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Analyzing human error in aircraft ground damage incidents

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Abstract

Ground damage incidents (incidents in which airline personnel cause damage to an aircraft on the ground) occur as airline personnel are working on, or around, an aircraft on the ground, either on the ramp or at a maintenance facility. Each incident can be quite costly to the airline, with costs both tangible (repair costs and lost revenue) and intangible (passenger inconvenience, increased maintenance workload). Thus, airlines have a financial incentive to reduce the number of ground damage incidents that occur. One of the airline's most difficult tasks has been to utilize the information collected in their existing error reporting systems to determine the common latent failures which contribute to typical ground damage incidents. In this study, 130 ground damage incidents from a major airline were reviewed to determine the active and latent failures. Twelve distinct hazard patterns (representing the active failures) were identified, with three hazard patterns accounting for 81% of all ground damage incidents. Nine major latent failures were identified, and the relationships between the hazard patterns and latent failures were examined in depth. This type of analysis allows the latent failures common to different hazard patterns to be identified, and provides a means for developing focused intervention strategies to prevent future ground damage.

Relevance to industry

Airlines have generally had a difficult time analyzing reports of human error to make improvements in their maintenance systems. This study provides a methodology that allows reports of human error to be analyzed, and interventions developed based on the results of the analysis. The methodology would also be applicable to, and useful in, other industries.

Keywords: Aircraft ground damage; Human error analysis

1. Introduction

Since the Aloha Airlines accident in 1988, in which the failure of airline inspectors to detect cracks in the fuselage resulted in the aircraft splitting apart in flight, the aviation community has recognized that there are other departments, besides flight operations, that have a serious impact on aviation safety. Errors in maintenance operations, especially, have the potential to result in serious safety problems, and/or cause an accident. However, most effort (by airline personnel, industry consultants, and human factors researchers) on reducing errors was concentrated on improvements to the flight deck, and on pilot training. McDonald and Fuller (1996a) point out that human factors efforts on the flight deck has been a recognized research field for 25 yr, while efforts on aviation

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maintenance have only just begun. Recognizing this shortcoming, the FAA's Office of Aviation Medicine established a program in 1988 to fund a broad range of human factors research in the airline maintenance domain.

Many projects within this program have focused on human errors in the maintenance environment, and on how to prevent similar errors from reoccurring. It is widely recognized that although a large number of errors may occur on a regular basis, it is very rare that a situation is elevated into a serious incident affecting flight safety. In most situations, an error is either caught immediately or the defenses of the maintenance system act to prevent the error from becoming an incident. Thus, the error is prevented from propagating through the system. Mechanics are especially conscious of the importance and seriousness of their work, and typically expend considerable effort to prevent, or at least recognize and correct, errors that could lead to safety concerns for personnel, passengers, and equipment.

Fortunately, airlines report few maintenance-induced incidents that affect the safety of personnel and passengers. However, ground damage, or damage to an aircraft caused by airline personnel while the aircraft is on the ground, remains a serious problem for most airlines, with costs in the tens of millions of dollars per year. Ground damage can occur while ramp personnel are servicing an aircraft, and/or while maintenance personnel are performing maintenance work. In fact, ground damage incidents (GDIs) can occur at any time personnel are working on, or around, an aircraft that is on the ground. This category of incident only includes damage that is inherently preventable by airline personnel on the ground: damage caused by hail, bird strikes, part failures, or even by foreign object damage is not considered to be ground damage, and some of these categories even have their own separate prevention programs.

1.1. Why is ground damage important to airlines?

Ground damage incidents are extremely costly to an airline; the total cost of an incident includes the cost of repairing the damage, as well as the less tangible costs of keeping an aircraft out of service. One example, documented in Airline Equipment Maintenance (Chandler, 1995), describes a typical American Airlines ground damage incident in which the cost of repairing a damaged aircraft was $39,300. However, the total cost of the incident was calculated to be $367,500 due to passenger and cargo revenue lost. In addition, there are non-tangible costs to the airline including: passenger inconvenience, affected flight schedules throughout the entire airline system, and increased maintenance workload. A typical airline may have 100–200 reportable GDIs each year, resulting in significant financial losses that could be prevented.

Thus, it is obvious that airlines have a significant financial incentive to reduce the number of GDIs that occur. However, due to the difficulty that often accompanies the calculation of the total cost of each GDI, airlines have not been able to quantify the magnitude of the losses with any accuracy. In addition, airlines have had a difficult time controlling these costs, since they have been unable to pinpoint the causes of recurrent incidents (McDonald and Fuller, 1996b).

1.2. Error reporting systems

Problems in identifying causes of recurrent incidents are at least partially the result of inadequate methods of collecting information about errors. In a typical airline, errors (above a certain threshold of severity) are strictly monitored and recorded. For example, airline management may maintain stringent records of on-time flight departures/arrivals, turnaround time for aircraft requiring maintenance, injuries to personnel, damage to aircraft and other ground equipment, and other measures that document the airline's overall performance. In addition, many errors (below the threshold of severity for reporting) may be detected and corrected routinely as part of the system with no records kept.

Most of the error-reporting systems in use at a typical airline are maintained and utilized by different departments, and are rarely used together to analyze the system as a whole. But, there are many inherent problems that may affect more than one of these performance measures, and similar errors may lead to an incident to be recorded in different error reporting systems. For example, if a mechanic drops a wrench on his foot, the incident would be recorded as an OJI (on-the-job injury). If a mechanic drops a wrench on an aircraft, damaging it severely, the incident would be recorded as Technical Operations Ground Damage. If the wrench were dropped on the aircraft, causing no damage, the incident would not be recorded at all! Finally, if a ground operations employee drops a wrench on an aircraft, the incident would be recorded as Ground Operations Ground Damage. In each of these scenarios, the error was exactly the same, only the final consequences differed, in turn affecting the way in which each of these incidents is recorded. Without compiling information from all of these error-reporting systems, it is quite difficult to get a full picture of the types, and frequencies, of recurrent errors.

The current project, as is typical of FAA Office of Aviation Medicine projects, was a joint effort between researchers and a partner airline. In our partner airline, ground damage incidents are recorded in narrative reports. In these reports, an investigative team produces a detailed written report, including: a problem statement describing the incident, a detailed description of the incident, a list of process, equipment and personnel factors that contributed to the incident, as well as recommendations for preventing this type of incident from happening again. The report generally includes photographs of the damage to the aircraft as well as the equipment that may have been involved. Also, written descriptions from all of the personnel involved are obtained and are included in the report. The recommendations from each GDI are supposed to be disseminated to all of the stations (airports where the airline has personnel) to allow other personnel to learn from the incident.

At other airlines, GDIs may be recorded using an investigative tool based on a checklist, or another 'form' based tool. Using such a reporting method, much of the factual data of an incident is recorded (including the type of accident, the type of injury, the type of equipment being utilized, etc.), although there is little (if any) opportunity to provide a detailed narrative description of the incident. There is little encouragement inherent in this type of reporting system to glean specific information concerning the factors leading up to the incident, or the other system factors that may have contributed to the incident. However, these type of reporting systems do provide for quantitative tracking of error data, including such information as the number of incidents per month at each station, number of incidents occurring on each type of aircraft, etc. They also allow the particular individuals responsible for the incident to be identified, and for blame to be assigned. Generally, these reporting systems are useful to monitor trends in performance, but little use is made of this information to redesign the systems that generated the errors in the first place.

In recent years, other error reporting systems with explicit human factors components have been introduced which provide investigators with tools to help identify latent failures that may have contributed to an error. Boeing's Maintenance Error Decision Aid (MEDA) system, and Aurora Safety and Information Systems Inc.'s Aurora Mishap Management System are examples of current error reporting systems which are being used by airlines to investigate GDIs. However, airline personnel are still having difficulty *applying* the information collected by such systems, since the information generated from such systems often does not point to specific interventions.

1.3. Errors vs. violations

The purpose of error reporting systems is to collect information about an error so that the factors that caused the error can be identified and eliminated from the system to prevent reoccurrence. However, it is not always easy to identify these error-producing factors.

When an error occurs in the maintenance system of an airline, the mechanic(s) who last worked on the aircraft is usually considered to be at fault. The mechanic may be reprimanded, sent for further training, or simply told not to make the same mistake again. However, to blame the mechanics for all of the errors that are committed is perhaps giving them too much credit for their role in the airline's maintenance system. Many errors result, in fact, from a combination of other failures inherent in the system and the mechanic involved is merely the source of one of such failures, often the final failure in a sequence (Maurino et al., 1995). In these cases, it may not matter which mechanic is involved at the time of the actual incident, since the system itself encourages particular errors or violations to be committed.

Errors, as defined in Maurino et al. (1995), are failures of planned actions to achieve desired consequences. Errors in formulating a plan of action or in executing the plan are possible. On the other hand, violations are willful deviations from safe operating procedures, practices, standards, or rules. The distinction between errors and violations is especially important in the airline maintenance environment, in which mechanics are often given conflicting goals and priorities to achieve. Mechanics are told to be safety conscious and to follow documented procedures, but are also pressured to keep on schedule, and to prevent delays that are so visible to passengers. The heavy workload at most maintenance stations, coupled with a limited number of personnel and sub-optimal equipment, make it difficult for all of the efficiency and safety goals to be achieved simultaneously. Mechanics often make a choice as to which goal is perceived by the supervisors to be currently most important: at times the mechanics choose efficiency, most work completed in the least amount of time, over safety considerations [essentially a speed–accuracy trade-off (Drury, 1994)].

Mechanics must also operate under a large number of rules and procedures, and it is often difficult for the mechanics to keep track of them all. Some of the procedures can describe a more difficult way to perform a task, or may require more personnel than is typically available. Thus, over time, certain procedures have become routinely violated. For example, a towing procedure may specify that six people are necessary whenever an aircraft is moved (a tug driver, a brakeman, a nose walker, a tail walker, and two wingwalkers). However, in actuality, it is very difficult to find six people who are not otherwise occupied every time an aircraft is moved. Thus, the tug driver may decide to move the aircraft using only a brake man and two wingwalkers, in order to prevent operational delays.

In fact, some of the newer personnel may not even know that they are violating documented procedures, since they have received only on-the-job training for how tasks are typically performed. Over time, the routine violations may be passed down as correct procedures to new personnel. Management and supervisors may not enforce the procedures, since the violations are often performed to prevent delays and promote efficiency. Generally, the violations do not lead to any further problems, the benefits greatly outweigh the costs of committing the violations, and management can look the other way. Only when an incident occurs due to the violation (e.g., ground damage when an aircraft contacts a parked object due to insufficient number of spotters), are the employees involved reprimanded for their behavior and everyone is reminded to follow the procedures. Thus, although violations are officially highly discouraged by management, they are often tolerated as part of normal operating practices.

1.4. Active and latent failures

The failures caused by those in direct contact with the system, i.e. the mechanics that are working on the aircraft, are considered to be active failures. Thus, active failures are errors or violations that have a direct and immediate effect on the system. Generally, the mechanic himself catches the consequences of these active failures; or the defenses, barriers and safeguards built into the maintenance system act to prevent the failure from causing an incident. Thus, the system must rarely deal with the consequences of active failures. However, when an active failure occurs in conjunction with a breach in the defenses, a more serious incident will result (Maurino et al., 1995).

Latent failures are those failures that derive from decisions made by supervisors and managers who are separated in both time and space from the physical system. For example, technical writers may write procedures for a task with which they are not totally familiar; if the procedure has even one mistake in it, the mechanic using the procedure will be encouraged to commit an error. The latent failures can often be attributed to the absence or weaknesses of defenses, barriers, and safeguards in the system. Latent failures may lie dormant in the system for long periods before they become apparent (Maurino et al., 1995). Fox (1992) defines latent failures as those decisions made in the organization which may create poor conditions, result in less than adequate training, poor supervision, etc. which may lie dormant for some time, but which have the potential to predispose active failures.

For an incident to occur, latent failures must combine with active failures and local triggering events, such as unusual system states, local environmental conditions, or adverse weather. There must be a precise 'alignment' of all of the 'holes' in all of the defensive layers in a system (Maurino et al., 1995). For example, rain may cause a mechanics' foot to be wet, allowing his foot to easily slip off the worn brake pedal in a pushback tug when the mechanic becomes distracted. The tug may then lunge forward contacting a parked aircraft. The latent failure in the system is that the brake pedal has no anti-slip surface in place, but the problem does not become an issue until the rainy conditions (a local trigger) cause an incident. If any one of these failures had not occurred (mechanic did not become distracted, the tarmac was not wet, or the brake pedal was in better condition), the incident would have been avoided.

Traditionally, the mechanic would be blamed for this incident, since he allowed his foot to slip off the pedal. Clearly, the mechanic did commit this error. However, it must be noticed that mechanics are required to drive pushback tugs daily, and cannot control the weather conditions, or even the condition of the equipment. They are required to work under strict time guidelines, and they are highly motivated, by management and personally, to keep on schedule. Mechanics therefore, should not face sole responsibility for such incidents when they occur. It is important to consider all of the other factors that affect their performance, and all of the other system-wide problems that may contribute to failures.

In any system that has been operating for long enough to experience sufficient incidents, examination of past occurrences makes it is possible to determine the types of errors, violations, and latent failures that typically have caused problems in the past. However, in order to prevent future incidents, it is necessary to predict, identify, and remedy latent failures that still may be lying dormant in the system. Addressing the latent problems in the system can eliminate many of the errors and violations. Violations can be discouraged by ensuring that the correct way for the mechanics to perform their tasks is also the easiest and most efficient. Errors (which can never be totally eliminated) can be reduced to as low a level as possible by improving or strengthening the various defenses, barriers, and safeguards which prevent propagation through the system.

2. Methodology

To prevent recurring incidents, it is necessary to identify factors in the system which can cause errors. This study provides a means of identifying such error-producing factors in a typical maintenance domain.

In this analysis, 130 Technical Operations GDI reports were analyzed, covering ground damage from January 1992 through April 1995. These reports were obtained from our partner airline. Each report described one GDI, and was prepared by an investigative team (usually at a middle management level) from the airline. Incidents analyzed in this study were based on data readily available in Technical Operations and included all reports completed in 1995 up until the date the data was obtained from the partner airline.

Initially, each GDI report was reviewed to determine the specific action that caused the ground damage. The reports could be sorted into twelve distinct patterns covering almost all of the GDI reports, termed here as a Hazard Pattern after Drury and Brill (1978).

Next, each GDI report was analyzed to determine the specific active failures, latent failures, and local triggers that contributed to the incident. A scenario was then developed for each hazard pattern, illustrating the common factors between all of the incidents. Each of these was also summarized as an event tree illustrating how each of the latent failures contributes to the final damage event. This form of analysis, which has much in common with Fault Tree Analysis, was originally developed by CNRS in France (Monteau, 1977). The scenarios developed for each hazard pattern are included in the next section.

2.1. GDI scenarios

2.1.1. Tools or materials contact aircraft (1.1.1)

In these incidents, a piece of equipment (tools, parts) falls onto the aircraft (or mechanic). Generally, gravity is the ultimate cause of these incidents. By examining the environment in which the incident occurred, and the steps in the process proceeding the incident, it is possible to see how other non-obvious factors contributed to the incident. One such example is presented below.

> During an engine change, a mechanic pulled out a forklift supporting an A-frame, causing the frame to fall on the aircraft. However, on further review of the steps leading up to the incident, it is possible to see how this incident came to happen. First, it was not obvious to the mechanics that the A-frame was top heavy and could not support itself. Second, the forklift was removed in order to facilitate disassembly of the A-frame and nose cowl sling, two pieces of equipment necessary for the engine change. The disassembly was required because the engine change kit was missing parts, requiring the mechanics to change their procedure while in the middle of the engine change. Unfortunately, the missing parts were not detected prior to beginning the procedure, since the engine change kit does not contain either an inventory or packing list for the parts to be checked against.

Thus, although this incident was eventually blamed on the mechanic who moved the forklift, the problem had its antecedents far earlier, when the engine change kit was prepared.

Other latent failures contributing to these types of incidents include poor communication between co-workers, and between shifts; inappropriateness of available equipment for the task; inadequate space in which to perform the task; and poor mechanical condition of the equipment. Many of these latent failures can all be considered to be failures of the workforce to become aware of the possibility of risks and hazards. This lack of awareness may be a failure of management to properly emphasize safety as the first priority (as opposed to emphasis on speed of task completion), and/or may be a result of the mechanics' repeated performance of similar tasks.

Other errors result because the equipment does not 'behave' as the mechanics expect. For example, the engine sling does not hang level from the hoist; the overhead crane has only one speed in the East–West direction and this speed is perceived to be too fast; and the work platform has sagged over time, creating a decline towards the front end. The mechanics' misperceptions of the equipment cause them to perform as they otherwise might not if they were aware of the correct state of the equipment. For instance, a mechanic may have chosen not to place a wheeled dolly on the work platform if he had known it was so slanted towards the front end.

2.1.2. Workstand contacts aircraft (1.1.2)

In these incidents, a workstand that is being used to service or repair the aircraft comes in contact with the aircraft. There are various scenarios in which this type of incident can occur. The mechanics working on the aircraft may misperceive the position of the workstand while maneuvering in close proximity to the aircraft. In other situations, the mechanic accidentally causes the workstand to move in a direction that is not intended. Mechanics may also fail to properly configure (e.g., raise/lower platform) the workstand before moving it. Finally, in almost all of these incidents, no ground spotter was used while moving workstands around the aircraft.

This last scenario, in which no ground spotter is used, is a routine violation of company policy. The ground equipment policy requires a spotter to be used at all times when moving equipment around the aircraft. However, the unavailability of excess personnel, and high workloads for ground personnel has made this requirement difficult to follow. Since this policy is rarely enforced (except following a ground damage incident) mechanics often feel than they can properly maneuver the equipment and can properly judge distances from the aircraft.

There are, however, many latent failures that can be identified as contributors to these incidents. For example, in some situations, the workstand has unused metal brackets attached that cannot be seen by the workstand operator. In other situations, the equipment suffers from a mechanical problem that contributes to the incident (e.g., the stand jerks forward when placed in stop position, wheels do not swivel properly, design of dead man switch allows the foot to easily slip out). Furthermore, pressures to ensure on-time departures encourage the mechanics to quickly move their workstands into position, without properly checking for adequate clearance with the aircraft.

Another contributor to this category of incidents is the use of improper, or ill-suited, workstands to perform assigned tasks. In these situations, the mechanic uses workstands (or other ground equipment as workstands) for purposes for which they were not designed. The mechanic may choose to use an improper workstand because either: the maintenance station does not own the correct equipment, the correct equipment is unavailable (e.g., the correct equipment is in the shop for repairs or is being used elsewhere), or the correct equipment is less accessible than the incorrect equipment (e.g., the correct equipment is parked in a remote location). An improper workstand may offer the mechanic quicker access to the work, but may cause additional problems. Since the workstands are not designed for the work they are doing, they are often difficult to correctly position without contacting the aircraft, and may require excessive relocation throughout the task is duration. The increased difficulty of moving the equipment around the aircraft, as well as the increased number of times the position of the workstand must be adjusted increases the chances for the workstand to contact the aircraft.

2.1.3. Ground equipment is driven into aircraft (1.1.3)

In these incidents, equipment (trucks, belt loaders, etc.) is driven by airline maintenance personnel into the aircraft. The drivers either misjudge the amount of space available, misjudge the size of the equipment, or in some cases, accidentally continue moving forward when they know they are about to contact the aircraft. This last type of incident occurs when the mechanic is attempting to stop the vehicle by depressing the brake pedal, but fails to do so. All of these incidents are often attributed to the driver allowing his foot to slip off the pedal. However, on closer examination, it can be seen that this is simply an accident type waiting to happen. Often, the ground on which the mechanic must work is slippery, due to a combination of oil, cleaning fluids, and rain. This makes the mechanic's footwear slippery, and may cause his foot to slip off the pedals while driving a vehicle. Although these conditions are often present at many stations, the pedals in the vehicles do not all have anti-skid surfaces. In some situations, the anti-skid surface has simply worn off, and has not been replaced. Therefore, these types of incidents can be traced back to poor vehicle maintenance.

As in the previous category of incidents (see Hazard Pattern 1.1.2), some of these incidents (ground equipment is driven into the aircraft) are further aided by the use of ill-suited ground equipment for the particular task to be performed. For example, in one incident, mechanics using a pushback tug as a work platform backed the tug into the #1 engine thrust reverser. Specifically, the high windshield on the tug contacted the aircraft. In this situation, the station did not have a lift that was suitable for work in tight locations, and the work platforms that the station does own are difficult to locate when needed. Additionally, in many of these incidents, no ground spotter was used when moving equipment in close proximity to the aircraft. This is a violation of a company policy that is rarely enforced.

Many of these incidents occurred in congested areas, where the mechanic was forced to maneuver his vehicle through other parked ground equipment. Pressure to ensure on-time departures often causes the mechanics to take 'short-cuts', instead of waiting for other vehicles to be moved out of the safer path. For example, in one incident, a mechanic drove a tug with an airstart unit attached under the right wing of a parked aircraft, contacting the aircraft. The mechanic was attempting to leave a refueling station, and all of the other exit points were blocked with equipment and other vehicles. The mechanic decided to take the open path under the aircraft in order to facilitate on-time departure of his next flight. Although this was a conscious choice by the mechanic to violate the company policy against driving under the aircraft, the decision was made in what the mechanic considered to be the best interest of the company.

2.1.4. Unmanned equipment rolls into aircraft (*1.1.4*)

In these incidents, equipment (tugs, etc.) which is left unattended by airline personnel, rolls into the aircraft. These incidents can be divided into two categories, those in which an unmanned parked vehicle rolls into an aircraft, and those in which a piece of equipment rolls into the aircraft. In most of the incidents in the first category, the vehicle was left unattended, with the engine running and the parking brake set. This is in violation of company policy that requires all vehicles to be turned off when left unattended. However, in many of the northern stations, it has become standard practice to leave the vehicles running at all times during the winter months, to prevent any problems restarting the vehicles when they are needed. Ground damage incidents occur when the vehicle's parking brake fails, allowing the vehicle to roll into a parked aircraft.

In some situations, the mechanics are aware that the parking brake on the vehicle is not working properly, but are reluctant to pull the vehicle out of service for repair. This reluctance is driven by the shortage of suitable equipment, and the feeling that the maintenance department will not be able to fix the problem satisfactorily within a reasonable amount of time. In other situations, the mechanic is not aware of the limitations of the parking brake and/or the supplemental braking systems installed by the airline. The lack of awareness of potential hazards causes the mechanics to leave the vehicle unattended with complete confidence that it will remain where it was parked. The limitations of the braking system can be considered a latent failure in the system.

The second category of incidents, those in which equipment rolls into an aircraft, occur when the equipment is not properly fastened into place (hitch pin engaged, or brakes set). For example, in one incident, a cart that was being towed came loose and rolled into a parked aircraft. During the subsequent investigation, it was found that the hitch on the tug had been modified. The modified hitch was not as safe as the standard hitch, since it did not have a positive lock feature to ensure that the hitch pin did not come loose. However, the standard hitch required more time to install, and more strength (usually more than one person) to use as compared to the modified hitch. Since usually only one person was assigned to a tow, the hitch had been modified to allow easier connections/disconnections. Plant maintenance, the department responsible for the condition of the ground equipment, was unaware of the modifications to the hitch on this vehicle. A worn hitch pin that had worn small enough to come out of the hitch body during the tow exacerbated this particular incident.

2.1.5. Hangar doors closed onto aircraft (*1.1.5*)

In these incidents, airline personnel close the hangar doors onto the aircraft. Misjudging the position of the aircraft within the hangar usually causes this type of incident. In most situations, the mechanics who close the hangar doors have simply assumed that the aircraft is correctly parked in the hangar, and have closed the hangar doors without checking for clearance. However, in most cases when this type of incident has occurred, the aircraft had been parked incorrectly in the hangar. Thus, it is useful to consider why the aircraft could be parked incorrectly.

Since aircraft hangars are often quite congested, and are filled with other aircraft and equipment, there is often only one correct place in which the aircraft can be parked. To correctly park an aircraft in a hangar it is necessary for the aircraft to be towed into the hangar on the proper towline for that type of aircraft, and the tow stopped on the proper block. The tow line and stop block are painted lines on the floor of the hangar. Ideally there is one line for *each* type of aircraft using that hangar. Problems arise when the painted lines do not match the type of aircraft, and the mechanics have to choose a different set of guidelines to follow. For example, in one incident, a DC-9 was pulled into a hangar on a 727 towline. The only two painted lines in this hangar were for the 727 and 757 aircraft. Additionally, it is necessary to properly align the aircraft on the guidelines before it is too far into the hangar, since it is difficult to adjust its position once the aircraft is in the hangar. Therefore, it is desirable to have the guidelines extend outside of the hangar, to allow the tug driver and spotters to properly align the aircraft as they enter the hangar. In places where the guidelines do not extend outside of the hangar, it is much more difficult to properly position the aircraft in the hangar.

Proper positioning also assumes that it is possible to correctly position the aircraft in the hangar. If equipment/workstands are in the path of the aircraft, or a tug that is too large is used, it may not be possible for the mechanics to properly park the aircraft.

In other situations, an aircraft may be parked temporarily in a hangar that is not suited to that type of aircraft. The hangar may not be big enough for the aircraft to fit completely inside. However, if mechanics are not aware of this, they may routinely close the hangar doors without checking for clearance. It is proper procedure for the door controls to be 'red-tagged' to indicate to everyone else that the controls should not be used. This should be done by the mechanics that tow the aircraft into the hangar. These mechanics should recognize that the aircraft is too long for the hangar. However, in incidents where the doors were closed on an aircraft, the door controls were not red-tagged.

2.1.6. *Position of aircraft components changes* (*1.2.1*)

In these incidents, the position of aircraft components (e.g., stabilizer, flaps, rudder, etc.) is changed, either manually or through the activation of a hydraulic system, causing the components to contact obstacles in their path. The first category of incidents, those in which an aircraft component was manually adjusted, generally occurred because a workstand was left in the path of the component. The mechanic failed to perform a walk-around check to ensure that the area was clear before adjusting the component. In addition, no ground spotters were utilized to ensure that the component did not contact anything during its move. It is the crew chief's responsibility to ensure that the proper personnel are assigned to perform a given task. In many situations, the crew chief failed to assign enough personnel and/or failed to ensure that the ground spotters were in place. Since the policy of using ground spotters is rarely followed, many mechanics fail to even ask for assistance when they have to adjust the position of an aircraft component. In addition, the time pressure to ensure on-time departures encourages mechanics to complete their tasks as quickly as possible. The time used to arrange for ground spotters might have been seen as time that can be used more effectively on actually performing the task.

In the second category of incidents, the hydraulic system is activated (or deactivated), causing aircraft components to return automatically to a neutral position. Often, the movement of these components is unintended by the mechanic, who simply activates the hydraulic system for a different purpose. However, the lack of awareness of the implications of hydraulic system activation has caused many incidents. Since the mechanics do not consider what will happen all around the aircraft when the hydraulic system is activated, they often fail to perform a complete walk-around to check for proper clearance. Thus, the aircraft components may contact equipment that is being used by another mechanic, performing an unrelated task. There are many other latent failures that can be shown to contribute to this type of incident.

Most importantly, there seems to be no standard method of communicating the impending activation of the hydraulic system to all of the mechanics working on the aircraft. Some mechanics simply yell their intentions to all within earshot, but the noise in the hangar environment makes it very difficult to hear and understand. In addition, as required by the company policy manual, the controls for the hydraulic system should be 'red-tagged' (with a Do Not Operate tag) if a mechanic is working in the path of any of the components that may be affected by the hydraulic system. This is often not performed.

These incidents are likely to occur because mechanics are often unaware of other work that is being performed on the aircraft. Poor communication between the crew chiefs and the mechanics at the beginning of the shift leaves each mechanic only with an understanding of his task assignment, not the larger picture. Better communication will help mechanics become more aware of the hazards and risks associated with their assigned tasks.

2.1.7. *Center of gravity shifts* (*1.2.2*)

In these incidents, the center of gravity of the aircraft shifts unexpectedly, causing the aircraft to contact the ground with either its nose (center of gravity shifts forward) or its tail (center of gravity shifts backwards). In most of these incidents, the mechanics left a workstand or other piece of equipment under the aircraft while they were working. When the center of gravity shifted, the aircraft settled onto this equipment, causing damage to the aircraft.

In some situations, the passengers were allowed on board while the mechanic was working on the aircraft. The mechanics were unaware that the loading had begun until the aircraft's center of gravity began to shift. The poor communication among all of the airline personnel connected to a single aircraft (mechanics, gate agents, ground crew, flight crew) is a latent failure behind many of these incidents. Similarly, the work of other mechanics on the aircraft may cause the center of gravity to shift as well. For example, if other maintenance work requires the aircraft to be jacked up, the center of gravity shift will affect all other mechanics working on this aircraft. Lack of awareness of other work on the aircraft, as well as poor communication between the different mechanics contributes to these incidents.

In other incidents, improper procedures or equipment that is being used to complete an assigned task causes the center of gravity shift. For example, one mechanic did not follow the DC-9 manual for supporting and jacking the aircraft, and chose to jack the aircraft improperly. This caused the aircraft to be unstable, and the aircraft's center of gravity shifted. In other situations, the mechanics use improper tools that cause the landing gear to collapse during functional tests, causing damage to the nose of the aircraft. The mechanics may not even know that they are using the wrong tools, since it is a common practice at this airline. This lack of awareness prevents the mechanics from taking the correct precautions to avoid damaging the aircraft.

2.1.8. *Aircraft rolls forward/backwards* (*1.2.3*)

In these incidents, the aircraft rolls either forward or backward under its own power. This unexpected movement causes the aircraft to contact obstacles in its path. In many of these incidents, the aircraft is parked, and the wheels are not chocked (or are improperly chocked). In these cases, the mechanics parked the aircraft in a remote parking area, and forgot to bring chocks with them. They returned to the hangar, but were distracted before they could return to the aircraft with the chocks.

In other incidents, the mechanics request the cockpit crew to release the aircraft brakes while the aircraft is connected to the pushback tractor. Then, the towbar is detached before the brakes are reset. These incidents can also be attributed to the poor communication between the airline personnel working on this aircraft. In some instances, the mechanics asked the cockpit crew to release the brakes, without informing the pushback crew. The pushback crew then continued to prepare the aircraft for pushback, without being aware of the maintenance problem that the mechanics were working on. In other instances, one member of the pushback (wingwalker) was struggling to disconnect the towbar, when the tug driver requested that the brakes be released to allow the towbar to be repositioned. The wingwalker then successfully pulled the hitch pin, without knowing that the brakes had been released, and the aircraft rolled forward into the tug.

2.1.9. *Towing vehicle strikes aircraft* (*2.1*)

In these incidents, the pushback tug being used to tow the aircraft, or the towbar connecting the tug and the aircraft, comes in contact with the aircraft. In some of these incidents, the tug being used to tow the aircraft slips on the ramp surface, causing it to jackknife and contact the aircraft. In these incidents, snow and ice usually cover the ramp. Other latent factors contributing to this type of incident include: the lack of traction augmentation for the tugs (e.g., chains for the tires); the use of towbars which are too short (which allow the tug to contact the aircraft); the use of light tow tractors that are subject to sliding; and poor ramp maintenance in snow/ice conditions. In fact, the snow policy at one station even discourages the mechanics from calling to have the ramp sanded. At this particular station, because of the high cost, sanding overnight can only be arranged by first calling the manager at home. Since mechanics are reluctant to call their manager at home in the middle of the night, they often choose to forgo sanding.

Other incidents occur when the mechanic is working alone to connect the aircraft to the tow tractor. Generally, it is preferable to have two people connecting the towbar: one to drive the tug, the other to connect the towbar. When only one mechanic is assigned to this task, he must repeatedly climb in and out of the tug in order to ensure that the tug is properly aligned with the aircraft. Combined with equipment problems, this may increase the potential for a problem to occur during the towbar hookup. For example, in one incident, the mechanic's foot accidentally slipped from the brake to the accelerator pedal while he was connecting the towbar. The brake pedal surface was worn completely smooth, but the mechanic's footing may have been slippery from the conditions on the ramp. This particular incident was compounded by additional problems with the gear selector on the tug, which allowed the gear selector to slip into Drive from Neutral. This type of incident emphasizes the need to keep all ground equipment in good operating condition at all times.

The need to maintain ground equipment in good condition is also illustrated by the following example. In one incident, the mechanic used a tug with a known problem with the door latch. The door latch had been broken for a few days, but it had not been red-tagged and the tug was allowed to remain in service. In addition, no safety restraint had been installed on the tug's door to prevent it from swinging open. During a routine tow, the door of the tug swung open, contacting the aircraft and causing damage. This incident was obviously preventable, had the defective equipment been removed from service when the problem was initially detected.

2.1.10. *Aircraft is not properly configured for towing* (*2.2*)

In these incidents, the towing operation was initiated before the aircraft was ready to be moved. The movement of the aircraft caused damage to occur. These incidents are characterized by poor communication between various members of the pushback crew. For example, in one incident, the airstairs were left down when the pushback was initiated. The cockpit crew did not inform the tug driver as to the status of the door light annunciator. This would have alerted the tug driver that the door was open, and the aircraft was not ready to be towed. Although this is not required by the company's general practices manual, the ramp standards practice manual suggests it. The communication from the cockpit that the door was open would have prevented costly damage to the aircraft. Another factor contributing to this incident is that the mechanic in charge of the aircraft tow (the tug driver) was interrupted during his/her walk around, and failed to complete the walk around before beginning the tow. Finally, since this aircraft was parked in a wide open parking area, the tug driver decided that no wingwalkers would be necessary (as per usual ramp practice). This prevented one last preventive measure from working as designed.

In another incident, the pushback tug driver initiated the pushback while a lavatory truck was still servicing the aircraft. The wingwalkers knew that the lavatory truck was still connected to the aircraft, but failed to communicate this information to the tug driver. In addition, the wingwalker was not using his wands to indicate the obstruction to the tug driver. The tug driver initiated the pushback before the wingwalkers were in their proper positions, and before the 'all-clear' signal was given by the wingwalker. Apparently, there was some confusion as to whether the wingwalker must give the all-clear signal before the pushback can begin, or whether the pushback should begin when the tug driver sees all of the wingwalkers in their proper positions. The wingwalker mistakenly assumed that the tug driver would wait for the all-clear signal before beginning pushback, so he did not indicate the obstruction to the tug driver. The tug driver had been instructed to clear the gate to allow another incoming aircraft to enter the gate, and was feeling pressure to maintain his departure schedule. The latent failures of poor communication and confusion concerning the pushback procedure contribute to this type of incident.

2.1.11. *Aircraft contacts fixed object/equipment* (*2.3.1*)

In these incidents, the aircraft contacts a permanent, unmovable fixture (e.g., the doors/walls of the hangar) while being towed. Semi-permanent fixtures, such as snowbanks that exist for relatively long periods of time, are included in this type of incident. Many incidents of this type are caused by problems with the guidelines that are used to tow aircraft into maintenance hangars. The aircraft might contact a fixed object when it is towed into the hangar off-center, i.e. when the aircraft is improperly aligned on the guidelines. In some situations, the guidelines are incorrectly painted or are quite confusing. In fact, in some hangars it is standard practice to park the aircraft in the hangar off-center. In other situations, the guidelines do not extend outside of the hangar, making it quite difficult to properly align the aircraft before entering the hangar. Congestion both inside and outside of the hangar increases the difficulty of properly aligning the aircraft, by making it harder to maneuver the aircraft into the correct position.

Another factor that contributes to this type of incident is the failure of the tug driver to stop the tow when the wingwalkers leave the field of view. Although this violates company policy, line managers regularly permit this behavior to occur. In addition, in some cases the proper number of guidepeople is not even used during the tow. Also, in some situations the tug driver consciously decides to turn attention away from one or more of the guidepeople in order to concentrate on other related matters (e.g., locating the guideline, checking clearance on one particular point on the aircraft, etc.). In these situations, the tug driver is not attending to signals that the other guidepeople may be giving, and thus will not be able to avoid contacting an obstacle in the path of the aircraft.

Incidents of this type are also caused when an aircraft is being pushed out of a hangar, and the hangar doors are not completely open. This situation has occurred when a company aircraft is being repaired in a hangar belonging to another company, or when another company's aircraft is being repaired in this company's hangar. The damage to the aircraft is often caused by the visiting mechanics' unfamiliarity with the hangar, as well as poor communication between the two sets of mechanics.

2.1.12. Aircraft contacts moveable object/equipment (2.3.2)

In these incidents, the aircraft contacts moveable objects/equipment while being towed. The objects/equipment are not necessarily in the same location each time an aircraft is moved. Thus, it is necessary for the mechanics to detect the objects before beginning the aircraft tow, and make the necessary efforts during the tow to prevent contact with the aircraft. Many of these incidents involve the aircraft contacting objects/equipment parked within the aircraft safety zone. The aircraft safety zone is supposed to be indicated by painted lines at each aircraft parking area, and indicate where it is safe to leave equipment. Objects left within the safety zone are at risk to be contacted by the aircraft during the tow. It is company policy for the tug driver (who is in charge of the tow) to ensure that the parking area for the aircraft is clear before beginning the tow. In many of these incidents, the safety zone is not cleared before the aircraft is towed into the area. Generally, the tug driver, or other guidepeople, assumes that the aircraft will clear the objects/equipment that are left within the safety zone. In other situations, malfunctions of the equipment parked in the safety zone prevent it from being moved to a safer area. For example, in one incident, a loader was parked within the safety zone. However, the right wheel of the loader was broken off, so it could not easily be moved from its position. In a second example, a tail dock in one hangar was inoperative, and the tail dock could not be lowered to the correct position. In this situation, the mechanic had not been informed of the problem with the tail dock, although it had been red-tagged the previous day. There are also situations where it is considered normal for equipment to be parked inside the safety zone. For example, at one particular gate it is normal for the catering truck to be parked nearly eleven feet into the safety zone for the adjacent gate. Such situations make it even more difficult for tug drivers to ensure that the area is clear before the tow is initiated.

Another factor contributing to this type of incident is that the correct number of guidepeople is not always used during aircraft tows. Although this is a violation of company policy, the policy is rarely enforced, and the mechanics have become accustomed to moving aircraft with a limited number of personnel. The reduced number of personnel makes it more difficult for the tug driver to ensure clearance around the aircraft. In fact, some mechanics report that there are many more instances of minor aircraft damage that goes unreported. In addition, the congestion that surrounds the ramp and hangar areas increases the difficulty of safely towing the aircraft.

There are also problems of communication that contribute to this type of incident. One of the common problems is miscommunication between the tug driver and the guidepeople. In some situations, the tug driver failed to recognize the hand signals given by the wingwalkers. In other situations, the tug driver initiated the tow before the guidepeople were ready. Another latent communication problem is that tug drivers do not routinely give verbal responses to commands from the guidepeople. This becomes a problem when a guideperson gives a command to the tug driver, and assumes that the tug driver sees and understands the command. This problem also manifests in situations when verbal communication between the towing crew is difficult. Since the tug driver must simultaneously attend to many areas of the aircraft, it is very difficult to ensure that the tug driver will see the hand signals given by any one guideperson. However, the guidepeople are usually not in radio contact with the tug driver, so verbal communication is also difficult, due to the excessive noise inherent to the airport environment. When communication between the members of the tug crew is difficult, it is likely that the tug driver will not be able to respond in time to any obstacle that may lie in the path of the aircraft.

3. Results

The number of incidents in each of the GDI hazard patterns is summarized in Table 1. To determine the validity of these classification schemes, the hazard patterns were re-coded by two independent researchers using the definitions developed. Neither researcher was familiar with airline ground operations. Percent agreement on how to categorize the incidents was 70%. The inconsistencies were found to result from misinterpretations of the various terms used in the hazard patterns. The hazard patterns have been reworded to be more explicit, and it is expected that percent agreement will be much higher for categorization of future incidents.

3.1. Latent failures in ground damage incidents

From the highly detailed GDI reports it has been possible to identify consistent hazard patterns, and within these to derive the latent failures in addition

Table 1
GDI hazard patterns

Hazard pattern	Number of incidents			% of Total
1. Aircraft is Parked at the Hangar/Gate/Tarmac	81			62
1.1. Equipment Strikes Aircraft		51		39
1.1.1. Tools/Materials Contact Aircraft			4	3
1.1.2. Workstand Contacts Aircraft			23	18
1.1.3. Ground Equipment is Driven into Aircraft			13	10
1.1.4. Unmanned Equipment Rolls into Aircraft			6	4
1.1.5. Hangar Doors Closed Onto Aircraft			5	4
1.2. Aircraft (or Aircraft Part) Moves to Contact Object		30		23
1.2.1. Position of Aircraft Components Changes			15	12
1.2.2. Center of Gravity Shifts			9	7
1.2.3. Aircraft Rolls Forward/Backward			6	4
2. Aircraft is Being Towed/Taxied	49			38
2.1. Towing Vehicle Strikes Aircraft		5		4
2.2. Aircraft is Not Properly Configured for Towing		2		2
2.3. Aircraft Contacts Fixed Object/Equipment		42		32
2.3.1. Aircraft Contacts Fixed Object/Equipment			13	10
2.3.2. Aircraft Contacts Moveable Object/Equipment			29	22
Total	130	130	130	100%

to the more usual active failures. Latent failures were tabulated for each GDI using an iterative procedure to produce a workable taxonomy specific to ground damage. Other taxonomies exist for error in general (Reason, 1990; Senders and Moray, 1991) and some are implied by current error classification schemes in aircraft maintenance (Marx, 1992). The taxonomy developed here used elements of all of these. After consistent latent failures were identified, a logical structure was imposed using ICAO's SHELL Model (ICAO, 1989). For the tasks leading to ground damage, no software failures (e.g. documentation design) were found. Hence, the remaining categories have been used as follows to classify the latent failures: hardware, environment, liveware (individual) and liveware–liveware (interpersonal). Each of the latent failures has been described in detail in the hazard pattern scenarios. However, a short description of each latent failure is provided in Table 2.

Latent failures are considered to be problems that exist in the system independently (distinct in time and space) of active failures that cause an incident. However, it is important to note that problems such as complacency, bad attitudes of mechanics, etc. were not considered to be latent failures. The concentration here was on latent failures that could be addressed through changes to the maintenance system, rather than characteristics of individual maintenance personnel.

Table 3 summarizes the incidence of latent failures in the 130 GDIs analyzed. From Table 3, it can be seen that the most frequently occurring latent failures are problems with the equipment, use of an improper number of personnel, and a lack of awareness of risks and hazards. This last latent failure is a broad category, including such failures as inadequate training and the assumption that adequate clearance exists without checking. However, it is not possible to fully eliminate any of these latent failures using only the traditional technique of reprimand, motivate and train.

3.2. Relationship between hazard patterns and latent failures

While it is possible to intervene across all ground operations in an attempt to eliminate both active and latent failures, a more focused strategy may be more effective. If the contribution of each latent failure to each hazard pattern can be found, then typical scenarios and sequences can be developed to address particular losses. This means understanding the sequence(s) of each hazard pattern, and finding common latent failures that contribute to that sequence. As a first step, event trees were constructed for each hazard pattern. One example is shown in Fig. 1.

We can, however, go further than this and test statistically for any associations between latent failures and hazard patterns. Tables 4–7 show a complete cross-classification of the hazard patterns from Table 1 with the latent failures from Table 3. Note that Tables 4–7 provide intermediate totals, e.g., for Hazard Pattern 2 and for Hazard Pattern 2.3, as well as individual counts at the lowest level (Hazard Patterns 2.3.1 and 2.3.2). Table 4 addresses the hardware latent failures, Table 5 addresses the environment latent failures, Table 6 addresses the liveware latent failures, and Table 7 shows the total number of latent failures for each hazard pattern. It is important to remember that each latent failure does not contribute to each incident within a hazard pattern, but is simply a latent failure that has resulted in an incident of this type in the past.

Chi-square tests of independence of frequencies are appropriate for such analyses. The data from Tables 4–7 can be examined by chi-square tests at any level of aggregation of either hazard pattern or latent failures. However, many of the cells in Tables 4–7 contain very low numbers of latent failures, which give low expected frequencies, invalidating the assumptions of the Chi-square test even with a relatively high total of 265 latent failures.

For this reason, the analysis was performed at two levels of aggregated hazard patterns and two levels of aggregation of latent failures. The higher aggregation of hazard pattern was at two levels, HP1 and HP2, while for latent failures it was at the four levels H, E, LI and LL. This analysis gave the results in Table 8, with a highly significant association between hazard pattern and latent failure ($\chi^2_{(3)} = 15.2, p < 0.001$). In Table 8, cells which are over-represented, i.e. cells with a large contribution to Chi-square and greater than the expected frequency, are indicated using[a].

Table 2
Latent failure descriptions

SHELL category	Latent failure	Latent failure description
Hardware	Poor Equipment	Equipment was not suitable for the task being performed, and this contributed to an incident
	Poor Equipment: Inappropriate for Task	Equipment used to perform a task was not the correct type of equipment for that task, and the use of improper equipment contributed to the incident
	Poor Equipment: Mechanical Problem	Equipment used to perform a task had a mechanical problem that caused it to behave erratically, contributing to the incident
Environment	Inadequate Space	Space in which a task was performed was not sufficient, and the lack of space contributed to the incident
	Inadequate Space: Congested Area	Space in which a task was performed was crowded with other equipment/aircraft/etc., causing special attention to maneuvering within this space to be required. The crowded nature of the space contributed to the incident.
	Inadequate Space: Ill suited for Task	Task was performed in a space that was known to be inappropriate for the work to be performed, and this lack of space contributed to the incident.
	Problems with Painted Guidelines	Guidelines used to position aircraft contribute to the incident
	Guidelines: Do Not Exist	Guidelines are not painted at a particular location, requiring maintenance personnel to use their 'best guess' in positioning aircraft.
	Guidelines: Do Not Extend Out of Hangar	Guidelines for positioning aircraft in a hangar begin at the Ghangar door, requiring maintenance personnel to use their 'best guess' to position aircraft to begin the tow into the hangar.
	Guidelines: Not Suitable for Aircraft	Guidelines for a different type of aircraft than the one being moved are painted on the ground, and the lack of suitable guidelines contributes to the incident.
Liveware (Individual)	Lack of Awareness of Risks/Hazards	Maintenance personnel are unaware of the possible risks associated with their actions, and the lack of awareness contributes to the incident.
Liveware–Liveware	Poor Communication	Problems with the transfer of information between maintenance personnel, and this lack of information contributed to an incident
	Poor Communication: Between Crew	Problems with the transfer of information between maintenance personnel working together on one shift
	Poor Communication: Between Shift	Problems with the transfer of information between maintenance personnel on different shifts
	Personnel Unaware of Concurrent Work	Maintenance personnel working on one area of the aircraft are unaware of work being performed by other personnel (who may be from other departments or other agencies) on other areas of the aircraft. This lack of awareness contributes to the incident
	Pressures to Maintain On-Time Departures	Maintenance personnel are subjected to subtle and not so subtle pressures to remain on schedule at 'any cost'. These pressures affect the decisions made by the maintenance personnel, and these decisions contribute to the incident
	Pushback Policies Not Enforced	Pushback policies, as written in the operating procedures of the airline, are not enforced on a regular basis, leading to company norms on how a pushback should be conducted. These norms are followed by all personnel, without being questioned (and perhaps even encouraged) by management, until an incident occurs, when the personnel involved are reprimanded for not following the operating procedure. The willingness of management to accept a company norm for day-to-day operation contributes to the incident

Table 3
Incidence of latent failures[a]

SHELL model category		Latent failure	Number of incidents			% of total
Hardware					72	27
	H1	*Poor Equipment*		72		27
		H1.1. Poor Equipment: Inappropriate for Task	39			15
		H1.2. Poor Equipment: Mechanical Problem	33			12
Environment					51	19
	E1	*Inadequate Space*		30		11
		E1.1. Inadequate Space: Congested Area	22			8
		E1.2. Inadequate Space: Ill-suited for Task	8			3
	E2	*Problems with Painted* Guidelines		21		8
		E2.1. Guidelines: Do Not Exist	7			3
		E2.2. Guidelines: Do Not Extend Out of Hangar	4			1
		E2.3. Guidelines: Not Suitable for Aircraft	10			4
Liveware (Individual)					34	13
	L1	*Lack of Awareness of Risks/Hazards*		34		13
Liveware–Liveware					108	41
	LL1	*Poor Communication*		29		11
		LL1.1. Poor Communication: Between Crew	24			9
		LL1.2. Poor Communication: Between Shifts	5			2
	LL2	*Personnel Unaware of Concurrent Work*		8		3
	LL3	*Correct Number of People Not Used*		36		14
	LL4	*Pressures to Maintain On-Time Departures*		19		7
	LL5	*Pushback Policies Not Enforced*		16		6
		Total			265	100%

[a]Note: Totals exceed the number of incidents due to multiple latent failures per incident.

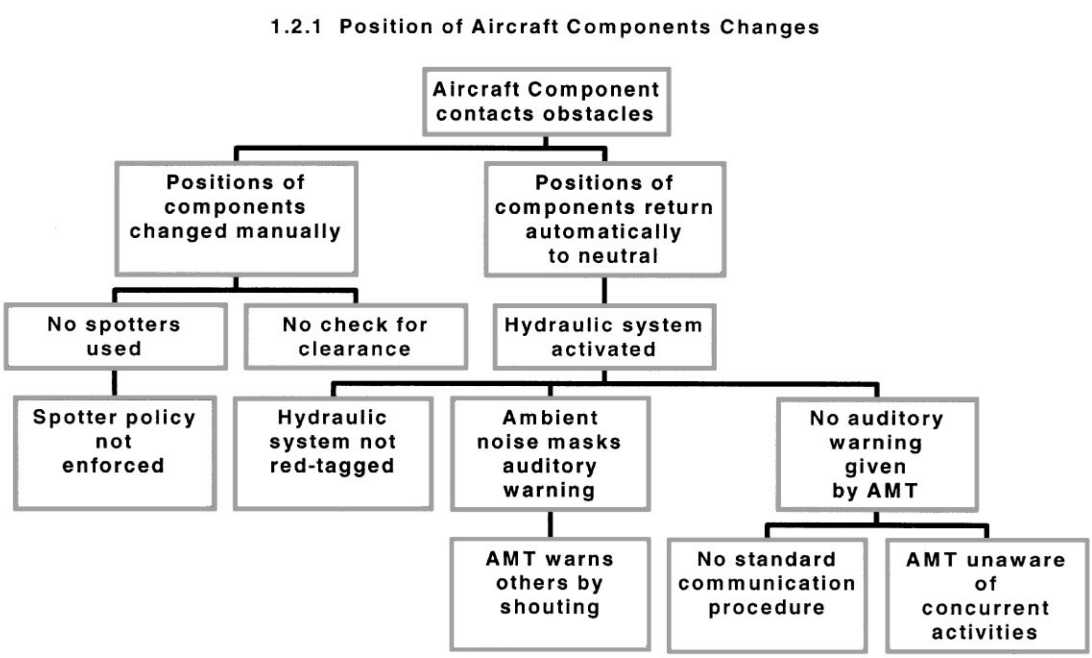

Fig. 1. Example of hazard pattern event tree.

Table 4
Summary of hardware latent failures by hazard patterns

Hazard patterns	Hardware latent failures		
	PE: Inappropriate for task	PE: Mechanical problem	Poor equipment (PE)
Aircraft Parked	33	20	53
Equipment Strikes Aircraft	*30*	*17*	*47*
Tools/Materials Contact Aircraft	1	2	3
Workstand Contacts Aircraft	25	4	29
Ground Equipment Driven into Aircraft	4	3	7
Unmanned Equipment Rolls into Aircraft	0	8	8
Hangar Doors Closed onto Aircraft	0	0	0
Aircraft (or Aircraft Part) Moves to Contact Object	*3*	*3*	*6*
Position of Aircraft Component Changes	1	0	1
Center of Gravity Shifts	2	1	3
Aircraft Rolls Forward/Backward	0	2	2
Aircraft is Being Towed/Taxied	6	13	19
Towing Vehicle Strikes Aircraft	3	5	8
Aircraft Not Properly Configured for Towing	0	0	0
Aircraft Contacts Object/Equipment	*3*	*8*	*11*
Aircraft Contacts Fixed Object or Equipment	1	3	4
Aircraft Contacts Moveable Object or Equipment	2	5	7
Total	39	33	72

It appears from Table 8 that two latent failures (LI and LL) are equally associated with both hazard patterns, while the other two (H and E) are associated with specific hazard patterns. Thus, hardware failures are over-represented for parked aircraft and environmental failures are over-represented for towed aircraft.

Going to the next level of aggregation, there are too few entries in cells representing Hazard Patterns 2.1 and 2.2 for Chi-square assumptions, so that only Hazard Patterns 1.1, 1.2 and 2.3 were analyzed. New patterns begin to emerge at this level. No latent failure is generally applicable across all hazard patterns. Hardware is still associated with parked aircraft, now specifically 1.1 Equipment Strikes Aircraft. Environment is still associated with aircraft under tow, now specifically with 2.3 Aircraft Contacts Fixed Object/Equipment. However, both liveware latent failures are now associated with parked aircraft, specifically 1.2 Aircraft Part Moves to Contact Object.

Moving to the lower level of aggregation of latent failures, we again have two analyses, each now involving the nine lower level latent failures.

At the highest level of aggregation of hazard patterns there are two hazard patterns (1 and 2) and nine latent failures. Overall, the Chi-square test showed a significant association between hazard patterns and latent failures ($\chi^2(8) = 28.4, p < 0.001$). The following latent failures were over-represented in the two hazard patterns, as shown in Table 9.

For the next level of aggregation, hazard patterns were counted at the secondary level (1.1, 1.2, and 2.3), again with Hazard Patterns 2.1 and 2.2 eliminated. A Chi-square analysis of Hazard Patterns 1.1, 1.2 and 2.3 for the Latent Failures again gave significant results ($\chi^2(16) = 90.6, p < 0.001$). The same pattern of individual cell χ^2 contributions was seen for Hazard Pattern 2.3 as had been found for Hazard Pattern 2 above. However, when Hazard Pattern 1 was split into 1.1 and 1.2, this split the latent failures found above, and added a new one, as shown in Table 9.

We can summarize the findings of all of these analyzes by classifying each latent failure as to its association with specific hazard patterns, as shown in Table 10.

Table 5
Summary of environment latent failures by hazard pattern

Hazard Patterns	Environment latent failures						
	IS: congested area	IS: Ill-suited for task	Inadequate space (IS)	PG: do not exist	PG: do not extend out of hangar	PG: not suitable for aircraft	Problems with painted guideliness (PG)
Aircraft Parked	8	4	12	2	1	5	8
Equipment Strikes Aircraft	*8*	*3*	*11*	*1*	*1*	*5*	*7*
Tools/Materials Contact Aircraft	0	1	1	0	0	0	0
Workstand Contacts Aircraft	0	0	0	0	0	1	1
Ground Equipment Driven into Aircraft	7	0	7	0	0	1	1
Unmanned Equipment Rolls into Aircraft	0	0	0	0	0	0	0
Hangar Doors Closed onto Aircraft	1	2	3	1	1	3	5
Aircraft (or A/C Part) Moves to Contact Obj.	*0*	*1*	*1*	*1*	*0*	*0*	*1*
Position of Aircraft Component Changes	0	0	0	0	0	0	0
Center of Gravity Shifts	0	0	0	1	0	0	1
Aircraft Rolls Forward/Backward	0	1	1	0	0	0	0
Aircraft is Being Towed/Taxied	14	4	18	5	3	5	13
Towing Vehicle Strikes Aircraft	0	0	0	0	0	0	0
Aircraft Not Properly Configured for Towing	0	0	0	0	0	0	0
Aircraft Contacts Object/Equipment	*14*	*4*	*18*	*5*	*3*	*5*	*13*
Aircraft Contacts Fixed Object/Equip.	4	4	8	1	1	3	5
Aircraft Contacts Moveable Obj./Equip.	10	0	10	4	2	2	8
Total	22	8	30	7	4	10	21

Table 6
Summary of liveware (individual and liveware-liveware) latent failures by hazard pattern

Hazard Patterns	Liveware latent failures							
	Lack of Awareness of Risks and Hazards	PC: Between Crews	PC: Between Shifts	Poor Comm. (PC)	Personnel Unaware of Concurrent Work	Correct Number People Not Used	Pressures to Maintain On-Time Departures	Pushback Policies Not Enforced
Aircraft Parked	22	13	4	17	8	22	11	4
Equipment Strikes Aircraft	*10*	*2*	*3*	*5*	*1*	*17*	*6*	*2*
Tools/Materials Contact Aircraft	2	1	2	3	0	0	0	0
Workstand Contacts Aircraft	2	1	0	1	1	6	4	1
Ground Equipment Driven into Aircraft	0	0	0	0	0	9	2	1
Unmanned Equipment Rolls into A/C	4	0	0	0	0	2	0	0
Hangar Doors Closed onto Aircraft	2	0	1	1	0	0	0	0
Aircraft (or A/C Part) Moves to Contact Obj.	*12*	*11*	*1*	*12*	*7*	*5*	*5*	*2*
Position of A/C Component Changes	5	7	1	8	2	5	3	0
Center of Gravity Shifts	5	2	0	2	5	0	1	1
Aircraft Rolls Forward/Backward	2	2	0	2	0	0	1	1
Aircraft is Being Towed/Taxied	12	11	1	12	0	14	8	12
Towing Vehicle Strikes Aircraft	3	0	0	0	0	2	0	0
Aircraft Not Properly Configured for Towing	0	2	0	2	0	0	1	1
Aircraft Contacts Object/Equipment	*9*	*9*	*1*	*10*	*0*	*12*	*7*	*11*
Aircraft Contacts Fixed Object/Equip.	3	1	1	2	0	2	1	4
Aircraft Contacts Moveable Obj./Equip.	6	8	0	8	0	10	6	7
Total	34	24	5	29	8	36	19	16

These analyses show that different latent failures are over-represented in different hazard patterns, i.e., their occurrence is non-random. These over-represented latent failures are not the only antecedents of the incidents within a hazard pattern, but rather the 'causes' unique to that hazard pattern. For example, Latent Failure LL3: Not Enough Personnel contributed to all hazard patterns in proportion to their relative frequencies, and thus was an underlying 'cause' of many incidents across all hazard patterns. However, when equipment struck an aircraft (Hazard Patterns 1.1.1–1.1.5), a unique 'cause' was deficiencies in the equipment. Thus appropriate interventions for this class of incidents would be to ensure that correct equipment was always available, that it was properly maintained, and that personnel knew not to substitute inappropriate equipment.

Conversely, appropriate interventions for Hazard Pattern 1.2, where an aircraft or aircraft part moves to contact an object, should concentrate on coordination between individuals as the uniquely associated latent failures were Latent Failure LL1: Poor Communication and Latent Failure LL2: Unaware of Concurrent Work. Thus, splitting Hazard Pattern 1.1 from Hazard Pattern 1.2 in the Chi-square analysis can focus management attention onto quite different strategies of intervention.

For Hazard Pattern 2, where the aircraft is being towed, the associated latent failures directly address aircraft movements. Towing often takes place in a small, crowded, or difficult. The area may also have inadequate, misleading, or missing painted guidelines. Appropriate unique interventions would be to address the physical issues of aircraft movement, and how the operators control the direction and speed of these movements. Finally, lack of enforcement of pushback policies is a latent failure that contributes to aircraft movement incidents. Managerial issues of why the

Table 7
Summary of total latent failures by hazard pattern

Hazard Patterns	Total Latent Failures	
Aircraft Parked	157	
Equipment Strikes Aircraft	*106*	
Tools/Materials Contact Aircraft		9
Workstand Contacts Aircraft		45
Ground Equipment Driven into Aircraft		27
Unmanned Equipment Rolls into Aircraft		14
Hangar Doors Closed onto Aircraft		11
Aircraft (or Aircraft Part) Moves to Contact Object	*51*	
Position of Aircraft Component Changes		24
Center of Gravity Shifts		18
Aircraft Rolls Forward/Backward		9
Aircraft is Being Towed/Taxied	108	
Towing Vehicle Strikes Aircraft	*13*	
Aircraft Not Properly Configured for Towing	*4*	
Aircraft Contacts Object/Equipment	*91*	
Aircraft Contacts Fixed Object or Equipment		29
Aircraft Contacts Moveable Object or Equipment		62
Total	265	

Table 8
Chi-square analysis of the hazard patterns/latent failure relationship

	HP 1: Aircraft Parked	HP 1.1: Equipment Strikes Aircraft	HP 1.2: Aircraft (or Component) Moves to Contact Object	HP 2: Aircraft Being Towed/Taxied	HP 2.3: Aircraft Contacts Equipment
Hardware	53[a]	47[a]	6	19	11
Environment	20	18	2	31[a]	31[a]
Liveware (Individual)	22	10	12[a]	12	9
Liveware–Liveware	62	4	31[a]	46	40

[a]Indicates a frequency larger than expected

Table 9
Latent failures over-represented in specific hazard patterns

	Hazard patterns			
	HP 1 Aircraft Parked	HP 1.1 Equipment Strikes Aircraft	HP 1.2 Aircraft (or Component) Moves	HP 2 Aircraft is Being Towed
Latent Failures	H: Poor Equipment LL2: Unaware of Concurrent Work	H1: Poor Equipment	LL1: Poor Communication LL2: Unaware of Concurrent Work	E1: Inadequate Space E2: Painted Guideline Problems LL5: Pushback Policies not Enforced

Table 10
Summary of associations between HPs and LFs from chi-squared analyses

Latent Failures	Associated Hazard Patterns
Hardware	
H1. Poor Equipment	1.1. Equipment strikes parked aircraft
H1.1. Poor Equipment: Inappropriate for Task	
H1.2. Poor Equipment: Mechanical Problem	
Environment	
E1. Inadequate Space	2.3. Aircraft under tow
E1.1. Inadequate Space: Congested Area	
E1.2. Inadequate Space: Ill-suited for Task	
E2. Problems with Painted Guidelines	2.3. Aircraft under tow
E2.1. Guidelines: Do Not Exist	
E2.2. Guidelines: Do Not Extend Out of Hangar	
E2.3. Guidelines: Not Suitable for Aircraft	
Liveware (Individual)	
LI. Lack of Awareness of Risks/Hazards	1.2. Aircraft or part moves to contact object
Liveware-Liveware	
LL1. Poor Communication	1.2. Aircraft or part moves to contact object
LL1.1. Poor Communication: Between Crew	
LL1.2. Poor Communication: Between Shifts	
LL2. Personnel Unaware of Concurrent Work	1.2. Aircraft or part moves to contact object
LL3. Correct Number of People Not Used	(General)
LL4. Pressures to Maintain On-Time Departures	(General)
LL5. Pushback Policies Not Enforced	2.3. Aircraft under tow

operators violate the policy should be addressed. Is the policy good but inadequately enforced? Does the policy conflict with others, such as flexibility of workforce assignment or departure processes? For this hazard pattern, unique interventions need to cover both the physical and managerial aspects of the task.

It is not suggested that managers discount the active failures that occur in the system, since clearly, if the active failures are eliminated the incident will be prevented. However, working beneath the surface to expose latent failures can:

(a) identify many different problems that have common interventions (e.g., better maintenance of equipment can eliminate many typical hazard patterns, and thus prevent future incidents),

(b) allow proposed interventions to go beyond the traditional personnel actions of reprimand/motivate/train, which heretofore have proven to be ineffective.

3.3. Summary of the GDI analysis

1. There are only 2 major hazard patterns, each with some sub-structure.
   1.1. There are 3 relatively large hazard patterns, which account for 94% of all GDIs.
   - Hazard Pattern 1.1: Aircraft Parked and Equipment Strikes the Aircraft (39%)
   - Hazard Pattern 1.2: Aircraft Parked and an Aircraft Part Moves to Contact an Object (23%)
   - Hazard Pattern 2.3: Aircraft Under Tow and Contacts a Fixed or Moveable Object (32%)
2. There are only 9 major latent failures, some with sub-structure.
   2.1. Some of the latent failures are general, while others are more associated with specific hazard patterns.
   2.2. General latent failures across all hazard patterns account for 21% of all latent failures.
   - LL3: Correct Number of Personnel Not Used (14%),
   - LL4: Pressures for On-Time Departure (7%).

   2.3. Latent failures associated with specific hazard patterns account for 66% of all latent failures.
   - H1: Poor Equipment is associated with Hazard Pattern 1.1: Equipment Strikes Aircraft (27%)
   - LL1: Poor Communication is associated with Hazard Pattern 1.2: Aircraft (or Aircraft Part) Moves to Contact Object is associated with Latent Failures (11%)
   - LL2: Personnel Unaware of Concurrent Work is associated with Hazard Pattern 1.2: Aircraft (or Aircraft Part) Moves to Contact Object is associated with Latent Failures (3%)
   - E1: Inadequate Space is associated with Hazard Pattern 2: Aircraft is Being Towed/Taxied (11%)
   - E2: Problems with Painted Guidelines is associated with Hazard Pattern 2: Aircraft is Being Towed/Taxied (8%)
   - LL5: Pushback Policies Not Enforced is associated with Hazard Pattern 2: Aircraft is Being Towed/Taxied (6%)

4. Addressing ground damage

The analysis of ground damage incidents in this study showed that there are relatively few causes which contribute to most ground damage incidents, which suggests that by introducing a small number of interventions, a large number of ground damage incidents can be prevented. Results also indicate that simply using the "blame-and-train" approach to preventing ground damage is ineffective, since ground damage incidents are often caused, at least partly, by latent failures in the system. These latent failures cannot be eliminated without making changes in the system further upstream than the mechanics, or even the first line supervisors. Changes must be initiated by upper levels of management, and must become integrated into the existing maintenance system.

Recently, airlines and other groups have begun developing programs to specifically address ground damage. The Aerospace Psychology Research Group at Trinity College Dublin developed the Safety Courses for Airport Ramp Functions (SCARF) program in conjunction with other university and airline partners. SCARF was developed to address the ramp safety concerns at airlines, and is described as "an integrated set of four training programs for the promotion of best demonstrated practice in the safe and cost effective operation of airport ground handling services (Fuller et al., 1994)." These training programs are aimed at ramp personnel, first line supervisors, managers, and trainers, recognizing that all members of an organization must recognize how their job contributes to ramp safety. The SCARF program has been implemented at airport sites in Europe, and its effectiveness is currently being evaluated.

Various airlines have implemented maintenance resource management (MRM) and situational awareness (SA) training programs in their maintenance departments to help foster the safety culture. Delta Airlines has been developing a ground crew human factors training program, to reinforce the importance of human factors in ramp operations (Transport Canada, 1997), and a research group from Purdue University is currently working with another major air carrier on the problem of ground damage. In addition, Transport Canada has released the Ground Crew Dirty Dozen poster series, to parallel their Maintenance Dirty Dozen series, to make ground crew personnel aware of potential latent failures and local triggers in their environment.

Although all of these programs clearly address the possibility of failures relating to personnel related factors (e.g., using an inadequate number of spotters, or using the wrong piece of equipment), they may only tangentially address other latent failures in the system. Other interventions may still be necessary to eliminate, or reduce, these latent failures. For example, technological changes (e.g., redesigning the tug hitch, or adding mirrors to facilitate ensuring proper clearance) may be necessary to simplify tasks and reduce the possibility of errors. Further, procedural changes (e.g., improving the equipment maintenance policies) may be necessary to align the procedures with how the maintenance personnel actually work.

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