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Identification, Evaluation, and Causal Factor Determination of Maintenance Errors Common to Major U.S. Certificated Air Carriers

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A mixed methods study was conducted to identify common errors, causal factors, and corrective actions related to maintenance errors that have occurred on aircraft operated by major U.S. air carriers. An initial review of FAA compliance action letters obtained via FOIA for American Airlines, Southwest Airlines, and United Airlines identified errors and causal elements for categorization and further study. Study participants were randomly selected from FAA listings of certificated mechanics and asked to complete a survey. Quantitative data was acquired from participants who completed the survey, and qualitative data was acquired by interviewing a selection of those who completed the initial survey. The study found common errors with the completion of maintenance entries, handling of maintenance documents, the content of maintenance instructions, installation of parts, deviations from maintenance procedures, and maintenance steps or tasks that were overlooked or not performed. Dominant causal factors were identified as a failure to follow instructions or procedural requirements and maintenance instructions that contained inaccurate information or lacked sufficient detail. Dominant human factors identified in the study were complacency and lack of attention. Repetitive or simple tasks were identified as a contributor to complacency and the failure to follow instructions. Demands on mechanics to quickly return aircraft to service also contributed to the performance of maintenance without the use of instructions. Corrective actions included rectification of the initial errors, counseling of employees, and correction of instructions and documentation.

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Introduction

The operation and maintenance of large commercial passenger aircraft are prone to errors that can have devastating consequences. These consequences can include the loss of aircraft, injuries, or even fatal outcomes to aircraft occupants or those on the ground. Errors committed by flight crews operating passenger aircraft tend to receive greater attention from the public and investigators. However, flight operations are just one operational segment wherein errors can be committed. Ground operations and aircraft maintenance comprise other operating segments that are prone to errors. Aircraft maintenance is susceptible to the commission of errors due to the multitude of maintenance tasks which typically require technicians to remove and replace parts in confined spaces and who are often under time constraints to return aircraft to service (Reason & Hobbs, 2003).

Aircraft maintenance is not only costly for air carriers, but errors committed by maintenance personnel can further impact airlines through operational delays or accidents (Kanki & Hobbs, 2008). Maintenance errors committed by aircraft maintenance personnel have been determined to be responsible for 12 to 15 percent of all aircraft accidents and incidents (Rashid et al., 2014). Human factors are recognized as causal factors that lead to the commission of errors, and they have been identified as the root cause of 80 to 90 percent of all aircraft accidents (Erjavac et al., 2018; Shanmugam & Robert, 2015). A 1997 study conducted by Alan Hobbs, who interviewed aircraft technicians, noted 86 safety-related incidents, of which over half were of a type that had previously occurred (Reason & Hobbs, 2003).

Previous studies focused on specific errors that can impact maintenance. A study on maintenance errors reviewed 1,182 Aviation Safety Reporting System (ASRS) reports and found that insufficient communication comprised eight percent of all the reports received, and of that eight percent, over one half were directly related to work turnover communication issues (Parke & Kanki, 2008). The repetitive and monotonous nature of maintenance tasks drove complacency leading to the failure to use or follow technical instructions (Liang et al., 2010). Environmental factors such as poor lighting, confined spaces, and weather conditions can hide defects that would normally be found during a visual inspection by a maintenance inspector (Marais & Robichaud, 2012).

Human factors play a key role in the commission of maintenance errors, but these studies do not identify repetitive maintenance errors shared in common by commercial passenger air carriers. The identification and categorization of these errors and their causal factors would help determine what proactive efforts are required to eliminate or reduce the occurrence of such errors, which in turn would enhance the safety of aircraft operated by air carriers.

Statement of the Problem

Research conducted on aircraft maintenance errors related to United States (U.S.) registered commercial aircraft has predominantly been reactively utilizing statistical data available from the NASA Aviation Safety Reporting System (ASRS) and reports published by the National Transportation Safety Board (NTSB) (Erjavac et al., 2018; Lattanzio et al., 2008). Proactive research such as that conducted by Liang et al. (2010) explored the use of maintenance instructions using an online maintenance assistance platform providing visual instructions as a supplement to traditional printed maintenance instructions. Both reactive and proactive research provides conclusive evidence that a variety of factors affect the commission of maintenance errors, but past studies have not identified the most common maintenance errors shared by U.S. air carriers or actions that could be collectively undertaken by the air carrier industry to prevent those errors. With few exceptions related to events that prompt media and public attention, the vast majority of errors identified by the Federal Aviation Administration (FAA) during their air carrier oversight activities are not made available to the public. In addition, errors discovered internally by air carriers are not shared with the public and are considered privileged information if voluntarily shared with the FAA. The lack of information specific to maintenance errors impacting aircraft operated by U.S. air carriers drove the need to perform this study and identify the most common types of maintenance errors shared by U.S. air carriers and the causal factors for these errors.

Purpose of the Study

This study was conducted to identify and analyze maintenance errors committed by major U.S. certificated air carriers with the intent of identifying and categorizing common errors, the causal factors that led to the commission of these errors, and corrective action measures that mitigated the errors.

Research Questions

Three research questions were proposed for this study:

1. What errors are common to maintenance performed on aircraft operated by major U.S. air carriers certificated under FAR Part 121?
2. Why are these maintenance errors committed?
3. What actions have been or could be instituted to prevent the commission of maintenance errors on aircraft operated by major U.S. air carriers?

Research Methodology

This study employed a mixed-methods research approach to provide initial confirmatory research using quantitative data gathered through the use of surveys followed sequentially by the performance of interviews to gather qualitative data (Patton, 2015). Creswell and Plano Clark (2018) describe the core characteristics of mixed method research as the means to acquire both qualitative and quantitative data allowing integration of the data to achieve results using a research design that is both logical and lies within established principles and theory. According

to Patton (2015), "Qualitative data can put flesh on the bones of quantitative results, bringing the results to life through in-depth elaboration" (p.230).

Initial research was conducted by reviewing reports of compliance actions identified by the Federal Aviation Administration (FAA) during their inspections of the four largest US air carriers over the FAA's 2018 fiscal year. This information was requested in accordance with the provisions of the Freedom of Information Act (FOIA) for the four US air carriers that had the highest number of air seat miles (ASMs) for the twelve-month period ending on September 30th, 2018. The four air carriers were identified as American Airlines (247,763,901 ASMs), United Airlines (241,075,102 ASMs), Delta Air Lines (235,325,726 ASMs), and Southwest Airlines (157,317,793 ASMs). Each of the FOIA requests asked for copies of compliance action documents consisting of the compliance action letter sent to the air carriers and closure letters. The FAA Certificate Management Offices (CMOs) for American, United, and Southwest provided copies of documentation that allowed for the categorization of 11 types of errors along with six types of causal factors. Delta's FAA CMO declined to provide information claiming that all of its inspections were considered a component of Delta's voluntary disclosure program.

Analysis of the FAA's 2018 compliance action letters identified maintenance errors that fell into 11 categories. The most predominant maintenance errors are associated with maintenance record entries (93 instances), task deviations (58 instances), tasks not performed (44 instances), and errors noted with the content of maintenance instructions (28 instances). The remaining seven categories of errors are categorized as training or qualification issues (22 instances), missing documentation or tags (16 instances), tool calibration issues (14 instances), parts and material storage (11 instances), management control (10 instances), procedure not FAA approved (5 instances), and missing parts or equipment (3 instances).

Analysis of the FAA's compliance action closure letters noted causal factors that fell into six causal factor classifications. They are categorized as failure to follow instructions (92 instances), failure to make correct maintenance entries (89 instances), inaccurate or incorrect maintenance instructions (29 instances), inadequate administrative programs (20 instances), lack of training (14 instances), and ineffective maintenance process controls (10 instances). The FAA compliance action closure letters seldom mentioned human factors as causal factors. Of the few letters that referenced human factors, eight errors were attributed to lack of awareness by one or more employees, seven were attributed to complacency, three were attributed to lack of attention, and one was attributed to distraction.

The quantitative portion of this study was conducted using a survey containing a structured set of questions with a set of ordinal frequency-based responses. The survey was designed in four parts. The first contained 11 questions focused on the type of errors previously identified during the review of the FAA's compliance actions. The second section contained six questions focused on the causal factors identified during the analysis of the air carrier responses noted in the FAA compliance action closure letters. The third section contained four questions focused on the human factors noted in the closure letters as contributors. All the survey questions for the first three sections were based on the categories previously identified from the review of the FAA's compliance action letters. Designing the survey in this manner provides the ability to compare the results directly with the FAA data. The fourth section contained

demographic questions to help identify respondents who were involved in maintaining air carrier passenger aircraft. Additional open-text questions were added to each of the first three sections to prompt participants for comments regarding errors, causal factors, and human factors.

The qualitative portion of the mixed methods study was based on a grounded theory design using interviews to gain deeper insight into the commission of errors, the causal factors, and corrective actions. The same set of open-ended questions was employed in a semi-structured format supplemented with additional unstructured questions to elicit personal stories to add validity and depth to the survey results.

Study Participants

Participants selected for this study were FAA-certificated mechanics involved with the performance of maintenance on passenger aircraft owned or operated by a U.S. air carrier and having more than 70 seats. The initial population consisted of certificated mechanics listed in the FAA's database that was downloaded from their website in January 2021. The FAA's database contained over 270,000 individuals who held airframe and/or powerplant mechanic certificates. The listing was sorted to identify individuals by United States Postal Service (USPS) zip code that reside within 15 miles of the major airport maintenance hubs belonging to American Airlines, United Airlines, Delta Air Lines, and Southwest Airlines. These locations were identified as Tulsa, Oklahoma; Chicago, Illinois; Dallas, Texas; Ft. Worth, Texas; Atlanta, Georgia; and Houston, Texas.

The resultant listing of 12,064 individuals was subsequently sorted using a table of random digits generated by using a Microsoft Excel software command. From this randomly sorted list, the first 1000 individuals were selected to receive a request to participate in the study. The method used to identify the sample population for the first phase of this study is multistage cluster sampling. This method allows the selection of the sample to be conducted in several stages if the subject population is large and cannot be easily defined (Creswell & Guetterman, 2019). Of the 1000 survey requests that had been sent, 71 survey responses were received, of which 48 responses were completed by individuals that perform maintenance on airline-operated aircraft having more than 70 seats.

The second phase involved the selection of individuals from those who completed the survey and who indicated their willingness to be interviewed. Interview participants were randomly selected from survey respondents who indicated that they were involved with the performance of maintenance on aircraft operated by major U.S. airlines and had a minimum of two years of experience. Ten participants were randomly selected from those who had indicated their willingness to be interviewed and were mailed consent forms for review and signature. Nine of these individuals returned the consent forms and were subsequently interviewed by one of the researchers.

Validation Process

The reliability of the survey used for the initial quantitative phase of this mixed-method research study was measured to ensure that participant scores were consistent and meaningful

with respect to the elements under study. The validity with respect to quantitative research is best described as how well an instrument measures what it is supposed to measure (Creswell & Guetterman, 2019). The questions in the survey were written so that they were clear to the participants. Pre-testing of the survey was accomplished by test subjects who were certificated mechanics with experience working for a major U.S. air carrier. They were asked to take the survey and provide their comments and recommendations. Their comments and recommendations were then used to further edit and improve the survey. These test participants were subsequently excluded from the sample of participants selected for the survey.

Once surveys were received from eligible participants, the internal consistency of the survey was subsequently measured using Cronbach's alpha. This test is applied to the survey results by comparing how the results for each survey question relate to each other and to the results of the entire survey. To support the internal consistency of a test or survey, the questions should be interrelated with each other and unidirectional. Cronbach's alpha values that range from 0.70 to 0.95 are considered acceptable values to indicate internal consistency, although values in excess of .90 may suggest that several of the questions on the survey measure identical items (Tavakol & Dennick, 2011). A low alpha value is undesirable as this indicates that the survey questions are not interrelated or that the survey lacks enough questions.

The survey contained 27 questions, of which 21 were designed as Likert-style questions using the same series of ordinal frequency-based responses. Cronbach's alpha was calculated on the entirety of the 21 questions and repeated using the data from the first 11 questions that focused on the frequency of specific error types and on the combination of 10 questions that focused on the causal and human factors and maintenance errors. The results of the measurements found that Cronbach's alpha for the 21 questions was .915, which indicates a high level of internal consistency. The measurement was repeated but limited to the 11 questions related to maintenance errors, and this resulted in a Cronbach's alpha of .869 which also demonstrates a high level of internal consistency. The remaining ten questions related to causal and human factors were also analyzed and were found to have a Cronbach's alpha of .839. Cronbach's alpha was also calculated to determine how internal consistency would change upon the removal of each question from the groupings that were measured. The removal of an individual question from each grouping resulted in a change to Cronbach's alpha of plus or minus .01 which does not impact the overall reliability of the survey.

Findings

Survey Results

The results from the first section of the survey were tabulated and displayed in Table 1. Descriptive statistics were used for analysis due to the limited number of survey responses received, which precluded analysis by variance. The descriptive statistics were calculated based on the number of responses received for each question and adjusted for instances where survey participants chose not to respond. The first six questions were found to have a higher mode of three, whereas the last five questions had a mode of two. A closer review of the frequencies attributed to the responses for these six questions found that over 50 percent of participants indicated they selected *Sometimes* for having seen errors concerning the handling of maintenance documents, records, tags, forms, or placards; errors with the installation of parts or equipment; and errors regarding the completion of maintenance entries. It was noted that in addition to the three errors that had mid-point frequency distributions of over 50 percent, a fourth error related to the content of maintenance instructions was observed to have high-frequency distributions at the far right of the frequency scale. This error was seen *Regularly* by 25.0 percent of the participants and *Often* by 8.3 percent.

Table 1
Frequency of Maintenance Errors

Variable	n	Mode	Never	Rarely	Sometimes	Regularly	Often
			n %	n %	n %	n %	n %
Have seen errors with respect to the storage of parts and materials	48	3	4.2%	27.1%	47.9%	12.5%	8.3%
Have seen errors with the content of maintenance instructions	48	3	0.0%	20.8%	45.8%	25.0%	8.3%
Have seen errors with the scheduling and/or control of the maintenance process	48	3	2.1%	33.3%	39.6%	18.8%	6.3%
Have seen errors with the handling of maintenance documents, records, tags, forms, or placards	48	3	0.0%	16.7%	50.0%	22.9%	10.4%
Have seen errors with the installation of parts or equipment	48	3	2.1%	39.6%	52.1%	4.2%	2.1%
Have seen errors with the completion of maintenance entries	47	3	0.0%	12.8%	51.1%	27.7%	8.5%
Have seen errors regarding maintenance steps or tasks performed using procedures that are not accepted or approved by the FAA	47	2	21.3%	46.8%	27.7%	4.3%	0.0%

Have seen errors regarding maintenance steps or tasks performed that deviate from written instructions or procedures	47	2	8.5%	42.6%	42.6%	6.4%	0.0%
Have seen errors regarding maintenance steps or tasks that were overlooked or not performed	47	2	12.8%	44.7%	31.9%	10.6%	0.0%
Have seen errors with the handling, usage, or control of calibrated tools and equipment	48	2	18.8%	52.1%	22.9%	6.3%	0.0%
Have seen errors with training requirements, recurrent training, or maintaining of qualifications for those assigned to perform maintenance	48	2	12.5%	43.8%	29.2%	10.4%	4.2%

The data gathered by the survey is considered ordinal non-parametric data, and as such, the precise interval between each of the responses is undefined. However, by calculating the total percentage of survey participants that answered each question with a selection of either *Sometimes*, *Regularly* or *Often*, the top three errors observed by the majority of participants become more apparent and were identified in order of percentages as follows:

- Errors observed with the completion of maintenance entries – *87.3 percent*
- Errors observed with the handling of maintenance documents, records, tags, forms, or placards – *83.3 percent*
- Errors observed with the content of maintenance instructions – *79.1 percent*

The results from the second section concerning causal factors were tabulated and are displayed in Table 2. Four of the six questions were found to have a mode of three, whereas the other two questions had a mode of two. However, an examination of the response frequencies for the two questions that had a mode of two found that one question received high-frequency responses of *Regularly* and *Often* when compared to similar response frequencies for the four that had a mode of three.

Table 2
Frequency of Maintenance Error Causal Factors

Variable	n	Mode	Never	Rarely	Sometimes	Regularly	Often
			n %	n %	n %	n %	n %
Policies and procedures that are inadequate, lack sufficient detail, or do not contain current information cause maintenance errors	48	3	8.3%	37.5%	41.7%	10.4%	2.1%
Failure to follow instructions or procedural requirements causes maintenance errors	48	3	4.2%	39.6%	43.8%	10.4%	2.1%
Ineffective controls over the maintenance process or the lack of a measurement process cause maintenance errors	47	2	10.6%	55.3%	25.5%	6.4%	2.1%
Maintenance and process instructions that contain inaccurate information or lack sufficient detail cause maintenance errors	48	3	12.5%	35.4%	39.6%	2.1%	10.4%
Maintenance personnel lacking sufficient training or knowledge cause maintenance errors	48	2	8.3%	37.5%	31.3%	10.4%	12.5%
Failure to make maintenance entries or omitting relevant information in logbooks, maintenance records, or other record-keeping documents causes maintenance errors	48	3	16.7%	33.3%	37.5%	8.3%	4.2%

Prioritization using the mode alone was insufficient to identify the primary cause of maintenance errors. Selecting the causal factor having the highest percentage calculated for the mid-point frequency selection of *Sometimes* would not take into consideration the high response percentages allocated to the greater frequency responses for *Regularly* and *Often*. Therefore, the six causal factors were ranked in order from high to low by totaling the frequency percentages allocated to the selections of *Sometimes*, *Regularly*, and *Often* by the participants in the survey.

- Failure to follow instructions or procedural requirements – *56.3 percent*
- Policies and procedures that are inadequate, lack sufficient detail, or do not contain current information – *54.2 percent*
- Maintenance personnel lacking sufficient training or knowledge – *54.2 percent*
- Maintenance and process instructions that contain inaccurate information or lack sufficient detail – *52.1 percent*
- Failure to make maintenance entries or omitting relevant information in logbooks, maintenance records, or other record-keeping documents – *50.0 percent*

- Ineffective controls over the maintenance process or the lack of a measurement process – *34.0 percent*

With the exception of the causal factor regarding ineffective controls over the maintenance process or the lack of a measurement process, the survey results found the remainder of the causal factors equally responsible for maintenance errors.

The results from the third section concerning the contribution of human factors as causal factors were tabulated and are displayed in Table 3. The descriptive statistics noted that all four listed human errors resulted in responses with a mode of three. There were variations in the frequency response rate percentages, particularly for the three higher response rates of *Sometimes, Regularly,* and *Often.*

Table 3
Frequency of Human Errors that Induce Maintenance Errors

Variable	n	Mode	Never	Rarely	Sometimes	Regularly	Often
			n %	n %	n %	n %	n %
Lack of awareness causes maintenance errors	48	3	2.1%	37.5%	52.1%	4.2%	4.2%
Complacency cause maintenance errors	48	3	2.1%	20.8%	45.8%	22.9%	8.3%
Distractions cause maintenance errors	47	3	0.0%	25.5%	59.6%	14.9%	0.0%
Lack of attention cause maintenance errors	47	3	0.0%	27.7%	57.4%	12.8%	2.1%

To provide some degree of prioritization between the four human factors addressed in the survey, they were ranked in order from high to low in accordance with the total of the response rate percentages allocated to participant selections of *Sometimes, Regularly,* and *Often.*

- Complacency cause maintenance errors – *77.0 percent*
- Lack of attention causes maintenance errors – *72.3 percent*
- Distractions cause maintenance errors – *64.5 percent*
- Lack of awareness causes maintenance errors – *60.5 percent*

Comparing the total percentage of participants who observed these human factors at higher frequencies of *Sometimes* or greater illustrates that complacency and lack of attention were identified by the survey participants as the two key factors that caused or contributed to maintenance errors. However, the remaining two human factors must be considered equally important given that over 50 percent of the respondents indicated that they also contribute to errors at frequencies of *Sometimes* or higher.

The survey questions in the third section of the survey were limited to human factors that had been identified from the review conducted by the FAA compliance action closure letters.

Although prior studies have identified additional human factors that affect aviation maintenance, this survey was constructed to query only those that were identified in the FAA closure letters. The survey included an open question that asked participants in the survey to identify additional human factors that they believe cause or contribute to maintenance errors. One participant cited physical and environmental factors such as fatigue, heat, and working too many hours as the cause of not following written instructions. Other participants identified the lack of morale, increased stress, or pressure to accomplish tasks as human factor-related contributors to errors.

Interview Results

The second phase of the study gathered qualitative data through interviews of survey participants selected from those participants that completed the survey. The interviews were performed using a semi-structured interview process where participants were asked a specific set of questions supplemented by additional non-structured questions to allow further exploration of responses provided to the structured questions (Merriam & Tisdell, 2016). Nine participants were interviewed for this study and provided information concerning maintenance errors and causal factors.

Maintenance Errors

Of the maintenance errors identified by the participants, eight were related to the installation of parts, and four were related to the storage and handling of parts. Other errors discussed included three instances where maintenance steps or tasks were performed that deviate from written instructions or procedures, three instances where maintenance steps or tasks were not preformed or overlooked, three errors regarding the content of maintenance instructions, two errors concerning the scheduling and/or control of the maintenance process, one error with the completion of maintenance entries, and two maintenance related errors that fell outside of the categories listed in the original survey.

Examples of errors related to the installation of parts included an instance where flight augmentation computers were not properly secured in the aircraft electronics compartment and had slid out of their mounting racks during flight. Another participant described an installation error involving a brake anti-skid module that had been installed on the aircraft with its two high-pressure hydraulic lines reversed. Installation of incorrect parts was reported with a hydraulic actuator that failed a pressure test due to an o-ring that had been installed incorrectly and another instance where an incorrect elevator/aileron control computer was installed on an aircraft that had already been modified for operation with a different version of the computer.

Incorrect storage of parts and materials was noted, with descriptions of serviceable and unserviceable parts comingled together in the same storage bins. Incorrect storage of hoses, lines, and other parts with openings that were not covered with protective caps or covers was also described. Errors related to the deviation from instructions or procedures included elevator free-play checks that were performed to airline instructions that deviated from those published by the manufacturer. Procedures were also not followed with two aircraft spoilers that had been placed into a maintenance configuration instead of an operational configuration as required by the maintenance instructions.

Examples of errors related to steps or tasks not preformed or overlooked included wing to body fairing fasteners that were not torqued upon installation as required by the aircraft maintenance instructions. Another example was described as a failure to release the main landing gear oleo strut pressure in accordance with instructions prior to removal and partial disassembly of the landing gear. Circuit breakers that had been pulled in addition to others specified by the maintenance instructions but were not reset following maintenance were also noted.

Errors with the content of maintenance instructions were identified by some of the participants. One participant described an issue with a lavatory door hinge pin that was discovered to have protruded through the top of the fuselage but had been overlooked due to maintenance instructions that limited visual inspection of the downward migration of the pin through the lower lavatory door hinge. Other examples included work cards that had editing errors when they were re-written into a different format recently adopted by the airline.

Examples of errors with the scheduling and control of maintenance included a scheduling issue with an aircraft that required repetitive inspections but had over-flown the dates or flight hours due to scheduling errors. A similar error was noted with the operation of an aircraft that was scheduled and flown on an Extended Twin-Engine Operations Performance Standards (ETOPS) over-water flight, even though it was not qualified for such operations. This error was compounded by another type of error involving the completion of maintenance entries where maintenance personnel had signed for the accomplishment of an ETOPS inspection in the logbook, even though the aircraft was clearly not an on-ETOPS aircraft.

Causal Factors

Causal factors were identified during the interviews with some of the participants noting errors that were caused by multiple factors. There were 11 reported instances where errors were attributed to maintenance and process instructions that contained inaccurate information or lacked sufficient detail. Nine instances were reported where the failure to follow instructions or procedural requirements caused the errors to occur. Five instances were identified where the lack of training or knowledge contributed to the maintenance errors. One instance was described where the lack of controls over the maintenance process was responsible for an error. No instances were reported for causal factors related to the omission or failure to make maintenance entries or causal factors related to the inadequacies of policies and procedures.

Human Factors

Human factors were identified as contributors to many of the errors discussed by the participants. The three most common human factors were identified as complacency, lack of attention, and lack of awareness. Distractions were not mentioned by the participants as factors related to the maintenance errors, although other factors, such as stress imposed by time constraints and management demands, were cited as reasons some technicians may resort to taking shortcuts while performing maintenance.

Complacency was identified as the most significant contributor to the commission of errors described by the interviewed participants. Several cited the repetitive nature and simplicity of various maintenance tasks that drive mechanics to accomplish maintenance without using maintenance instructions or proper tooling. Complacency is also driven by the content of the maintenance instructions and the complexity of part catalogs. One participant noted that the proliferation of modification programs on some aircraft had affected the installation eligibility of parts for those modified aircraft. Mechanics that look for replacement parts in the parts catalog are confronted with multiple notes that limit the installation of certain part numbers to different aircraft based on modification status. For an airline with a fleet of aircraft that includes one type of aircraft but at different modification levels, it can be difficult to determine the correct replacement part for each aircraft. A participant commented that mechanics are not "See Note A, See Note B, See Note C type people." They can get "worn out from that, and they say, 'yeah, yeah, yeah, It's the right one. It's the right one.' and they'll install that [incorrect] part, and that was happening a lot."

Lack of attention was also cited as a major contributor to some of the errors. The error that resulted in the bursting of the vacuum bag surrounding a flight control in an autoclave was attributed to lack of attention by one of the participants who believed: "I think its lack of attention that you just didn't pay enough attention to the stress points, the critical, I say critical points where the bag will fail if you don't get it protected properly." Lack of attention during the training process was cited as a contributor to the failure to release pressure from the main landing gear strut before it was disassembled and removed from the aircraft. In this instance, the maintenance card was described as having more than 200 pages and included a specific step to deplete the pressure. The participant stated, "The only thing I can think of is that either the person wasn't properly trained, or when they were being trained, they didn't pay attention carefully as to exactly what to do, or they did not read the aircraft maintenance manual very carefully."

A mechanic's lack of attention, together with complacency, can lead to the commission of significant errors. This was likely the combination that existed with an error regarding a non-ETOPS aircraft that was inspected and released for an over-water ETOPS flight. One participant noted that the process to release the aircraft required the completion of a pre-departure check where maintenance personnel must walk around the aircraft and perform inspections prior to releasing the aircraft for the over-water flight. The aircraft was inspected and found compliant despite the absence of emergency aircraft equipment, including life rafts and a hydraulic-driven generator.

Lack of awareness was identified as the third most common factor that contributes to the commission of errors. A participant noted that some mechanics become dependent on work cards and air carriers developed maintenance instructions for the work scope. As a result, they become unaware that they should be reviewing the aircraft maintenance manual (AMM) to retrieve additional information that supplements the work cards issued for the task. This was explained as a possible contributor to an error that was committed when a landing gear wheel and brake assembly were removed and caused impact damage to the axle. The cause of the damage was the failure to use the proper tool to protect the axle, but an additional error was made during the inspection of the axle after it was damaged. Rather than looking at the AMM

for damage tolerance and repair instructions, the mechanics relied on the use of an inspection work card originally written for heat damage to the axle, not impact damage. The mechanics' reliance on the applicability of the work card was due in part to its title, which simply referred to axle damage. Lack of awareness regarding the need to review other manuals for specific instructions and perhaps lack of awareness on the part of the work card author, who used a generic title on a work card specific for one type of axle damage, were contributors to the error.

Several interview participants commented that there were additional human-related factors that contributed to some of the errors they had described. These factors include stress-related situations encountered by mechanics, physical issues, and working conditions affecting the mechanics while they were performing repairs. The stress placed upon the mechanic to quickly return the aircraft to service was one such factor shared by several participants. This was previously mentioned with errors that were associated with complacency, but in some instances, stress can be the root cause of errors.

Corrective Actions

Qualitative data gathered from the interview participants included corrective actions which had been taken by their respective air carriers to mitigate the errors and prevent them from re-occurring. The participants noted that air carriers took immediate action to correct the actual errors. Mechanics were counseled, maintenance instructions and work cards were revised, and newsletter articles and bulletins were issued. Participants were asked to provide information regarding what corrective actions they believe should have been taken to address the errors. Technological improvements were identified by several participants as a partial solution that will provide mechanics with easier access to maintenance instructions. Ease of access may drive a greater number of mechanics to review the manuals before performing maintenance tasks. It was also suggested that air carriers allow for collaboration between mechanics and the writers of work instructions to improve accuracy and eliminate errors.

Assumptions and Limitations

The study made the assumption that participants selected for completion of the survey and those selected for interviews provided a true account of their experiences relevant to the scope of this study. It was also assumed that insight gained from the experiences shared by the participants is representative of what other members of the population that maintain aircraft for major U.S. air carriers experience.

Limitations affecting this study include the narrow focus and analysis of data specific to maintenance on U.S. certificated air carriers that provide scheduled passenger services under Part 121 of the Federal Aviation Regulations and who operate aircraft with more than 70 seats. The selection of study participants was limited to those residing within 15 miles of key airports used as maintenance hubs by American Airlines, United Airlines, Delta Air Lines, and Southwest Airlines. These hub cities were identified as Tulsa, Oklahoma; Chicago, Illinois; Dallas, Texas; Ft. Worth, Texas; Atlanta, Georgia; and Houston, Texas. The scope of the study excluded non-maintenance operations, including but not limited to flight operations, ground operations, fueling, deicing, and cargo activities. Initial research of reported maintenance errors was limited

to Federal Aviation Administration (FAA) air carrier inspection reports for the FAA's 2018 fiscal year from October 1st, 2017, through September 31st, 2018. These reports were obtained via FOIA from the FAA Certificate Management Offices for American Airlines, United Airlines, and Southwest Airlines. Although requested, no reports for Delta Air Lines were provided.

General limitations affecting this study include the small size of survey participants that responded to the survey requests. Those that did respond to the survey and who were interviewed may have induced limitations based on the relevancy of their experience with the subject matter, cultural differences, and varying backgrounds.

Conclusions

What errors are common to maintenance performed on aircraft operated by major U.S. air carriers certificated under FAR Part 121? The results of this study did not identify one category of error over another as the most common. However, certain error categories were reported by survey participants to have a higher frequency of occurrence than others. Survey data noted that frequent errors were observed with the completion of maintenance entries, the handling of maintenance documentation, and the content of maintenance instructions. Interviews with participants provided descriptions of errors related to the installation of parts, storage of parts, deviation from instructions, maintenance steps not performed, the content of maintenance instructions, scheduling errors, and errors related to the completion of maintenance entries.

Both the survey and interview data found commonality with three types of errors: completion of maintenance entries, deviation from instructions or procedures, and steps or tasks not performed or overlooked. This compares favorably with common errors identified from the examination of FAA compliance action letters that noted 86 errors related to maintenance entries, 37 errors involving deviation from maintenance instructions, and 31 errors related to tasks that were not performed. The high number of errors related to incorrect maintenance entries noted by the FAA agrees with the higher frequency of similar errors reported by the survey participants. Similarly, the high number of errors noted by the FAA regarding deviations from maintenance instructions, along with errors related to tasks not performed, agree with the higher incidence of errors reported by the interview participants. In contrast, the category related to errors observed with the handling of maintenance documents, records tags, forms, or placards was not mentioned as a common problem by the interview participants. Although such errors were frequently noted in the FAA data and survey results, this type of error may not be viewed as significant by the interview participants.

Why are these maintenance errors committed? The survey data noted that five of the six causal factors were highly considered responsible for maintenance errors, written comments included in the survey, together with the results from the interviews, identified two causal factors which were predominant. These were failure to follow instructions or procedural requirements and maintenance and process instructions that contained inaccurate information or lacked sufficient detail. The results from the survey correlate with the qualitative data obtained from the participants who were interviewed. A comparison of these causal factors with those identified during the initial research that examined FAA compliance action documents found that there is also a correlation. The FAA compliance action closure letters found that failure to follow

instructions and instructions that contained inaccurate or incomplete information were primary causal factors. However, the FAA data also identified the failure to make maintenance entries or omission of entries as a significant causal factor. The survey results and interview data do not suggest that this is a predominant causal factor. It is possible that the FAA may identify this more frequently during their inspections of air carrier maintenance records than the participants, who may spend the majority of their time physically working on aircraft.

The identification of common causal factors also included an analysis of human factors that cause maintenance errors. Four human factors were included in the survey, and the responses verified that all four were causal factors for maintenance errors. However, two of the human factors were observed by the survey participants at a higher frequency. These were identified as complacency and lack of attention. Qualitative data from both the survey comments and the interviews found that these two human factors were also of great significance. Of the two, complacency was established as the leading human factor that contributed to the commission of errors. This agrees with another study conducted by an airline over a two-year period that identified complacency as the cause of maintenance errors (Liang et al., 2010).

A causal factor that was not anticipated by this study was the impact of stress on complacency. As explained by several participants, the demand to return aircraft to service quickly, either implied or directed by supervision, can drive mechanics to take shortcuts and avoid using maintenance manuals. This happens frequently with simple or repetitive tasks that are familiar to mechanics who believe that they can complete the tasks without the need to retrieve the manuals instructions. Coupled with the perception that anyone looking up maintenance instructions may be doing so to slow the repair process, mechanics may purposely avoid using the maintenance manuals. Of the causal factors identified by this study, failure to follow instructions or procedural requirements due to complacency and the need to return the aircraft to service is of the deepest concern.

What actions have been or could be instituted to prevent the commission of maintenance errors on aircraft operated by major U.S. air carriers? Participants who were interviewed were asked to identify successful and unsuccessful corrective action measures that had been taken to mitigate errors. Most noted that corrective actions taken by the air carriers were limited to mitigation of the specific errors that had been identified. These included counseling mechanics who made the errors, correcting the errors by replacing components or repairing damage, issuing training bulletins, and in some instances, revising maintenance instructions to either clarify existing instructions or add wording to qualify any deviations that may have been taken. With few exceptions, most corrective actions taken by the air carriers were localized to that error and not universal in coverage.

Study Beneficiaries

Air carriers and maintenance providers are principal beneficiaries of this study as it provides information that helps identify the most common types of maintenance errors and causal factors that are shared by U.S. air carriers. The information from the study adds to existing research and may help future studies that look at errors and causal factors by category and which impact air carriers at higher frequencies.

Recommendations for Further Research

One of the key findings of this study identified errors where mechanics failed to follow instructions or procedural requirements. Participants noted that this could happen if the tasks are considered simple or repetitive. This study did not delve into the simplicity of these tasks or if the performance of those tasks would be considered acceptable without the need for specific maintenance instructions. While it is recognized that certificated aircraft mechanics received extensive training, at what level should maintenance instructions cover certain tasks or steps that could be considered generic, thus negating the need for describing simple actions?

This study also highlighted issues where maintenance instructions contained inaccurate information or lacked detail. Participants commented that such errors frequently appear on work cards published by the air carriers and attributed the causal factors to the lack of knowledge and experience of the work card authors. Corrective action suggestions included the pairing of mechanics with engineers and other work card authors to validate the instructions prior to publication. While this suggestion has merit, further study is recommended to determine if this would reduce or eliminate many of the errors currently associated with the accuracy of maintenance instructions.

Responses to the initial 1000 survey requests produced just 71 responses, of which only 48 could be used for this study, thus limiting the application of statistical analysis. One anomaly that limited the distribution of the survey requests was attributed to FAA-managed data. Of the 1000 survey requests that were sent to selected mechanics who appeared in the FAA's database, 128 survey request letters were returned as undeliverable. This represents an error of 12.8 percent which was not expected. Further research is recommended to identify the extent of erroneous information contained in the FAA's database, the causal factors that drove these errors, and identify what actions can be taken to ensure that the database reflects the current mailing addresses for FAA certificate holders.

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