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Causes and Trends in Maintenance-Related Accidents in FAA-Certified Single Engine Piston Aircraft

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Abstract

The accident rate for general aviation remains high. While most general aviation accident studies have been pilot-focused, there is little research on the involvement of aircraft maintenance errors. We undertook a study to answer this question.

The Microsoft Access database was queried for accidents occurring between 1989 and 2013 involving single engine piston airplanes operating under 14CFR Part 91. Pearson Chi-Square, Fisher's Exact Test, and Poisson probability were used in statistical analyses.

The rate of maintenance-related general aviation accidents was 4.3 per million flight hours for the 1989–1993 period and remained unchanged for the most recent period (2009–2013). Maintenance errors were no more likely to cause a fatal accident than accidents unrelated to a maintenance deficiency. Inadequate/improper maintenance (e.g., undertorquing/non-safetied nuts) represented the largest category causal for, or a factor in, accidents. Maintenance errors involving the powerplant caused, or contributed to, most accidents, but did not carry a disproportionate fraction of fatal accidents. Noncertified airframe and powerplant (A&P) aircraft maintenance technicians (AMTs) performed maintenance on 13 out of 280 aircraft involved in maintenance-related accidents. While there is current concern as to the safety of the aging general aviation fleet, the fraction of fatal accidents for aircraft manufactured prior to 1950 was not higher than those manufactured more recently.

We conclude that the general aviation accident rate related to maintenance deficiency, while low, is static. Increased emphasis should be placed on tasks involving torquing and improper rigging as well as maintenance related to installation/assembly/reassembly. Whether a maintenance error decision aid plan, shown to reduce maintenance errors at airline facilities, would benefit general aviation deserves consideration.

Keywords: general aviation accidents, aircraft maintenance, aging general aviation fleet

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Author Note

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Introduction

General aviation, governed by 14CFR Part 91 regulations, includes all civilian aviation with the exclusion of operations involving paid passenger transport—the latter covered under the comparable 14CFR Part 121 and 135 rules. Although accidents for the airlines (14CFR Part 121) have dramatically declined over recent decades (Aviation Safety Institute, 2012; Li & Baker, 2007), such a decrease is not as evident for general aviation, although preliminary data (NTSB, 2014b) indicate a decline for the most recent year (2013). Still, general aviation accounts for the overwhelming majority (94%) of civil aviation fatalities in the United States (Li & Baker, 2007), and represents an unresolved safety challenge for aviation. Furthermore, general aviation accidents carry an associated annual cost of $1.6 to $4.6 billion to individuals and institutions affected (e.g., family and nonfamily incurring injury and/or loss of life, insurance companies, accident investigation costs) when taking into account hospital costs, loss of pay with a fatal accident, and loss of the aircraft (Sobieralski, 2013). In all likelihood, these costs would be even higher if litigation costs were assessed as well.

Most studies on general aviation accidents to date (Bazargan & Guzhva, 2011; Bennett & Schwirzke, 1992; Groff & Price, 2006; Li & Baker, 1999; Li, Baker, Grabowski, & Rebok, 2001; Rostykus, Cummings, & Mueller, 1998; Shao, Guindani, & Boyd, 2014) have focused on the pilot either in terms of pilot error, or corresponding risk factors such as pilot flight experience, certification, demographics, and flight conditions. This is not surprising since the airman has been faulted in 55–85% of general aviation accidents (Li et al., 2001; Shkrum, Hurlbut, & Young, 1996). Therefore, the remaining general aviation accidents likely have pilot-independent causes, and it is hypothesized that maintenance errors represent such a subset. No peer-reviewed studies on the involvement of aircraft maintenance errors in general aviation accidents were discovered in a search of the literature. However, an FAA publication (Goldman, Fiedler, & King, 2002), published well over a decade ago, reported that 7.1% of general aviation accidents were maintenance-related. Of these, 13–27% were fatal across the period spanning 1988–1997. That study, however, aggregated all aircraft categories, such as balloons, ultralights, rotorcraft, gliders, and airplanes. In a separate FAA study, Boquet and colleagues (2004), using the Human Factors Analysis and Classification System (HFACS) approach (Shappell & Wiegmann, 2001), reported that skill-based errors accounted for 40% of maintenance-related accidents. While informative, the HFACS approach, which is most appropriate for facilities that have a supervisory component and an organizational structure, is less ideal for general aviation where these components are lacking. The biennial Joseph T. Nall Report (Aviation Safety Institute, 2012) (hereafter referred to as the Nall Report), a comprehensive study on general aviation accidents, reported that maintenance-related crashes represented 15% of all accidents for 2010. However, the Nall Report not only aggregates mechanical failures and maintenance errors, but also does not differentiate piston from turbine aircraft.

In view of the paucity of research on maintenance-related general aviation accidents in piston aircraft, and given that pilot error in one report (Shkrum et al., 1996) only accounts for 55% of general aviation accidents, the present study was undertaken to determine the involvement of maintenance errors in single engine piston accidents. For the period spanning the last 25 years, the study sought to: (1) determine the rates of general aviation accidents caused, or contributed to, by maintenance deficiency, (2) categorize accident-related maintenance errors to determine the most frequent and whether such errors are associated with a higher fatal accident rate, (3) determine the extent to which noncertified personnel were engaged in maintenance, and (4) determine the fatal accident rate for aging aircraft (manufactured prior to 1950) for which special maintenance-related tasks have been recommended.

Methods

Query Strategy

All accident data were derived from the publicly available NTSB (2014a) aviation accident Microsoft® Access database. Aircraft manufacture year data was acquired from the FAA (2014) aircraft registry database and imported into the NTSB database by cross-referencing the aircraft registration number.

The database was queried for accidents occurring between 1989 and 2013 involving single engine piston aircraft (airplanes) operating under 14CFR Part 91 regulations and weighing less than 12,501 lbs. The present analysis was restricted to maintenance-related accidents in single engine aircraft to remove the confounding effect of a higher fatality rate associated with multiengine aircraft (Aviation Safety Institute, 2012; Boyd, 2015). The researchers did not query beyond 2013 since the typical NTSB accident investigation takes 13 months to complete (Fielding, Lo, & Yang, 2011). Accidents involving experimental amateur-built aircraft and instructional flights were also excluded. To restrict the query to maintenance-related accidents, a Boolean search of the "narrative cause field" was performed using the following terms: *maintenance* OR *servicing* OR *installation* OR *rigging* OR *modification* OR *service bulletin* OR *repair* OR *airworthiness directive* OR *overhaul*. To identify accidents unrelated to maintenance deficiency, the aforementioned search terms were prefixed with "not." The data were exported to Microsoft® Excel and checked for duplicates. The narrative cause of all records was manually parsed for accidents unrelated to maintenance (e.g., maintenance of taxiway) and the corresponding records deleted. Maintenance personnel qualifications were identified from the probable cause or the factual report of the NTSB (2014a) record.

Note that although the NTSB database is coded by subject (e.g., 24100–24124 corresponding to maintenance) and personnel (airframe and powerplant aircraft maintenance-related technician (A&P/AMT) codes-4107, 4108), the researchers elected not to query via such codes for two reasons. First, a preliminary query of the database excluding the corresponding maintenance codes still returned many accidents that nevertheless were maintenance-related. Conversely, a parallel query, but now including the aforementioned maintenance codes, returned some records unrelated to maintenance deficiency. Second, the former codes were changed in 2009.

Flight activity across the general aviation piston fleet for the period spanning 1990–2013 used the FAA General Aviation and Part 135 Activity Surveys (FAA, 2013). The comparable data for 1989 was kindly provided by Brad Wacker at the FAA.

Maintenance category taxonomy

The researchers found the current NTSB taxonomy for maintenance categories to be ambiguous and/or uninformative, such as annual inspection and maintenance. Accordingly, a taxonomy was developed, drawing in part from the recommended one for the maintenance and error decision aid (MEDA) process (Rankin, Hibit, Allen, & Sargent, 2000) utilized at 14CFR Part 121 repair stations and the NTSB system. While the categories are, for the most part, self-explanatory, the "inadequate/improper maintenance" category includes those accidents in which the NTSB narrative cause or full report either referred to: (a) inadequate and/or improper maintenance in the absence of any further information, or (b) the following deficiencies: improper rigging, incorrect wiring, servicing hydraulic system, undertorquing, non-safetied nuts, and improperly serviced brakes.

Statistics

Contingency tables employed Pearson Chi-Square, with the exception of tables where the expected count was less than five, whereby Fisher's Exact Test was used (Field, 2009) to determine if there was an overall difference in proportions. The p values for cells in multinomial tables were derived from adjusted standardized residuals (Z-scores) in post hoc testing. A p value of <0.05 was considered significant. IBM® SPSS® (v 22) software was used for the statistical analyses. To determine whether the rate of accidents related to maintenance deficiency changed relative to the initial period (1989–1993), the cumulative Poisson probability was performed using online statistical software from Stat Trek (n.d.).

Results

The rate of accidents involving a maintenance deficiency has not decreased over the past 25 years

No peer-reviewed publications were identified that address trends in maintenance-related general aviation accidents. Herein, the rate of general aviation accidents (for single engine piston aircraft) involving a maintenance deficiency was determined to be 4.3 per million flight hours for the period spanning 1989–1993 (see Figure 1), and considerably lower than the corresponding rate for accidents unrelated to a maintenance error (82 per million flight hours). Longitudinal analysis indicated little change in the maintenance-related accident rate over time with 3.7 accidents per million flight hours for the most recent period (2009–2013). A Poisson rate analysis comparing the first and last time periods indicated no statistical difference ($p=0.628$) in the maintenance-related accident rates.

Maintenance deficiency-related accidents are not at a greater risk for a fatality

The researchers then sought to determine whether general aviation accidents involving maintenance errors were more likely to be fatal than those in which maintenance deficiency was not causal, or contributory, to the accident. Of 361 maintenance-related accidents for the period spanning 1989–2013, 34 (9.4%) were fatal (see Figure 2). This rate is similar to 10% per the Nall Report for 2010 (Aviation Safety Institute, 2012), which, unlike the present study, also includes mechanical failures. In contrast, 11.1% (n=826) of accidents unrelated to a maintenance deficiency were fatal. Contingency table analysis indicated that this difference was not statistically

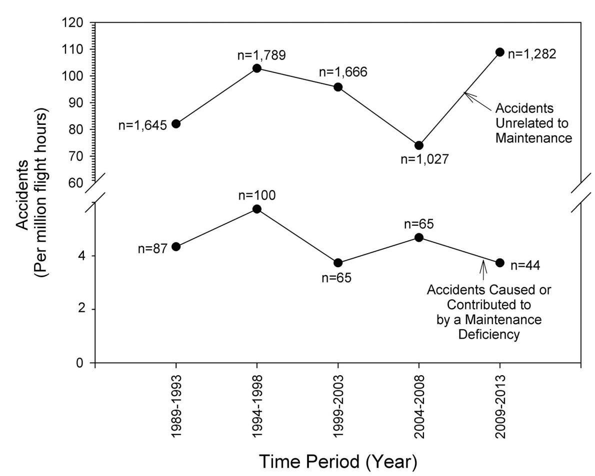

Figure 1. Temporal change in accident rate. Accident count (n) related, or unrelated, to a maintenance deficiency are shown in Figure 1 for the indicated time period adjusted to flight hours of the general aviation, piston fleet.

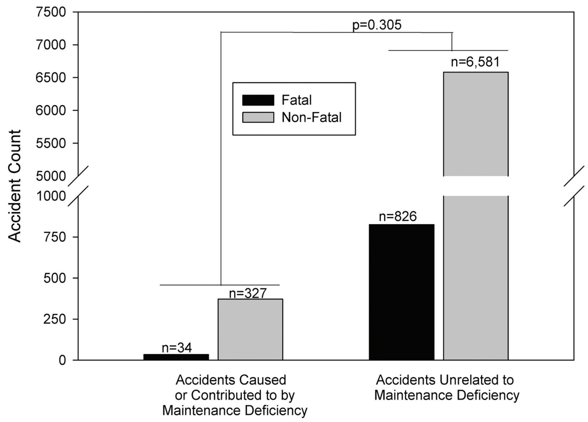

Figure 2. Distribution of fatal and non-fatal accidents related or un-related to a maintenance deficiency. The number (n) of fatal and nonfatal accidents, related or unrelated to maintenance deficiency over the 1989–2013 period are shown. Chi-Square statistical analysis was used to test for the proportion of fatal accidents between both groups.

significant (Chi-Square, p=0.305). Thus, at least in context of single engine piston aircraft, maintenance errors are no more likely to cause a fatal accident than accidents unrelated to a maintenance deficiency.

Category of maintenance deficiency causal for, or contributory to, an accident

Errors in maintenance related to an accident were then categorized (Figure 3). Inadequate/Improper maintenance represented the largest category as a cause of, or a factor in, a total of 172 accidents, of which 16 were fatal. For this category, undertorquing/non-safetied nuts and improper rigging (landing gear, flight control surfaces, propeller governor control) were the most common subcategories. Improper Installation/Assembly/Reassembly was the second most frequent category of maintenance deficiency leading, or contributing, to 87 of 357 accidents (24.4%), similar to the 20% reported by the FAA (Goldman et al., 2002). The third most prevalent category was Inadequate Inspection (inclusive of annual, 100 hour, and non-scheduled) accounting for 54 accidents, 3 of which were fatal. An overall Fisher's Exact Test for significant difference among all proportions was p=0.206. Consistent with these data, no maintenance category was determined to be over-, or for that matter, underrepresented for fatal accidents (p values are indicated above each maintenance deficiency category).

Aircraft systems disrupted in maintenance errors

For maintenance-related accidents, maintenance errors by aircraft systems were then categorized (see Table 1). Note that the total number of accidents (341) is smaller than that in the aforementioned data due to the exclusion of

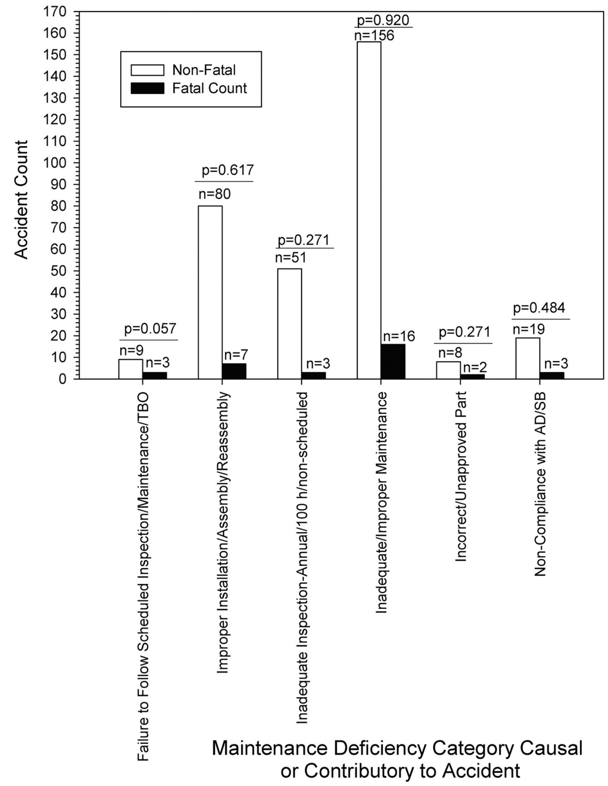

Figure 3. Category of maintenance deficiency causal for, or contributory to, an accident. Figure 3 shows the number (n) of fatal and nonfatal accidents categorized by maintenance deficiency. Statistics were post hoc using standardized adjusted residuals to derive p values for a disproportionate fraction of fatal accidents in each maintenance deficiency category. TBO is time between overhaul and AD/SB depicts airworthiness directive/service bulletin.

accidents for which there were few cases (e.g., banner release, exhaust muffler, seat track). A Fisher Exact Test indicated an overall significant difference in fatal/nonfatal proportions across aircraft systems (p=0.003). Maintenance errors involving the powerplant/mixture/throttle controls accounted for the largest number (169 of 341, or 49.1%) of all maintenance-related accidents; but, surprisingly, this category did not carry a disproportionate number of fatal accidents (p=0.134). Maintenance deficiencies related to the landing gear were also common, contributing to, or causal for, 56 of 341 (16.4%) accidents, and carried a lower fatality rate (1 of 55 accidents; p=0.036). Conversely, airframe maintenance errors, while rare (5 accidents), were overrepresented for fatal accidents (p<0.001).

Longitudinal distribution of accidents post annual inspection

Since an annual inspection, per 14CFR Part 43.15, is an extremely comprehensive process per the FAA (2015), aircraft handbooks and manuals performed by an

Table 1
Distribution of maintenance-related accidents by aircraft system.

Aircraft System	Accidents Caused or Contributed to by Maintenance Error			
	Nonfatal (n)	Fatal (n)	% Fatal	p Value
Airframe	2	3	60	<0.001
Brake System	17	0	0	0.162
Electrical System	8	2	20	0.23
Flight Control System	20	1	5	0.484
Fuel System	40	5	11	0.689
Landing Gear	55	1	2	0.036
Powerplant/Mixture/Throttle Controls	149	20	12	0.134
Propeller	18	0	0	0.162
TOTAL	309	32		

Fatal/nonfatal accident count (n) distribution by aircraft system is shown. Post hoc analysis using adjusted residuals to derive p values was used to determine the significance of over-/underrepresentation of fatal accidents for each aircraft system.

A&P/AMT maintenance technician with inspection authorization, the possibility that the temporal distribution of accidents post-inspection would be skewed was considered. Indeed, Figure 4 clearly shows a polarization of the accidents toward shorter times post-annual inspection. The median time for an accident was three months, with 25% of the accidents occurring within one month of completion of the annual inspection.

Personnel performing maintenance

The regulations (14CFR Part 43) governing aircraft maintenance mandate an authorized A&P/AMT, with the exception of preventive maintenance (e.g., tire installation, hydraulic fluid replenishment), which may be undertaken by the pilot/owner. Nevertheless, unauthorized individuals performing maintenance has been reported prior (Goldman et al., 2002). To determine the extent of this problem, the qualifications of personnel performing the maintenance from the NTSB accident record were examined. If pilots were A&P/AMT-certified, they were included in the latter group. If pilots who were not A&P/AMT-qualified performed nonpreventive maintenance, they were included in the "noncertified individual" group. Of the maintenance-related accidents, the qualifications of the individual undertaking the maintenance for 280 accidents could be identified (see Figure 5). Of these, the majority (n=252) of accidents involved aircraft for which maintenance was performed by A&P/AMTs. For this set of accidents, 25 were fatal. Pilot/operators undertook preventive maintenance in 11 cases, one of which was fatal. Noncertified personnel undertook maintenance on 13 aircraft that were involved in maintenance-related accidents, but none of these were fatal. A Fisher's Exact Test did not reveal an overall difference (p=0.815) in the proportion of fatal accidents for any personnel category performing maintenance.

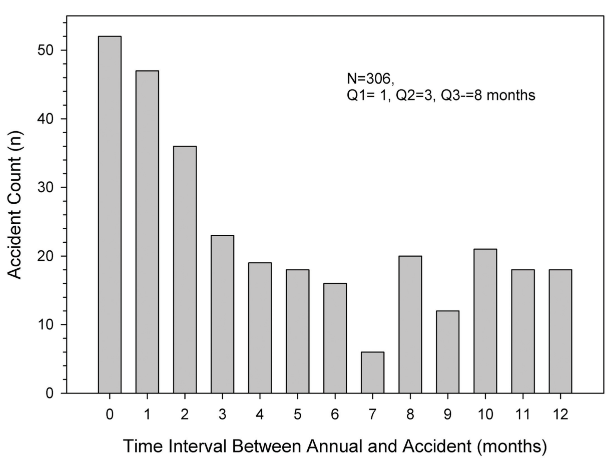

Figure 4. Time interval between annual inspection and accident. Note: The number of accidents as a function of time (months) post-annual inspection that an accident occurred. Q, quartile, Q2, median. N=total number of accidents for the 12 month interval.

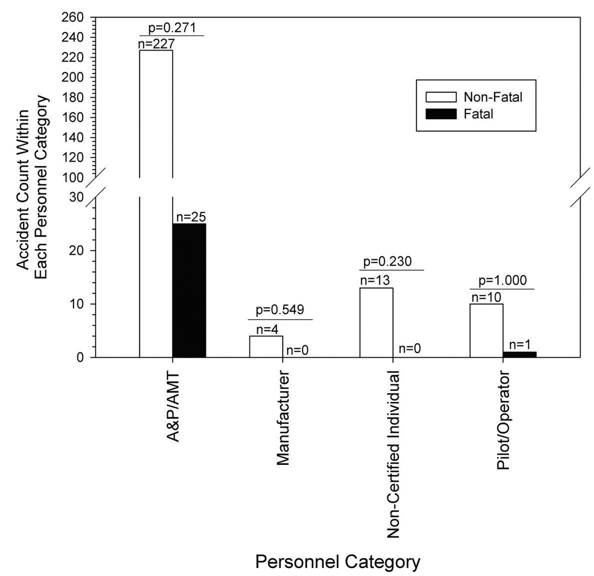

Figure 5. Personnel undertaking maintenance. Distribution of maintenance-related accidents based on category of personnel is shown. Statistics were as described for Figure 3 to determine over-/underrepresentation of fatal accidents for each personnel category. N is the number of accidents.

Fraction of fatal accidents for aircraft manufactured prior to 1950

There is ongoing concern as to the airworthiness safety of the aging general aviation fleet. In 2000, the average age of the general aviation single engine aircraft was in excess of 30 years, and by 2020, it is expected to approach 50 years, per an FAA (2003) report. Moreover, most of the general aviation fleet was designed to Civil Aviation Regulations (CAR) 3 standards that lacked fatigue and continued airworthiness requirements as part of their certification. Nonetheless, manufacturers and FAA engineers/inspectors have advanced the view in an FAA (2003) report on aging aircraft that if well-maintained/inspected, aging general aviation aircraft may not carry an excess risk of an accident compared with recently manufactured units.

Considering the potential contribution of aging-associated corrosion/fatigue failure to an airframe failure (and hence a fatal outcome), and the lack of denominator data for stratifying aircraft manufactured at different times by corresponding flight activity, the fraction of fatal accidents occurring between 1989 and 2013 for aircraft manufactured over a wide period (pre-1950 through 2013 was determined). Surprisingly, the researchers saw little evidence of a higher risk for a fatal accident for aircraft manufactured prior to 1950 when compared with those manufactured more recently (see Figure 6). Thus, the percentage of fatal accidents for aircraft manufactured prior to 1950 was 7.9% (108 of 1,267), which was no higher than those manufactured between 1950 and 1994. Surprisingly, aircraft manufactured over the 1995–2013 period showed a statistically higher ($p<0.001$) percentage of fatal accidents than those manufactured prior to 1950.

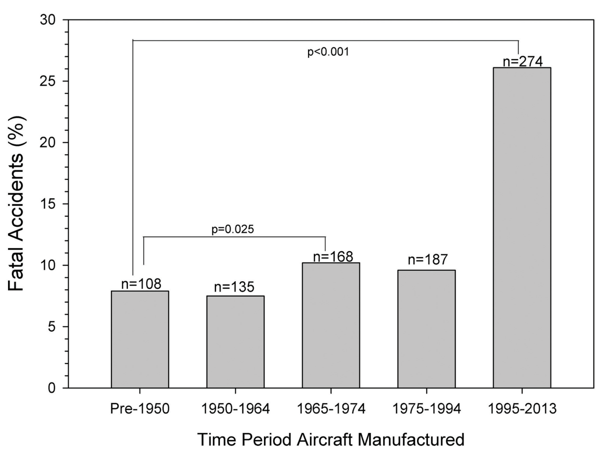

Figure 6. Distribution of fatal accidents occurring between 1989 and 2013 for aircraft manufactured at varying times. The percentage of fatal accidents occurring between 1989 and 2013 is shown as a function of aircraft manufacture year. For each time period, the percentage of fatal accidents was calculated using, as denominator, the sum of fatal and nonfatal accidents for that time frame. Chi-Square analysis was used to determine if the fraction of fatal accidents for a particular aircraft manufacture time period differed relative to the initial period (pre-1950). N represents the number of fatal accidents for the indicated aircraft manufacture period.

Discussion of Results

There is a dearth of research and, to the authors' knowledge, no peer-reviewed publications on maintenance-related general aviation accidents. The present research determined that for the most recent 25-year period, accidents in which a maintenance deficiency was causal for, or contributory to, constituted 4.8% of all accidents in single engine piston aircraft operating under 14CFR Part 91 regulations. While low, the fraction of accidents due to maintenance deficiency did not diminish over the 25-year study period. Maintenance errors were no more likely to lead to a fatal crash than accidents that were unrelated to a maintenance deficiency. Surprisingly, maintenance errors related to the powerplant/mixture/throttle system did not show a disproportionate increase in a fatal accident relative to other aircraft systems. Finally, scant evidence was found that aircraft manufactured prior to 1950 were associated with a greater proportion of fatal accidents, arguing for the effectiveness of maintenance practices advocated by the FAA and others for older aircraft.

The percentage (4.8%) of general aviation accidents that were maintenance-related was lower than that (7.1%) reported by the FAA for the period spanning 1988–1997 (Goldman et al., 2002). It is unlikely, however, that accidents caused, or contributed to, by a maintenance deficiency are on the decline. Indeed, as discussed above, there was no such evidence over the 25-year study period. It is more likely that other reasons account for the divergence in findings. First, the methodology employed in the two studies differed. Thus, while the earlier study had utilized NTSB codes to identify maintenance-related accidents, the present investigation employed maintenance-relevant phrases in the narrative as a query tool. Second, the prior study included accidents spanning aircraft category, thus inclusive of rotorcraft, gliders, ultralights, and balloons. Third, the present study was restricted to single engine piston aircraft while the FAA report was inclusive of all (single, multiengine, piston, turbine) airplanes operating under 14CFR Part 91.

Of the maintenance-related accidents over the 1989–2013 period, 10.4% were fatal. This rate was reduced compared with the 13–27% reported across the period spanning 1988–1997 per the Goldman et al. (2002) study. It is tempting to speculate that the more favorable outcomes in the current study reflect, to some extent, improved pilot training for malfunctions that in the past often had a fatal outcome, such as a powerplant failure. Indeed, in the current study, of 149 accidents related to the powerplant/mixture/throttle system, only 12% were fatal. However, again, the data are not necessarily comparable. As discussed above, the FAA investigation also included multiengine aircraft, which themselves carry a higher risk of a fatal accident (Aviation Safety Institute, 2012), while the present study was restricted to maintenance-related accidents in single engine piston aircraft.

It was noted that the fraction of noncertified personnel undertaking maintenance for accidents in which maintenance error was a cause, or a factor, appears to have declined. Of the 280 maintenance-related accidents in the current study for which it was possible to determine the certification of personnel undertaking maintenance, 13 (4.6%) did not hold an A&P/AMT certificate. For the FAA study (Goldman et al., 2002), 8.8% of the personnel involved in the maintenance were not qualified A&Ps/AMTs, although it is noted that this was for a subset of maintenance procedures. Nevertheless, caution should be exercised in interpreting these encouraging data due to differing query methodologies in the two studies and because the number of noncertified personnel involved was modest.

The finding that aircraft manufactured prior to 1950 were not associated with a higher proportion of fatal accidents argues for the success of current maintenance practices advanced by the FAA in conjunction with manufacturers and various pilot organizations. Nevertheless, the higher representation of fatal accidents for aircraft manufactured over the period spanning 1995–2013 was unexpected, especially since crashworthiness standards are higher for aircraft certified after 1988 (Soltis & Olcott, 1985). The authors suspect that this observation is not so much related to maintenance but reflects one, or multiple, confounders. For example, aircraft with higher speed, longer range, or of a higher certified maximum weight carry an increased risk of a fatal flight, as they traverse a range of weather patterns and terrain unsuitable for a forced landing (Freitas, 2014; Grabowski, Curriero, Baker, & Guohua, 2002; Groff & Price, 2006; Li & Baker, 2007; O'Hare & Owen, 2002). If such aircraft are overrepresented in the 1995–2013 manufacture period, this might account for the higher fatal accident rate.

The researchers recognize that this study had limitations. For example, NTSB probable causes sometimes cite more than one cause and/or contributing factors for a particular accident, yielding some subjectivity in assigning a maintenance deficiency category. To reduce ambiguity, best effort was made by the researchers to confer and come to agreement as to the ultimate category assigned. Second, although the search strategy was meant as a means of overcoming the limitations of NTSB database maintenance-related codes, nevertheless, the possibility that some maintenance-related accidents were missed using this query method cannot be dismissed. Third, in some instances, the number of events was small. Finally, NTSB reports are bereft of performance-shaping factors—data that may contribute to errors in maintenance (Rankin et al., 2000)—thus prohibiting the examination of these factors.

In conclusion, general aviation accidents in single engine piston accidents that are related to maintenance deficiency are infrequent. Nevertheless, in view of the static rate of maintenance-related accidents, there is room for improvement. Increased emphasis should be placed on tasks involving torquing and improper rigging, which accounted for the largest subcategories of Inadequate/Improper maintenance. Likewise, attention should be focused on maintenance related to improper installation/assembly/reassembly, which constituted the second most frequent category of maintenance deficiency. Finally, there should be discussion as to whether a general aviation-modified maintenance error decision aid (MEDA) process (Rankin et al., 2000) or an Aviation Safety Action Program (per AC 120-66B), designed to reduce errors at 14CFR Part 121 repair stations, should also be applied to general aviation maintenance operations.

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