide with the Boeing 757 which was also responding to a TCAS warning to avoid the other aircraft. The official BFU report into the accident was issued in 2004. It provides a relatively thorough analysis of the causes that led to the confusion over the warning from the TCAS software. Scheduled maintenance procedures exacerbated some preconditions which increased the likelihood of the ATCO making a mistake. Our paper focuses on the consequences of latent failures and degraded modes of operation for the staff in the Zurich Air Traffic Control Centre.

The Linate accident happened on the 8th October 2001 when an MD-87 was taking off from runway 36R at Milan's Linate Airport (ANSV, 2004). The MD-87 collided with a Cessna 525-A, which taxied onto the runway. The MD-87 carried two pilots, four attendants and one hundred and four passengers. The Cessna carried two pilots and two passengers. All occupants of the aircraft were killed along with four ground staff who were working in a baggage handling building struck by the MD-87 immediately after the runway collision. The official ANSV report identified the human factors causes that led the Cessna's crew to mistakenly cross the active runway under low visibility conditions. It also balanced these factors against a number of organizational and technical limitations in the systems in the airport's operational environment that created the preconditions for the accident.

The final case study focuses on a collision between an MD-83 and a Shorts Brothers 330 aircraft at Paris' Charles de Gaulle airport (BEA, 2000). The MD-83 was cleared for take off on runway 27, while the Shorts was then cleared to line up and wait as 'number two'. The official BEA report argued that the controller believed both aircraft were at the threshold of the same runway and that the Shorts should, therefore, have waited for the MD-83 before entering the runway. However, the Shorts had been cleared to use an intermediate taxiway and so entered the runway just as the MD-83, already moving down the runway for take off had reached rotation speed. The wing of the MD-83 entered the cockpit of the Shorts. It immediately killed the First Officer and left the Captain seriously injured. The conclusions from the accident report found that contributory factors included increased workload for operational staff including ATCOs at the time of the accident, light pollution which impeded visibility from runway maintenance operations as well as existing operational procedures and working methods.

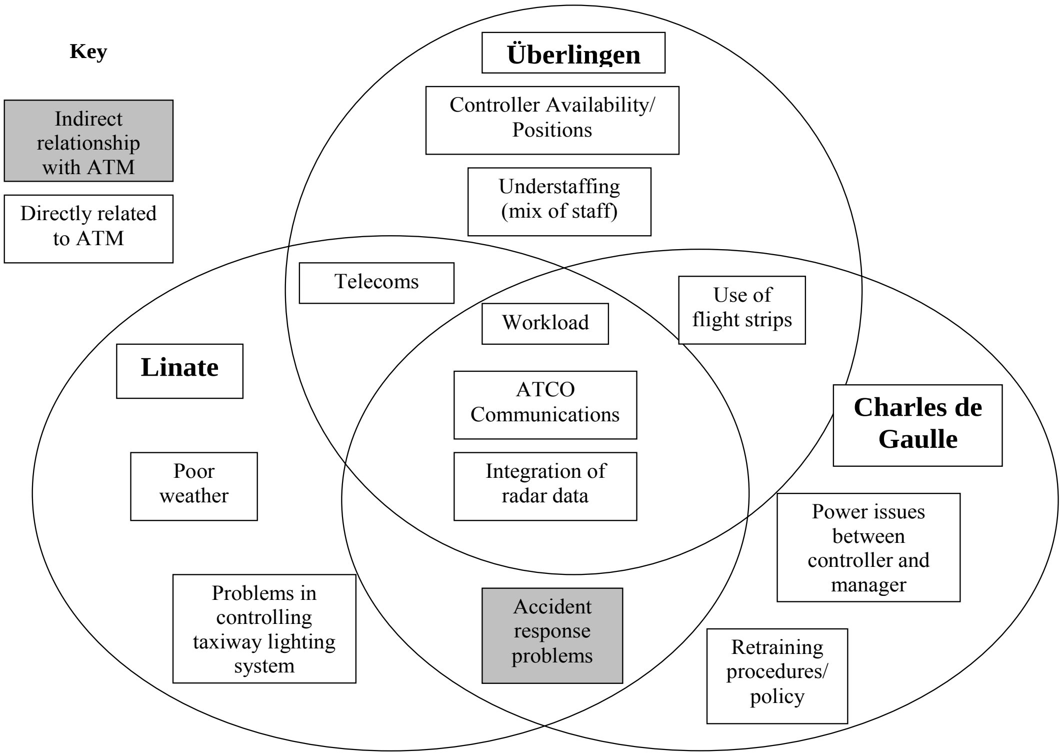

Figure 1: Different Aspects of Degraded Modes in the Case Study Incidents

1.3 Overview of the Paper

Figure 1 provides an overview of the relationships between these adverse events. It represents the results of an initial analysis in which we map aspects of degraded modes of operation in each of the case study incidents. Certain aspects were common to each of the accidents. For example, the diagram identifies 'ATCO communications' as a factor in all three incidents. To improve our understanding and potential to manage degraded modes of operation we must look in much greater detail at the circumstances surrounding each of the case studies. For example, the radar problems at Charles De Gaulle refer in part to the ASTRE system that "was not functioning correctly. The only visible echo attributable to aircraft in probable waiting positions on runway 27 could be seen at the runway 27 threshold. Radar operation was therefore not at all satisfactory, though no doubt was cast on the information displayed" (BEA, 2000, p.40). Similarly, the Überlingen accident occurred when system modifications work affected the ADAPT radar data processing and presentation system as well as MV9800 Multi radar data computer (BFU, 2004, p.38). The Linate runway incursion occurred at a time when the Surface Movement Radar system was not available to Air Traffic Control Officers. The previous Aerodrome Surface Movement Indicator (ASMI) radar at Linate was analogue. However, increasing traffic had exposed the unreliability and low definition of this system and a plan was made to introduce a NOVA 9000 Surface Movement Guidance and Control System (SMGCS) using video camera technology. The old AMSI system was taken out of service three years before the accident. However, plans to install the new system stalled when objections were raised over the proposed location for antennae. Consequently the operators lacked critical infrastructure resources.

Although these three different incidents were all in part caused by problems in using radar information to support the ATCO's tasks, the circumstances are very different. These circumstances can be used to illustrate the differences between latent causes and degraded modes that were introduced in the previous section. At Überlingen, the changes in radar resources were a consequence of short-term scheduled maintenance and led to a degraded mode of operation. At Linate and Charles de Gaulle, the radar problems were more persistent and hence can be viewed as latent causes that were triggered by the other more immediate failures that led to these accidents.

The following sections build on this initial analysis by providing more specific insights into the infrastructure failures that characterize latent causes and the degraded mode operations in all three case studies. We also identify interconnections between these infrastructure issues and the other factors identified in Figure 1. We argue that it is necessary to look beyond the impact of specific equipment and individual failures and investigate the interactions between these problems for instance, workload increases in relation to equipment failures in the hours and minutes before each accident set against the limits of human adaptation to longer term problems in equipment provision.

2.0 PRELIMINARY CONTRIBUTORY FACTORS IN EACH INCIDENT

Many accidents occur because organisations fail to learn from the insights that are provided by precursor incidents. This is unsurprising given the difficulty of extracting critical insights from the background 'noise' from spurious internal incident reports and problems such as under reporting. However, many incidents are the result of latent causes that are created by a steady degradation of infrastructure support over a prolonged period of time. Other accidents stem from degraded operating modes. These are short-term but planned changes in an operating environment. The potential consequences of these degraded modes are often known to key individuals in the organisation but may not be communicated to all co-workers, for example through organisational mismanagement.

2.1 The Organisational Response to Precursor Incidents Involving Degraded Modes of Operation

All three case study incidents had been preceded by superficially similar precursor incidents. For example, the Charles De Gaulle runway incursion had much in common with two airprox incidents that had occurred in the two years before the case study accident reviewed here. The first occurred in October 1998 when an aircraft lined up on runway 10 (now runway 08L) from an intermediate access taxiway while another aircraft was cleared to take off from the runway threshold. The second almost identical incident occurred in May 1999. An aircraft had received instructions to line up on runway 08L from an intermediate access taxiway while another aircraft was cleared to take off from the runway threshold. After the October 1998 incident, steps were taken to address some of the perceived problems that had led to the airprox following the opening of a parallel runway at Charles De Gaulle. These included:

- "development of pilots' and controllers' awareness of the parallel runway characteristics and the specific management of runway crossing, via the production of a widely distributed video;
- creation of the Prevention and Safety Group;

- acquisition of a high performance runway control simulator providing 360° viewing capability, and implementation of an intensive training programme for the controllers;
- transfer of South LOC position to the South Tower for improved visibility;
- installation of a second "ASTRE 2000" ground radar in the South Tower, to supplement the radar already installed in the North Tower" (BEA, 2000, p.36).

However, these measures were not reviewed after the airprox of 17 May 1999 though there were sufficient similarities between the two incidents to suggest that existing recommendations had not adequately addressed all of the underlying causes. Significantly these two previous incidents reveal that crucial safety concerns had been acknowledged - even under near optimal conditions. In retrospect, it is possible to argue that degraded mode operations acted to compound these latent or underlying concerns. It appears that there was no systematic approach to learn from incidents and subsequently manage appropriate changes.

There were also precursor incidents to the mid-air collision at Überlingen. Two previous airproxes had occurred at ACC Zurich under what were known as Single Manned Operation Procedures (SMOP). The SMOP procedures had emerged informally over time. Historically, three ATCOs were rostered during night shifts. During quiet times, two controllers remained at their positions while the third took a break. However, this practice persisted even as recruitment and staff retention problems within the ANSP forced the introduction of two-ATCO rosters. In consequence, a single ATCO was left at their post while their colleague took a break. It should be reiterated that this informal practice was never approved for night operations and SMOP guidance was only developed for use during daytime shifts. However, two previous incidents had already led the Swiss BFU and BAZL to raise questions about these operations. ACC Zurich defended their practice by stating it was common in other European states. As noted in the Charles de Gaulle incident, no formal risk assessment was used to assess the acceptability of current or future practice though it appears that the ANSP felt that SMOP was not an acceptable operating mode over the longer term. Again we can see that the degraded operating modes which held at the time of the accident served to exacerbate the latent causes revealed by the previous incidents. The BFU's official report into the accident records that the ATCO's working environment failed to meet the requirements for SMOP because: "The radar system was being operated in the fallback mode and the optical STCA was not available; the telephone system was not working properly; the technicians working in the control room added to the controller's stress; operating two workstations with two different sectors from radar screens set to different scales was an additional strain and would probably not have been accepted by a DL although traffic flow was low; the ATCO could not use a headset as he was operating radios of two workstations. The regulatory authority had already voiced concern about SMOP. The general work conditions during the night shift and the additional strains of the night of the accident did not meet the requirements for SMOP" (BFU, 2004, p.92).

The ANSV lists five similar incidents to the Linate runway collision. Four of these occurred before the accident that is the focus of our case study while the final incident occurred in spite of interim safety improvements. One of these similar incidents occurred only twenty-four hours before the collision. An aircraft taxied along TWY R5 instead of R6; the Controller was only alerted to the incident when the crew realized their mistake. In the accident we review here, the Cessna crew followed taxiway R6 instead of R5. There had been some attempt to address the latent problems that led to the Linate runway incursion. In November 1999, responsibility had been delegated to the officer in charge of traffic inspections to monitor the 'environmental conditions' associated with the runways and taxiways. However, no explicit mention was made of the types of inspections that might be appropriate to meet this objective. There was a range of modifications to the runway and taxiway infrastructure at Linate that did not meet ICAO requirements. These included a non-standard stop sign before runway 18L/36R, the 1992 deactivation of white flashing lights at the runway intersection, the 1998 decision to deactivate incursion detectors etc. The inconsistent signage created problems for the aircrews that had to navigate onto appropriate runways and may explain the previous runway incursion incidents. Further problems were created by ATM personnels' lack of control over critical sections of runway and taxiway lighting. ATCOs could no longer alter the configuration of these light sources to provide positional cues to aircrew. Some of the inconsistencies with ICAO regulations and wider safety provisions stemmed from decisions made 7 or 8 years before the accident. The fact that they had not been addressed after previous incidents arguably reinforces the need for improved Safety Management Systems. It also underlines the need to provide better support for responsible individuals, such as the 'officer in charge of traffic inspections', and groups, including the 'runway safety teams' anticipated by the working groups on runway incursion. Thepoor runway environment at Linate evolved over many years. It seems clear that many of the deficiencies had been accepted as ‘normal’ prior to the accident. Management could argue that there had been no serious accidents even with the current marking problems, the lack of lighting control and the deactivated incursion sensors. However, the previous adverse incidents could equally have provided warnings about the potential consequences of these latent problems when they were combined with the degraded ‘low visibility’ operations that held at the time of the accident.

In hindsight we can argue that information about earlier incidents could have alerted operational staff and line management to the dangers of potential accidents. As we have seen, most of these precursor events did not result in severe, adverse consequences. However, it is the combination of the existing latent problems and the ‘degraded operations’ that triggered each incident. Unfortunately, operational staff cannot have the foresight to predetermine which particular features from a mass of previous incidents are the most likely to lead to future problems under degraded mode operation. The scale of this problem is illustrated by an analysis of adverse events recorded by the Aéroports de Paris (ADP) feedback system in September 2000, shortly after the runway incursion at Charles de Gaulle. Of the 33 events that were recorded in the system, three related to potential collisions during take off and one to landing (BEA, 2000, pp.26-7). The circumstances in each of these incident reports varied markedly hence it is unclear how to use such information in a systematic manner to identify the latent problems that are often exposed by the particular triggers of human error and system failure that arise under degraded modes of operation.

The use of reporting systems, often instituted as a first step to collecting incident information in order to begin learning from incidents, may be less successful than anticipated due to concerns about their anonymity and effectiveness. For example, the BEA report into the Charles de Gaulle collision record that “for events which do not lead to filing an Airprox, controllers may now fill in (anonymously if they wish) a feedback form when they deem the event has jeopardised safety. This form is also analysed by the Quality and Safety subdivision. This incident reporting procedure was first used in October 2000, but it is seldom used” (BEA, 2000, p.35). The BFU also note in their report on the Überlingen accident that “the internal reporting scheme for safety-relevant incidents (OIR, Operational Internal Reporting) suffered from lack of acceptance by some of the controllers. They suspected it might be used for punitive action. This is why it was inoperative as a confidential internal reporting system for identifying error sources” (BFU, 2004, p.91). Ultimately it makes a difficult job harder when trying to identify latent failures from incomplete sources of information.

2.2 Consequences of Degraded Modes across the Functional Boundaries between ATCOs and Aircrews

The operational shortcomings of ATM systems form part of a wider picture of suboptimal systems. For example pilots must often cope with partial system failures at the same time as ATCOs are finding ‘work arounds’ for infrastructure problems. In the Charles de Gaulle incident, limitations with the ASTRE radar system may have prevented the controllers from identifying the Shorts as it approached the runway. At the same time, the crew of the MD83 were struggling to resolve a Ram Air Temperature (RAT) warning. The Cockpit Voice Recorder indicates that this failure made it impossible to use the automatic throttle and consumed finite resources of time and attention in the moments before the accident. The First Officer for example was forced to consult documentation to prepare the engine operating parameters in the absence of automatic throttle and then to verify the associated engine parameters once they had been set (BEA, 2000, p.20).

The same latent, infrastructure problems that complicated the ATCOs’ tasks at Linate incident also exacerbated the difficulties that faced the aircrews under ‘degraded’ weather conditions. Previous sections have described how the use of inconsistent signs and inadequate control over runway and taxiway lighting made it difficult for controllers to identify the precise locations of the aircraft. The same issues added to the complexity that flight crews had to face when attempting to follow the directions and instructions issued by the ATCOs. The “lack of position, direction, location signs and proper markings on the West apron were three factors that made situation awareness for the Cessna crew difficult. When the Cessna commenced taxiing, albeit in the wrong direction, position and direction signs were missing all the way up to the only and final sign CAT III before entering the main runway 18L/36R, the active runway. Further on, taxiway designators showing R6 along the taxi route would have served the purpose of a ‘trigger’ to the Cessna crew.

So would also a ‘runway vacated’ sign 150 meters from the centre line of the main runway 18L 36R” (ANSV, 2004, pp.106-7).

The degraded mode of operations that affected both the ATCOs and the flight crews at Linate and at Charles De Gaulle can be contrasted with the events leading to the Überlingen mid-air collision. In this accident, it cannot be argued that the aircraft suffered from technical failures. In particular, the Traffic Collision Avoidance System (TCAS) worked ‘flawlessly’ on both the TU154M and the B757 (BFU, 2004). The system correctly issued advisories for TU154M to climb and for the B757 to descend. However, the TU154M crew followed the ATC instruction to descend and continued to do so even after TCAS advised them to climb” (BFU, 2004, p.112). Hence the problems did not result from any malfunction in the TCAS system but, arguably, from the interaction between the ATCO, who’s working situation was degraded affecting his decision making, and the actions taken by the crew of the B757, who ignored the automated advisories from TCAS.

There were also notable and significant flaws in the *design and regulation* of the TCAS systems; “The integration of ACAS/TCAS II into the system aviation was insufficient and did not correspond in all points with the system philosophy. The regulations concerning ACAS/TCAS published by ICAO and as a result the regulations of national aviation authorities, operational and procedural instructions of the TCAS manufacturer and the operators were not standardized, incomplete and partially contradictory” (BFU, 2004, p.112). In particular, it was unclear whether or not aircrews should follow the TCAS advisories or the ATCOs instructions when there was any conflict. The official investigation voiced a clear opinion in the aftermath of the accident “TCAS only makes sense if worldwide all crews rely on the system and comply with the advisories... The crew must comply with the RA without delay and report the initiated TCAS manoeuvre to the controller. Any other procedure which does not sufficiently take into account the priority of an RA would be contradictory to the purpose of TCAS” (BFU, 2004, p.77). Subsequent changes to the TCAS system arguably provide valuable insights into design issues that weakened or degraded previous versions of these applications. For instance, recent versions of TCAS generate ‘Reversal Resolution Advisories’. These change the direction of the initial advisory as further information is obtained about the likely position of any other aircraft involved in a conflict. Such additional functionality increases system complexity and there is a danger that this may create further risks. Hence the conditions in which a reversal can be issued are tightly defined in order to “maintain the trustworthiness of TCAS” (BFU, 2004, p.78).

3.0 PERFORMANCE RELATED FACTORS

Much effort has been devoted to understanding and assisting ATCOs in safely managing the complexities of air traffic control particularly as air traffic rapidly increases. (see for example Endsley and Smolensky, 1998) Our aim in this section is to identify at a high level the common factors across the three incidents that negatively impacted ATCO performance during the ‘degraded operations’ in each incident.

3.1 Workload

Workload i.e. the demands or load placed on a person’s cognitive processing abilities has been shown to significantly influence how efficiently and effectively individuals process information and make decisions. As Lichacz (2005) noted in his study of the effects of combined stressors on dynamic task performance ‘ATC performance was susceptible to the effects of time pressure and workload’. Traffic complexity and volume also had an impact. A review of our incidents suggests that workload may have been a contributory factor in each case and can be considered as a contributory factor in the degraded modes that lead to adverse events.

At the time of the Linate collision, visibility was reduced to between 50 and 100 meters. From 05:10:47 to 06:10:21, when the accident occurred, controllers had assisted 24 aircraft varying between English and Italian depending on the crews. There was no possibility of using technical means to verify the position of these aircraft and several messages were relayed to each crew during this interval. This combination of traffic density, poor technical infrastructure and meteorological conditions created a ‘demanding’ environment for the ATCOs (ANSV, 2004, p.4). Immediately before the Charles de Gaulle runway incursion both the controllers and one of the aircrews were under considerable additional workload. The ATCOs had to coordinate additional flights associated with the Champions League final between Madrid and Valencia in Paris (BEA, 2000, p.27). A number of measures had been introduced the ease the additional workload on staff at Charles de Gaulle. These included extending the use of approach room from 21:45 until 00:45, using three runways; increasing the number of controllers and setting up a special operations centre. An engineer was provided on “standby” to the controllers and another liaised between the tower and the special operations centre to identify any flights that might be delayed (BEA, 2000, p.27). Meanwhile, increasing levels of workload also affected the flight crews. While the pilot and co-pilot of the MD83 lined up on the runway, they “were preparing the aircraft and performing the pre-takeoff checks; taking into account the malfunction on the auto throttle, their workload had increased”. (BEA, 2000, p.52). At Uberlingen, the official investigation summarised the controllers difficulties by stating that “With regular monitoring of the upper air situation as presented on the radar screen the conflict between the two aircraft at FL360 should have become evident to the ATCO. However, as the situation deteriorated the controller’s workload increased subtly and continuously, reducing his ability to maintain an awareness of the upper air situation and be proactive in its control” (BFU, 2004, p.85).

In the CDG incident the ATCO, though experienced and an ENAC instructor, had not been in active service for five months prior to the incident. The night of the accident was his sixth day on active duty and ‘the controller had not had to control an aircraft using an intermediate access taxiway, which reinforced the false picture he had made of the situation’. (BEA, 2000, p. 47) Additionally ‘control had been grouped in the North Tower [the night of the incident]. Work on taxiways 17 and 17.1 caused access problems to holding point 27. On the ASTRE radar screen (situated on the right-hand side on the combined station) there were many fixed and mobile plots within and around the work area, with a lot of garbling also on the whole image. The AVISO screen was not accessible due to its distant location, bearing in mind that only the SOL positions are equipped therewith. [Additionally] Direct visibility was difficult since there was a lot of light pollution due to the works. Visual monitoring of an aircraft in this context was impossible, except by “tracking” (i.e. without losing sight of it) (BEA, 2000, p.38). Not only was the ATCO having to re-familiarise himself with practice and procedures following a significant time away from active duty thus having to move between the cognitive demands of knowledge and rule based processing (Rasmusssen, 1983) he was also juggling the impact of the construction work including the use of the intermediate access taxiway, a lack of information required to make accurate and efficient decisions due to the ‘garbling’ and poor radar images available from the ASTRE system while the AVISO radar screen was inaccessible without recourse to visual monitoring due to light pollution from the construction work..

The investigation into the Linate incident similarly highlights the additional demands on ATCOs reporting that ‘each aircraft called more than one time during that time interval just prior to the accident and given the existing meteorological conditions, the workload on both controllers was demanding. They [also] had no possibility to confirm the position reported by aircraft by means of technical aids’ (ANSV, 2004, p.4). Additionally the report notes that in the 16 minutes from the time that the MD-87 requested taxi clearance to the collision, the GND controller managed 126 radio communications. The TWR controller managed 73 radio communications (ANSV, 2004, p.28). Workload was clearly high and circumstances were complicated.

In the Überlingen incident ‘the ATCO worked on two work stations using two radar screens of different scale, with two separate radio facilities, with a phone failure, with the distraction of the technicians, but without the full radar system capabilities or the backup of an additional ATCO. He was [also] working under circumstances, he was not accustomed to. As the technical work was planned, at least some elements were foreseeable, but steps were not taken to mitigate the risks created’ (BFU, 2004, p.86). The demands on the ATCO were again greater than average, typifying many aspects of degraded operations. Under normal conditions i.e. with at least one other ATCO working alongside him, the demands could have been shared. The BFU note ‘With regular monitoring of the upper air situation as presented on the radar screen the conflict between the two aircraft at FL360 should have become evident to the ATCO. However, as the situation deteriorated the controller’s workload increased subtly and continuously, reducing his ability to maintain an awareness of the upper air situation and be proactive in its control.’ (BFU, 2004, p.85) This finding emphasises not only the increased demands on the ATCO but also the most challenging aspect of workload; how to assist an individual in recognising when it may become too much.

3.2 Communication Issues

Communication issues often play a key role in the path towards an accident or incident when different groups fail to communicate with each other. Communications problems may also arise from and characterise relations between many groups of co-workers within ATM service providers. For instance, numerous hazards arise when operational staff, managers and maintenance teams do not realise that particular safety features are unavailable. Similarly, a failure to provide information about the location of particular aircraft can remove yet another safety barrier when, for example, ground movement radar systems have been compromised. It can be difficult for the members of these different groups to accurately convey their tasks and priorities to co-workers who have little experience or understanding of their different activities. These communication problems are compounded when both operational staff and maintenance teams are unaware of and/or do not appreciate their significance for each other as they attempt to operate and manage latent failures and degraded operating modes. For example, the Überlingen report described how the controller on duty 'had not been informed' about the presence of an additional manager who was supposed to act as a 'coordinator between controllers and technicians'. Nor was the ATCO informed of a systems administrator who was also added to the roster to support operational staff during the maintenance procedures on the night of the accident. Instead, the controller "assumed that the systems manager's (SYMA) shift had ended on schedule at about 21:00 hrs and that he had to take over these tasks during the night shift" (BFU, 2004, p.39). One reason for this lack of communication about additional maintenance staff was that neither the manager nor the systems administrator were mentioned in the directives documenting the work that was taking place at the time of the collision.

Similar communications problems arose over the maintenance activities that were scheduled while the runway incursion occurred at Charles de Gaulle airport. When analysing the human 'errors' that contributed to the accident, the BEA interviewed the Tower Controller. His testimony indicated that he had "formed a picture of the situation based on a false hypothesis: the fact that, because of the works, taxiways 16 and 17 would not be in use. For him, departures were to take place from the runway threshold" (BEA, 2000, p.45). This erroneous perception was perpetuated by the lack of any integrated briefing between the maintenance managers and the tower team. Such a meeting might have helped to ensure that all controllers shared a common understanding of the impact of subsequent maintenance and may have created greater resilience to degraded modes of operation.

At Linate, it can be argued that there was a breakdown in communication between the groups responsible for the maintenance of the infrastructure and the operational staff. The gradual degradation of taxiway signage, the loss of critical runway lighting systems and the failure to update the analogue ground movement system gradually removed critical support from the air traffic control officers. The ANSV investigators found that these latent problems contributed to the degraded operating modes under reduced visibility. The investigators found it 'remarkable' that the radar and lighting systems had not been improved in the months and years before the accident (ANSV, 2004, p.107). Such observations are symptomatic of a breakdown in communication between maintenance management and teams of operational staff who must continue to maintain levels of service in the face of latent failures.

3.3 Failure to Effectively Disseminate Information/Documentation on State of the Infrastructure

Communications failures often exacerbate degraded modes of operation, for example, if staff are not told about short term problems with key infrastructure. Our case studies provide evidence that operational staff may either not have studied or acted upon documentation describing infrastructure problems. Communications problems can also lead to latent failures if faults go unresolved over long periods of time. These problems cannot, however, only be attributed to operational or maintenance staff. The previous section has described problems in higher levels of management, for instance, in ensuring that the presence of additional staff was adequately documented.

Many of the individuals and groups that were involved in the Überlingen accident did not make full use of the information sources that were available. The BFU recognise this when they stress that the controllers were unaware of the scheduled maintenance work when they reported for duty on the evening of the accident. Although documents were available for self-briefing "…they did not seize the opportunity to read them even though the duty schedule and their work contract allow time for such reading" (BFU, 2004, p.74). It is ironic; however, that such self-study would only have had a minimal impact on the course of the accident because the available documentation did not provide a detailed analysis of the impact of planned work on the underlying infrastructure. For example, two 'official instructions' (Z 2002-022 and Z 2002-024) provided a high-level description of the work that was to be completed at ACC Zurich on the night of the Überlingen accident. These were available in the ATCOs' briefing room and at the supervisor's workstation. However, these documents did not describe the consequences of the changes for ATM operations. The necessary additional details were contained in a memorandum that was issued approximately one week before the accident. This document described the systems that would be affected and explicitly mentioned that ATCOs would have to operate in 'Fallback Mode'. The use of this term is particularly significant in the context of degraded modes of operation. 'Fallback' procedures in ACC Zurich were used to define appropriate working practices when specific items of infrastructure were not available to operational staff. For example, there is an assumption that staff will enforce a minimum radar separation of 7 nautical miles rather than 5 nautical miles. However, these constraints were not reiterated in the memorandum and there is evidence to show that the operational staff did not follow them fully in the hours leading to the accident (BFU, 2004, p.38). Under Fallback Mode, the visual Short Term Conflict Alert (STCA) system was not available. There was no automatic correlation between the flight plan data and target symbols. However, these limitations were not explicitly mentioned in the memorandum that was issued to operational staff. Neither did it mention that the SWI-02 communications system would be unavailable during the maintenance procedures. This proved to be significant because the SWI-02 infrastructure might have enabled other centres to alert ACC Zurich to the conflict between the aircraft. It might also have helped the ATCO to reduce his workload in the moments leading to the accident because he struggled to contact neighbouring controllers before he realised that this system was not functioning.

The failure to communicate extends beyond ATCOs and maintenance staff. Aircrews have also struggled to access the documentation that is intended to provide warnings about latent failures and about degraded modes of operation. For instance, the building work for the new North dual runways at Charles de Gaulle airport was explicitly mentioned in NOTAM No. 109/99. Additional information was provided at regular intervals by the Aéroports De Paris via the Aeronautical fixed telecommunication network to airline staff present at the airport. These updates included the list of taxiways that were closed. However, they were not passed on to the Air Liberté (MD83) and Streamline (Shorts) crews because they do not have permanent staff at Charles de Gaulle. On the night of the accident, taxiways 16.1, 17.1, 17 and HP1 were closed. Runway threshold 27 was served by lanes B2, B1, 18.2 and 18.1, and Q. From 20:30 until 04:30, approximately ten vehicles worked on the site using orange emergency lights with high-power halogen lamps lighting the work site. The lights were pointed towards the ground (BEA, 2000, p.18-19). The significance of this information is that it might have helped the crews to better orient themselves as they manoeuvred around the open taxiways in response to the ATCOs' guidance. Although this information was not specifically delivered to the the Air Liberté and Streamline crews, it could have been accessed using the Automatic Terminal Information Service. This provided information about the closed taxiways that were updated by the Ground subdivision and approved by the Control unit each day. This map contained details relating to the work in progress, i.e. hours of work and identification of the taxiways closed for work purposes.

Similar problems affected the aircrews at Linate. It was particularly difficult to use the existing documentation to gain an accurate understanding of the latent problems that continued to affect the operational environment. The crucial fork between taxiways R5 and R6 was indicated by yellow markings indicating the name of each route and by lines leading in the appropriate directions. However, there were no other indications between the bifurcation of R6 and the intersection with runway 18L/36R. The yellow line indicating the path of the taxiway had also been partially obscured by black paint that had been used to cover an old path that had been modified. In consequence, the Jeppesen charts used by the crews did not provide accurate information about the state of the taxiways (ANSV, 2004, p.34). There were further inconsistencies. For example, stand markings had been painted on areas adjacent to the taxiways. These stands were no longer in regular use. However, they might have been used by the crews to confirm their position on the taxiway given the relative lack of other markers on the routes themselves. However, the official runway maps issued by AIP Italy reported some of the markings such as the yellow lead-in lines for the stands but omitted others, such as the yellow taxi lines of some stands without numbering (ANSV, 2004, p.34). The official investigation argued that the lack of information about the taxiway signage may have adversely affected the situation awareness of the Cessna's crew. The investigators also argued that the lack of documentation about the signage and markings for these stands "added difficulty for the controllers to assess aircraft position in the manoeuvring area" (ANSV, 2004, p.119). The ICAO Aerodrome Design Manuals provide guidance on the correct markings to use in these circumstances, and there is an obligation to ensure that any changes in runway signage are reflected in the documentation that is made available both to ATCOs and aircrews to ensure safe air traffic management. The response at Charles de Gaulle illustrates how alternate information sources can be used to provide periodic updates when changes occur in runway infrastructure at a rate that cannot be reflected in the annual changes in printed maps. However, the Charles de Gaulle case study also shows the importance of ensuring that these updates are easily accessible to the operational staff who must use this information to guide their interaction. If such support is not provided then it is little surprise that crews and ATCOs are ill prepared to face the additional demands under degraded modes of operation.

3.4 Management of Environmental/Meteorological Conditions

Many of the factors that contribute to degraded modes of operation are directly under the control of ANSPs, airport operators and the airlines. For instance, these organisations help to determine the budgets that are allocated to maintenance activities and they have a strong influence on the Safety Management Systems that help to guide acquisition policy. There are other factors that have an influence on latent failures and degraded modes that cannot be directly altered though their influence may be mitigated by human intervention. In particular, the weather has a considerable impact on the safety of air traffic management. Poor meteorological conditions can transform a system in which there is adequate provision for safe operations into one in which there is a significant risk of an adverse event.

The importance of meteorological conditions is illustrated by the reiteration of these factors in several of the causes that were identified in the Linate runway incursion. For example, the ANSV identify the fact that "visibility was low, between 50 and 100 meters" as the primary cause of the accident (ANSV page 162). The official report then identifies several additional causes that are strongly related to meteorological conditions, including the "operational procedures allowing high traffic volume (high number of ground movements) in [exceptionally poor] weather conditions as were current the day of the accident (reduced visibility) and in the absence of technical aids" and that the "instructions, training and the prevailing environmental situation prevented the ATC personnel from having full control over the aircraft movements on ground" (ANSV page 163). Such comments clearly illustrate the role of meteorological conditions in causing and exacerbating degraded modes of operation.

It is important and more helpful to place these high-level findings in the context of the specific events that led to the runway collision. For instance, Linate's Automatic Terminal Information System (ATIS) began to broadcast low visibility warnings from 04:50 on the morning of the accident. This broadcast was updated at 05:20, 05:24, 05:25, 05:50 and 06:20 (post accident) repeating the warning. Neither the Cessna nor its pilots were qualified to take-off under the Cat II/III conditions that held therefore the aircraft should not have started the flight. The ANSV provide an implicit analysis of the pressures that might have helped to shape the crews' decision when they consider the personal and commercial incentives to complete the flight. However, we have very little evidence of the discussions that took place before the crew requested permission to start their engines. The Cessna was not obliged to carry a cockpit voice recorder. It is possible to identify at least two possible explanations. Firstly, the crew may not have checked the ATIS announcements. Even if this were the case, the crews' own assessment of the prevailing meteorological conditions should have alerted them to the possible dangers. In contrast, the crew might have heard the ATIS announcement but failed to act on it. This failure can be explained by commercial and personal pressures or because the ATIS announcement did not spell out the Cat status of the aerodrome under the prevailing meteorological conditions.

The Cessna requested start-up clearance shortly after 05:58. GND control then provided permission to the crew. ATM personnel arguably should have checked the license conditions of the aircraft to ensure that they were permitted to operate in the low visibility conditions that held at Linate. For a variety of reasons this did not occur; ATCOs were very busy as described, workload was high and the initial dominance of local and regional general aviation at Linate may have led to the development of a culture of familiarity between ATM personnel and these aircrews. The reduction in traffic following the movement of slots to Milan Malpensa

Airport may also have contributed to the development of informal working practices that routinely cleared general aviation operations even though the controller's manual stated that ENAC was responsible for checking aircraft and pilots for low visibility operations. The outcomes of these decisions were, in turn, too readily accepted by ATM personnel. In consequence, the crew of the Cessna and ATCOs were forced to cope with degraded technical infrastructures as the aircraft attempted to cross taxiways and take off under adverse weather conditions.

Severe meteorological conditions played a less important role in the Charles de Gaulle case study. However, the same general comments apply – adverse weather conditions causing poor visibility helped create degraded operating conditions that exacerbated latent problems in the underlying safety systems. At Charles de Gaulle, it was hard for the ATCOs to directly observe the aircraft as they taxied because of the interaction between rainfall and light pollution from construction work. The BEA argues that "Visual monitoring of an aircraft in this context was impossible, except by 'tracking' (i.e. without losing sight of it)" (BEA, 2000, p.38). The investigatory team also review the interaction between adverse weather conditions and the other factors that contributed to the degraded mode of operations at the time of the incursion. The ATCO might have corrected an initial error of perception in the location of the Shorts aircraft if he had reviewed the circled 16 on the strip that indicated the access taxiway or if he had conducted more sustained checks either using radio communications or the ground radar systems or by direct visual observations. Meteorological conditions only explain part of the reasons why he did not take advantage of these different mechanisms. "Visual surveillance of the manoeuvring area around the threshold of runway 27 was very difficult to perform. It was dark, the rain had made the ground reflective and the lighted area of the work-site was located between the north tower and threshold 27. Furthermore, bearing in mind his mental picture of the situation and his failure to take into account the information on the strip, he had no reason to focus his attention on taxiway 16". (BEA 2000, p.48). In addition, the strip had been passed to him in a 'banal' fashion by the senior controller and this may have reduced his opportunities to review the information that it contained at a time when the MD83 and its associated auto throttle problems were diverting most of his attention. These meteorological and environmental factors combined created a degraded mode of operation and combined with longer standing, latent problems in his working environment related to the AVISO and ASRTE ground movement radar systems. AVISO imagery was not displayed at his position and ASTRE imagery was poorly positioned for him. The display design of this information resource would also have forced him to concentrate for a considerable period of time in order to separate the aircraft from the traffic associated with the construction works.

4.0 Organisational Factors

The influence of organisational factors on day-to-day ATM performance cannot be underestimated. There are increasing pressures on ANSPs as the increasing impact of deregulation introduces new commercial pressures on an industry that must simultaneously cope with rising demands for its services. Operational staffing, including but not limited to ATCOs and pilots, are often caught at the 'sharp end' where these pressures meet. In particular, they must consider the commercial requirements to improve performance levels while at the same time maintaining extremely high levels of safety.

4.1 Flawed Safety Management Systems

In recent years, Safety Management Systems have been identified as an important means of protecting both operational and managerial staff from the commercial pressures that might otherwise undermine the safety of air traffic management operations. These systems typically use a risk-based approach that is intended to channel organisational resources to address those hazards that pose the greatest threat to operational safety. The intention is to detect potential problems, initiate corrective actions and then monitor the success of any interventions (ANSV, 2004, p.94). In consequence, they can be used to initiate corrective actions against latent problems and to, thereby, increase resilience to degraded modes. Organisations such as ICAO provide guidance on the development of Safety Management Systems within Annex 14. EUROCONTROL also advocate the development of Safety Management Systems. This approach is distilled into the regulatory provisions of ESARR3. In each of our case study accidents there were, however, serious problems with the implementation of Safety Management Systems. The ANSV investigation into the Linate runway incursion concluded that "the ATM was not responding to Safety Management System criteria such as those now being developed by ECAC States who shall collectively introduce the additional requirements contained in

EUROCONTROL Safety Regulatory Requirements (ESARR) documents" (ANSV, 2004, p.112). Similarly, the Uberlingen report recommended that the Federal authorities ensure "the air traffic service provider takes appropriate action to assure an effective operation of their safety management system in as much as that international requirements (ICAO SARPs, Eurocontrol ESARRs) are assured, and appropriate safety strategies, management techniques and quality procedures are incorporated and evaluated" (BFU, 2004, Safety Recommendation No. 17/2004, p.60).

There are no clear references to Safety Management Systems in the BEA investigation of the Charles de Gaulle runway incursion. This omission can be explained in a number of ways. The official report was published some four years before the other two case studies. In the interim, the prominence of organizational influences on safety management increased significantly. This does not imply, however, that safety management concerns were absent from the report. In particular, the investigation examined the impact that existing organizational reporting mechanisms may have had on the ANSP's ability to learn from the previous 'near-miss' incidents described in the opening sections of this paper. For example, the Prevention and Safety Group met on a monthly basis under the responsibility of the Aeroport de Paris' incident prevention representative. This group was created just over a year before the incursion following the commissioning of the South parallel runways at Charles de Gaulle. The perceived success of this group in identifying and responding to potential safety issues with the new facilities led to an extension of their responsibilities over the entire airfield. There are many aspects of this Prevention and Safety Group that made it well suited to its role within the wider safety management activities of the ANSP. It was multi-disciplinary and drew its members from the Service Quality subdivision, different ADP services, specialist controllers and pilots and Air France prevention and safety services. The scope of the group's activities included a requirement to define risk prevention and management policy as well as to coordinate the analysis of significant events. They were required to chart different safety indicators in order to identify recurring problems. The Prevention and Safety Group were intended to use this resource to "draw conclusions from the events, propose(s) action and monitor(s) performance" (BEA, 2000, p.36). There is relatively little analysis of the extent to which these duties were fulfilled. The investigation simply records a list of similar runway incursions and notes that the Prevention and Safety Group has responsibility for many of the functions that would routinely be associated with Safety Management Systems.

In contrast, the other two case studies provide detailed and sustained analysis of the shortcomings in the Safety Management Systems that arguably contributed to the Ueberlingen and Linate accidents. The BFU begin with the observation that a "Safety Management System and associated management systems are potentially effective tools an organization can use to influence the safety culture and support the stated priority of safe air navigation. A lasting behavioural change in individuals based on changes in personal attitudes takes a certain amount of time even with a well-structured and well-founded safety system" (BFU, 2004, p.90). This clearly draws a link between safety culture and safety management. These links were also emphasized during an analysis of the organizational structures that were intended to help manage safety related changes within the ANSP and Zurich ACC prior to the accident. Skyguide faced a time of change as deregulation and market pressures were increasingly being applied to their operations. The safety policy of the company had been redrafted a short time before the accident and embodied many of the principles, mentioned in the documents published by ICAO and EURCONTROL. The policy documents often went well beyond the mandatory requirements of these and other regulatory organizations. However, there were many practical problems associated with its implementation. It had been recognized that the previous, informal structures that guided safety management would be insufficient for the demands facing Skyguide. A Centre of Competence was, therefore, created to coordinate necessary improvements, for example in risk assessment and the development of safety monitoring functions. These audit and monitoring activities were relatively well understood within the existing organization. However, there was less experience of risk based approaches to system development and maintenance. The necessary skill base had to either be bought-in from outside or developed by providing appropriate training and experience to existing personnel. The BFU record that the ANSP "elected to develop these systems themselves rather than bring in the expertise from outside the organization" (BFU, 2004, p.91). There was a delay while these skills were built up.

The lack of trained and experienced safety managers also placed considerable demands on the existing personnel and, partly in consequence, staff and operations managers on the ground were not always clear when they could rely on the support of their co-workers. The BFU report argues that the Centre of Competence should have been formally involved in the infrastructure changes at ACC Zurich that contributed to the accident, according to the Safety Management provisions of the Safety Policy. However, this did not happen and without any further indication of the nature of the planned maintenance work there was little prospect that Skyguide's Risk Manager would become involved in a formal risk analysis of the upgrades (BFU, 2004, pp.90-91). This limited the likelihood that there would be a more sustained analysis of the safety implications for the operational changes that led to degraded modes of operation during the night of the accident.

As mentioned, the Linate report was heavily critical of the lack of Safety Management Systems before the incursion reviewed in this paper. The ANSV stated that the accident was caused in part because "no functional Safety Management System was in operation" (ANSV 2004, p.163). The reasons for this have some similarity with problems that were identified in the aftermath of the Uberlingen accident (Johnson, 2006). These related to the problems of implementing risk-based design and maintenance across complex organizational structures under increasing pressures for deregulation and competition within the aviation industry. In this case, a large number of organizations, including ENAC, the SEA, CAV, DCA etc, all contributed to or influenced the CASO, Airport Technical Safety Committee. Partly in consequence, this group was only able to meet sporadically. This creates a circular argument. The failure of the CASO to review the technical aspects of safety policy was in part due to the lack of an effective Safety Management System. Conversely, the failure to develop Safety Management Systems stemmed in part from the lack of effective tactical input from these technical subcommittees who might otherwise have been pushing for additional strategic guidance from higher levels of management. The practical consequences of these managerial and organizational failures included an apparent inability to learn from previous incidents, mentioned in previous sections. The lack of a fully-developed Safety Management System may also have contributed to the absence of a runway safety plan. Given the absence of a runway safety team it was difficult to identify all of the groups who were responsible for ensuring compliance with ICAO runway requirements. The key insight here is that managerial and organisational structures have a critical role to play in detecting and responding to longer term latent problems in an operational environment. They also support the Safety Management Systems and risk assessment techniques that can be used to identify the consequences of degraded modes.

4.2 Degraded Operating Procedures

The three case studies illustrate the problems that ANSPs face when ensuring that staff follow standard operating procedures. They also illustrate the problems of drafting those procedures in the first place. For example, the BEA contrast the recommended procedures and phraseology for handling taxiing aircraft with the steps taken and phraseology used prior to the Charles de Gaulle incursion. One excerpt relates to taxiing to a holding point where the operations manual states that "taxiing clearance is in the form: *Call sign, taxi to holding point runway… Time….* In paragraph 4.7.1, *Line-up from high speed exit (DGV)*, the manual indicates that line-up from a DGV is possible only if the RVR is over eight hundred metres and the ceiling over three hundred feet. In this case: *subject to acceptance by the crew and after co-ordination with LOC control, the aircraft is guided to the required taxiway. The taxiway number is indicated in the strip*. The phraseology [to be used during taxiing] is: *Call sign, do you accept departure from taxiway No. track x?* This issue is also addressed in the instruction manual, paragraph 3.4, *Before departure*, in the form of examples such as: *Do you accept departure from taxiway W7, distance available 2,650 metres?* It should be noted that the phraseology does not require systematic association of the taxiing instruction with the taxiway allocated" (BEA, 2000, p.30). A contrast is drawn between these documented procedures and the interaction between the controller and the crew of the Shorts aircraft. During taxiing, the ATCO asked the aircrew if they wished to take off from an intermediate access taxiway given the short take-off ability of their aircraft. The crew requested departure via taxiway 16 and the ground controller replied with the non-standard phraseology *"That's fine, so one six is approved, Streamline two hundred"*.

Further differences between standard procedures and operational practice stem from the lack of verbal co-ordination between the ground control tower position and tower controllers. The use of such informal clearances is also illustrated in the use of 'line up' in sequence instructions prior to the Charles de Gaulle incursion. ATCOs can authorise aircraft to line up behind another departing plane. These clearances are, typically, issues once the aircraft reaches a holding point. Pilots can then enter the runway at their own discretion after the previous aircraft has taken off. 'Line up' clearances reduce the workload on controllers because they avoid some of the tasks associated with line-up management. However, they are not mentioned in the national and international reference texts. There are obvious concerns over the consequences of any confusion in issuing or receiving line up clearances. As the BEA note, "the aircraft scheduled for departure after the Shorts received an in sequence line-up instruction some ten seconds before the collision: *Eurotrans 9263, line up in sequence, number 3"* (BEA, 2000, p.30).

A variety of different procedural violations were identified in the aftermath of the Linate runway incursion. Some of these show strong similarities with the problems identified by the BEA following the accident at Charles de Gaulle. For example, "radio communications were not performed using standard phraseology (read back) or were not consistently adhered to (resulting in untraced misunderstandings in relevant radio communications)" (ANSV 2004, p.163). Many of the phraseology problems stemmed from ambiguity between the clearances that were issued so that it was difficult, if not impossible, for aircrews to determine whether they related to taxiway R5 or R6, this in turn made it difficult for the Cessna's crew to identify that they had chosen the wrong direction at the junction point of these two routes. For example, the ANSV argued that "the words *report the stops, report the bars, report at the stop bars*, have been used both in clearances involving TWY R5 and TWY R6, without any other clarification or identification of the route to be followed" (ANSV, 2004, p.114).

It is important to stress that aircrews were complicit in the failure to follow approved procedures. An analysis of communications on a single radio frequency at Linate involving traffic on the West apron during the two days prior to the collision, revealed seven instances where the aircrews failed to read back part of the clearance that had been issued. There were four instances where the clearances were entirely missing from the read back. Further problems arose because the documentation available to the pilots did not provide them with sufficient information for them to meet requirements to identify their location. In particular, the AIP charts did not name the taxiway parallel to RWY 18L/36R; "consequently, the SAS Flight Support Charts, used by the MD-87 crew, and the Jeppesen charts, used by the Cessna crew also did not show a denomination for that taxiway" (ANSV 2004, p.115). Some of these informal practices emerged as strategies to help ATCOs and flight crew cope with latent problems in the operational environment. However, they also created an ambiguity and imprecision in communication that exacerbated the problems associated with degraded operations prior to the accidents.

A number of additional contributory factors can be identified in the Linate accident that relate to procedural violations. For instance, previous sections have discussed the contribution of meteorological conditions to degraded mode operations. There was a "[procedural]failure to check the Cessna crew qualification" for operations under the low visibility conditions that held at the time of the accident (ANSV, 2004, p.162). We have also discussed the problems that led the ANSV to conclude that "the aerodrome standard did not comply with ICAO Annex 14; required markings lights and signs did not exist (TWY R6) or were in dismal order and were hard to recognize especially under low visibility conditions (R5-R6), other markings were unknown to operators (S4)" (ANSV 2004, p.163) and that "the competence maintenance and requirements for recent experience for ATC personnel did not comply fully with ICAO Annex 1" (ANSV 2004, p.163). These citations document failures to follow accepted procedures.

The Linate incident also shows that inappropriate Standard Operating Procedures (SOPs) threaten safety by permitting degraded modes of operation. The ANSV recognized that the accident was partly caused by "operational procedures allowing high traffic volume (high number of ground movements) in weather conditions as were current the day of the accident (reduced visibility) and in the absence of technical aids" (ANSV 2004, p.163). It can be argued that inappropriate procedures might have been challenged by a risk based approach that underpins many Safety Management Systems. A more thorough analysis of the hazards associated with operating under such adverse conditions might have alerted operational and management staff to the potential risks of runway collisions under these degraded modes of operation.

The Uberlingen accident also provides examples of rules and procedures that did little to support operational staff. The BFU identified one of the systemic causes of the mid-air collision as "The regulations concerning

ACAS/TCAS published by ICAO and as a result the regulations of national aviation authorities, operations and procedural instructions of the TCAS manufacturer and the operators were not standardised, incomplete and partially contradictory" (BFU 2004, p.4). The evidence for this claim is based on a detailed analysis of the many different regulatory and procedural requirements that describe the operation of TCAS equipment. For example, the ICAO Procedure for Air Navigation Services – Aircraft Operations, Volume I, Flight Procedures (Doc 8186, PANS-OPS) there is a section on the 'Operation of ACAS Equipment'[1]. The requirements in this document have been described as 'insufficient and unclear' (BFU, 2004, p.79). In particular, the ICAO guidance contains the statement that ACAS 'assists' pilots and that "*Nothing in the procedures shall prevent pilots-in command from exercising their best judgment and full authority in the choice of the course of action to resolve a traffic conflict*". This contradicts the TCAS system philosophy embodied within the user manuals for these systems. For example, the BFU cite the following passage from the TCAS 2000/TCAS II Traffic Collision and Avoidance System Pilots Guide, Chapter 6.1 'Pilot Responsibilities':

> "If a TCAS 2000 RA requires manoeuvring contrary to an ATC clearance, satisfy the RA in a way that most nearly complies with the ATC clearance. If it is possible to both respond to a TCAS 2000 RA and continue to satisfy a clearance at the same time, you may do so. For example, you may respond to a climb RA while continuing to satisfy an ATC clearance to intercept a localizer. If a TCAS 2000 RA manoeuvre is inconsistent with the current ATC clearance, the pilot:
>
> - Must not delay in responding to the RA.
> - Must not modify a response to an RA.
> - Must follow the RA manoeuvre, unless invoking 'Emergency Pilot Authority'.
> - Must provide a vertical rate that minimizes ATC deviations" (BFU 2004, p.53)

The implication of the ICAO ACAS guidance is that pilots are free to decide whether or not to follow a resolution advisory. This clearly contradicts the previous guidance for TCAS2000. A further criticism of the ICAO guidance is that it fails to consider what might happen when TCAS resolution advisories occur at the same time as ATCOs issue an instruction to the same aircraft. To summarize, the ICAO ACAS documentation provides little guidance in circumstances such as those facing the aircrews during the incident. It is also inconsistent with information provided by device manufacturers on the intended application of TCAS systems.

The Uberlingen accident also illustrates the way in which procedures and regulations can be difficult to apply to degraded modes of operation that characterize many accidents and incidents. ICAO Procedures for Air Navigation Services - B Air Traffic Management, known as Doc 4444, PANS-ATM states that controllers must not issue instructions to alter that path of an aircraft when the aircrew reports a TCAS resolution advisory until the conflict has been resolved. This guidance could not be applied to the Ueberlingen accident because the crew of the TU-154M did not inform the ATCO of the advisory nor was there any automated system to provide such information to him (BFU, 2004, p.79). Further inconsistencies can be identified between, for instance, the TU-154M flight operations manual and the ANSP documentation covering TCAS advisories. Rules and regulations clearly failed to help avert our case study incidents. The plethora of contradictory or ambiguous guidelines on the operation of TCAS was not readily usable to support the ATCO - even if he had been aware of their different nuances or requirements.

4.3 Staffing and Competence Levels

Competency and staffing levels provide examples of generic factors that may undermine ATM and therefore ATCO performance during degraded modes of operation against a background of latent failures. The use of one controller in the Zurich ACC at the time of the Überlingen mid-air collision was an unofficial practice, however, the BFU report acknowledges that "this way of proceeding which does not provide any redundancy of human resources so that procedural errors, wrong distributions of attention or the omission of important

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[1] The term ACAS refers to Airborne Collision Avoidance System and has been adopted by the ICAO in contrast to the term TCAS, which is in more general usage in the United States. The BFU present a brief summary on the differences and similarities of the systems referred to by these terms on page 44 of the Ueberlingen report (BFU, 2004).

actions may lead to hazardous situations as nobody is there to notice these mistakes and to take corrective actions… Even though it was an unofficial procedure it was known to and tolerated by the management" (BFU, 2004, p.75). The second controller left ACC Zurich after the work had started and air traffic volume had decreased. Normally he would have returned to the control room as the volumes increased with early morning air traffic. The remaining controller, out of earshot of the second controller resting in the lounge had to perform the tasks normally associated with the Radar Planner (RP) and Radar Executive (RE) as well as the Chief Controller. Though he did have a Controller Assistant to support this work she had no rating for Air Traffic Management (BFU, 2004, p.41).

It is always important to consider such observations in the context of the environment that faced operational staff at the time of the accident. A control room designed for operation by greater numbers of staff could only ever be run in a 'degraded mode' by such a small number of controllers. This is illustrated by the Controller having to divide his attention between different areas of the control room since a workstation on the left was intended for the Radar Planner and presented all of the ACC Zurich airspace while a workstation on his right was dedicated to the Radar Executive. The controller used this to select a more detailed view of the sector for the approach to Friedrichshafen airport and switched the radio system to the frequency appropriate for movements in this area. This terminal could provide a view of the aircraft involved in the eventual collision. However, in order to contact them on their radio frequencies it was necessary for him to move to another workstation (BFU, 2004, pp.41-42). The demands of these various tasks and the consequent disruption caused by moving between the different positions played a significant part in undermining his situation awareness impairing his decision making ability during key stages of the accident.

The causes of insufficient or inadequate staffing levels and competency are specific to the particular circumstances of each accident. For example, the Tower Controller on duty during the incursion at Charles de Gaulle airport was an instructor at ENAC (National Civil Aviation College). As part of the requirements for this role, he had to maintain his operational qualifications by spending time as a controller. Following an initial day of familiarization, instructors can then be added to the roster of their host. The BEA note that "irrespective of the duration of their absence, no procedure for instructor controllers in-service adaptation is envisaged, due to their role as instructor, which keeps them in permanent contact with ATC" (BEA, 2000, p.33). The assignment of control position remains the responsibility of the centre depending on their rating and abilities. There has never been an instance in which a controller was unable to perform the duties assigned to them and maintain their qualifications. However, centres have shown some reluctance to host instructor controllers; "Instructors undergoing qualification maintenance generally generate additional workload for the instruction divisions of the centres. Instructors have also complained on some occasions of not being considered as an integral part of the team" (BEA, 2000, p.42). The integration of instructor controllers into operational teams provide insight into the specific events that led to the accident. The head of ATC at the airport was also in the tower to help manage an increase in traffic associated with a Champions League football match that was taking place on the night of the collision. The head of ATC began placing strips directly on the control board of the instructor controller. In most circumstances, the strips would have been placed on the side of the board to enable the controller to integrate the strips himself after considering any possible conflicts. By placing the strips directly on the board, the head of ATC may have removed a further check for potential conflicts performed by the controller (BEA, 2000, p.40). The status of the instructor controller as a 'guest' within the tower, may have given rise to social and cultural barriers preventing him from objecting to his colleague's actions.

A number of other human resource issues contributed to the Linate incursion. In particular, there is evidence that there were insufficient staff in the critical DCA (Airdrome Judicial Authority) and the UCT (Traffic documentation) sections during the accident. There would usually have been two UCT officers on duty but only one had turned up on the day of the incursion. Fortunately, their colleague on the previous shift was still present even though they had worked a continuous total of 13 hours on duty. This had important consequences as Air Traffic Managers and emergency personnel responded to the initial information about a potential collision. The accident report lists a number of specific "failures to adhere to prescribed obligations", most seriously including the UCT failure to provide the tower with critical information after the collision (ANSV, 2004, p.60).

4.4 Mixed Mode Operations

In any study of the relationship between latent failures and degraded mode operations, it is possible to identify generic features that seem common to many different incidents. These include issues to do with communication and workload. In contrast, some factors relate to specific features of particular incidents. For example, mixed mode operations can be identified as latent factors behind both the Charles de Gaulle and Linate accidents but did not contribute to the Uberlingen accident. Mixed mode operations refer to the integration of commercial and general aviation using the same taxiways and runways. It also refers to the integration of aircraft with very different performance characteristics on the same infrastructure. These operations created latent problems for the controllers that may have prevented them from identifying conflicts at an early stage in the accidents.

For example, immediately after the Second World War, Linate used separate runways to handle both general and commercial aviation. This simplified Air Traffic Management given that these operations rely upon aircraft with very different performance characteristics and the levels of support required are often quite different. However, subsequent developments to taxiway R6 opened up access for general aviation to runway 18L/36R which had previously been reserved for commercial operations. These developments did not significantly increase controllers' workload because of the relatively small scale of general aviation at this time. Partly in consequence, a culture of familiarity grew up between ATCOs and pilots. Over time, however, the performance of general aviation aircraft began to match that of commercial aviation and the demand from general aviation to use 18L/36R also increased. The airport did not develop any high level plan to deal with these changes. In consequence, ATCOs had to act as a buffer. They had to develop working practices and coping strategies that enabled them to continue service provision for a very diverse range of aircraft operating on 18L/36R (ANSV, 2004, p.30). Similar comments can be made about the emerging situation at Charles de Gaulle. In this case, Streamline Aviation developed a freight transport operation using aircraft that only needed a short runway length to take off. Therefore, it was usual for the crews to take off from an intermediate access taxiway at Paris Charles de Gaulle. Controllers had to monitor aircraft entering the runway at different points depending on their takeoff requirements, just as they did at Linate (BEA, 2000, p.34).

The key point here is that although 'mixed mode' operations were important in these particular case studies, we would not argue that they are equally significant across a broader class of adverse events. Such issues reflect problems in a relatively small number of 'degraded mode' accidents. They place additional demands on operational personnel that can act as a trigger to the longer term, or latent problems, that can exist within the ATM working environment. For example, the mix of aircraft performance levels using the same areas of an airport need not necessarily create any operational problems. However, when it is combined with degraded operations including poor visibility and latent failures, for example in runway signage, these mixed operations are likely to play a significant factor in runway incursions.

5.0 Conclusions

The previous sections have explored the role that latent failures and degraded modes of operation have played in a number of recent accidents and incidents in European Air Traffic Management. The intention has been to identify and begin to investigate why teams of co-workers continue to operate safety critical systems during obviously suboptimal circumstances particularly when known key elements of their technological infrastructure have been compromised, for example during routine maintenance. There is often a culture of 'making do' where managers and employees try their best to maintain services. The extent to which workers will adapt to latent failures and degraded modes illustrates the flexibility and resilience of socio-technical systems. However, as we have seen this can also undermine safety when infrastructure changes subtly but steadily increase workload and remove or impair necessary safety nets. By studying previous incidents and accidents, we can help staff and managers to understand the dangers that they face from latent failures and degraded modes.

It is important to emphasise that this is a preliminary study and that much work remains to be done. We have examined three case studies. These incidents were chosen because they are the most serious ATM-related incidents in European airspace in recent years. We can expand the study in several ways. For example, the FAA led many of the early studies into the causes of runway incursions. There are important differences in the traffic densities and procedures that govern ATM operations between Europe and North America. Future work should extend the study by considering the implications of latent failures and degraded mode operations using North American case studies.

It can also be argued that many of these problems are more significant for emerging economies. Infrastructure development may lag behind the levels available in areas with a longer history of ATM service provision. There is a pressing need not simply to criticise the lack of technical provision and support for individuals. We need to better understand the coping strategies and mechanisms ATCOs rely on to manage increasing levels of demand and critically. It is especially important to consider resilient means of supporting degraded mode operations when latent failures are created by severe resource limitations, in terms of the finance and skilled staff necessary to support ATM operations. However, there is little room for complacency in more established ATM service providers. Our case studies relate to incidents involving Swiss, Italian and French ANSPs. They demonstrate that latent failures and degraded operations can lead to accidents in organisations that have a significant history of safe and reliable service provision. In this view, the particular problems posed by degraded modes may be more acute for organisations that must maintain and update complex systems. It follows that established service providers in Europe and North America may have just as much to learn from the study of previous latent failures.

Our study has focused on understanding the reasons why accidents occur from the interaction between latent failures and 'degraded mode operations'. It is just as important to consider why accidents do not happen in similar circumstances. Previous sections have described how incident reporting systems have been established to gather information about 'near miss' occurrences. We have also considered the many problems, including under-reporting, which limit the usefulness of these information resources. However, there is significant potential to use the data from these sources across several different national systems as a means of learning how ATCOs and aircrews cope with the demands of degraded systems.

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