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Research Report

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Trends in U.S. Air Force Aircraft Mishap Rates (1950–2018)

The U.S. Air Force's aircraft inventory is old and getting older. Aircraft, such as the B-52 and KC-135, were designed and manufactured more than 60 years ago but remain critical elements of the Air Force's force structure. At the same time, newer aircraft, such as the F-22 and RQ-4, rely on more-complex technologies, materials, and software, potentially creating new operational and sustainment challenges. The aging of certain fleets and increasing complexity of newer military aircraft, coupled with continued overseas operations and a fluctuating budget environment, have led some to worry that the Air Force's inventory is likely to be more prone to incidents that result in a loss of aircraft or, worse, life.

These concerns were elevated following a March 15, 2018, HH-60 loss in Iraq that resulted in seven fatalities and a May 2, 2018, WC-130 loss in Savannah, Georgia, that resulted in nine fatalities and contributed to Congress establishing the National Commission on Military Aviation Safety as part of the 2019 National Defense Authorization Act.[1]

To investigate concerns over mishaps and support the commission, we assembled and analyzed mishap data from the Air Force Safety Center for 55 different aircraft types in operation since 1950.[2] A *mishap* is an "unplanned event or series of events resulting in death, injury, occupational illness, or damage to or loss of equipment or property, or damage to the environment."[3] Our analysis focuses on three types of mishap events, defined as follows:[4]

KEY FINDINGS

- Trends in average mishap rates suggest that major improvements in flight safety have been achieved, with the greatest rate of improvement occurring in the 1950s and 1960s. The rates of improvement in Class A mishaps and destroyed aircraft, although still meaningful, have been less dramatic since the 1970s. Mishaps involving pilot fatalities, however, have shown a more persistent rate of improvement.
- As an aircraft mission design ages, mishap rates tend to improve.
- Aircraft introduced more recently have tended to experience lower mishap rates.
- Multiengine aircraft tend to experience fewer Class A mishaps and destroyed aircraft when compared with single-engine aircraft, all else equal.
- There are meaningful differences in the frequency of mishaps across aircraft types over time. Mobility and trainer aircraft experience the lowest mishaps rates.

- Class A mishaps. Class A mishaps are currently reported any time an incident results in (1) $2 million or more in damage to the aircraft, (2) a fatality or permanent disability, and/or (3) destruction of the aircraft. The dollar-damage threshold has been updated over time since 1950 to account for inflation.
- Destroyed aircraft. The destroyed aircraft count includes only aircraft owned, designated, or leased by the Air Force. An aircraft is deemed "destroyed" if the system cannot be repaired and returned to service.
- Pilot fatalities. The pilot fatality count only includes Air Force personnel designated as a "pilot" by the Safety Investigation Board.

The incidents included in the Air Force Safety Center data exclude combat-related incidents. A summary of the Air Force Safety Center data for each aircraft considered in this analysis is shown in Table 1.[5]

Structure of This Report

Although descriptions of the changes in aircraft safety over time have been noted, there is very little research that has attempted to rigorously track and analyze these long-run trends for military aircraft. This report seeks to fill this gap. In the following section, we show trends in Air Force aircraft mishap rates since the 1950s. The trends are broken out by aircraft type. We then present a statistical analysis that seeks to control for and quantify factors that might be affecting mishap rates, including changes in flying hours, the age of an MD, the year in which an MD was introduced, the aircraft type, and whether the aircraft has a single or multiengine design. We conclude the report with a synthesis of key findings.

Abbreviations

ISR	intelligence, surveillance, and reconnaissance
MD	mission design
NA	not available or not reliably reported
PAF	Project AIR FORCE
RPA	remotely piloted aircraft

Trends in Mishap Rates

In this section, we review the empirical evidence on long-run trends in Air Force aircraft mishap rates. As is often done, we express mishaps as a rate per 100,000 flying hours.[6]

Trends in Mishaps Rates

Figure 1 shows trends since the 1950s in mishap rates per 100,000 flying hours, after applying logarithmic scaling. The data shown in Figure 1 are based on the 55 aircraft types shown in Table 1. Each data point in the chart represents a three-year average.[7] Because of reporting issues, pilot fatality data for the 1950s are excluded from the chart.

Figure 1 suggests a general decline in rates of mishaps, with the greatest rate of improvement occurring in the 1950s and 1960s. For example, the number of destroyed aircraft per 100,000 flying hours dropped from an average of approximately 23.6 for every 100,000 flying hours during the 1950s to 4.3 during the 1960s and 2.3 during the 1970s. The destroyed aircraft rate has continued to come down since the 1970s (but at a slower pace) and has averaged slightly fewer than one aircraft lost for every 100,000 flying hours between 2010 and 2018. We see a similar trend for Class A mishaps,[8] while pilot fatalities have declined at a more constant pace since the 1960s when reliable data were first reported. During the 1960s, there were approximately 2.2 pilot fatalities per 100,000 flying hours. The fatality rate fell to just 0.2 fatalities per 100,000 flying hours over the 2010–2018 period.[9]

The trend toward lower mishap rates generally holds when mishaps are broken down by aircraft MD. For example, Figure 2 shows the destroyed aircraft rate for five fighter aircraft over time. In general, the trend is declining for these five aircraft and suggests a reduction in the destroyed aircraft rate over time. The improvement could potentially be a product of a variety of factors, including investments to enhance aircraft reliability and safety;[10] the introduction of newer variants and retirement of older aircraft variants in fleets; and general improvements in piloting and maintenance training and practices.[11]

TABLE 1

Summary Statistics for Aircraft Included in the Analysis

				Number of Reported Incidents		
MD	Aircraft Type	Data Range	Total Flying Hours	Class A Mishaps	Destroyed Aircraft	Pilot Fatalities[a]
A-10	Fighter	1972–2018	5,573,747	106	106	51
A-37	Fighter	1967–1995	731,665	37	33	21
A-7	Fighter	1968–1993	1,768,958	101	102	40
B-1	Bomber	1984–2018	733,106	29	9	6
B-2	Bomber	1990–2018	136,973	1	1	0
B-47	Bomber	1950–1976	3,725,585	288	203	174
B-52	Bomber	1955–2018	7,891,843	104	78	101
B-57	Bomber	1953–1981	1,319,133	177	122	87
B-58	Bomber	1958–1970	221,928	22	22	8
C-12	Mobility	1975–2018	776,821	3	2	4
C-130	Mobility	1955–2018	19,679,625	162	92	146
C-135	Mobility	1957–2018	15,962,233	87	65	136
C-141	Mobility	1964–2006	10,641,969	34	15	35
C-17	Mobility	1991–2018	3,270,830	32	1	3
C-20	Mobility	1983–2017	169,862	0	0	0
C-21	Mobility	1984–2018	1,286,087	4	4	6
C-40	Mobility	2002–2018	100,062	0	0	0
C-5	Mobility	1968–2018	2,666,161	27	5	5
C-9	Mobility	1968–2011	902,001	3	1	3
E-3	ISR	1977–2018	876,885	2	1	2
E-4	ISR	1975–2018	71,509	6	0	0
E-8	ISR	1991–2018	207,267	3	0	0
F-100	Fighter	1953–1990	5,471,047	1,161	889	324
F-101	Fighter	1955–1982	1,993,445	292	192	78
F-105	Fighter	1971–1984	452,752	55	48	16
F-117	Fighter	1991–2008	215,844	7	3	1
F-15	Fighter	1972–2018	6,692,386	155	126	44
F-16	Fighter	1975–2018	11,086,919	376	337	86
F-22	Fighter	2002–2018	327,458	20	4	1
F-35	Fighter	2007–2018	76,200	3	0	0
F-5	Fighter	1963–1989	442,176	39	40	15
F-80	Fighter	1950–1953	932,806	870	373	0
F-84	Fighter	1950–1972	3,698,489	1,955	1,186	63

Table 1—Continued

MD	Aircraft Type	Data Range	Total Flying Hours	Number of Reported Incidents		
				Class A Mishaps	Destroyed Aircraft	Pilot Fatalities[a]
F-86	Fighter	1950–1971	5,543,631	2,449	1,422	70
F-89	Fighter	1951–1969	1,222,603	300	175	18
F/RF-4	Fighter	1971–2000	7,604,757	353	335	159
FB-111	Fighter	1970–1991	371,602	15	12	4
H-1	Helicopter	1959–2018	2,032,563	59	43	21
H-3	Helicopter	1962–1994	722,591	31	21	14
H-53	Helicopter	1966–2008	519,364	39	23	25
H-60	Helicopter	1982–2018	724,783	26	15	14
KC-10	Mobility	2000–2018	1,130,016	16	0	0
MQ-1	RPA	1996–2018	2,075,581	134	117	0
MQ-9	RPA	2001–2018	1,721,403	48	32	0
O-2	ISR	1967–1988	1,808,763	51	49	36
RQ-4	RPA	1998–2018	239,144	8	6	0
T-1	Trainer	1992–2018	2,078,775	2	1	0
T-37	Trainer	1956–2009	13,566,358	138	136	28
T-38	Trainer	1960–2018	14,553,992	207	199	82
T-41	Trainer	1964–2018	633,895	9	4	1
T-43	Trainer	1974–2010	371,573	1	1	2
T-53	Trainer	1974–2010	371,573	1	1	2
T-6	Trainer	2000–2018	2,314,894	6	7	2
U-2	ISR	1964–2018	660,490	32	23	9
V-22	Mobility	2006–2018	85,561	5	2	1

SOURCE: Authors' analysis of data accessed August 3, 2019, from Air Force Safety Center, "Aviation Statistics," webpage, undated.

NOTE: ISR = intelligence, surveillance, and reconnaissance; RPA = remotely piloted aircraft.

[a] Pilot fatality data were unreported or not reported reliability until the late 1950s.

The downward trend in destroyed aircraft rates over time shown in Figure 2 for the five fighter fleets is typical of what we observed for other fleets and for Class A mishap and pilot fatality rates. In the next section, we use more-sophisticated econometric techniques to isolate and estimate the effect of the MD age on mishap rates.

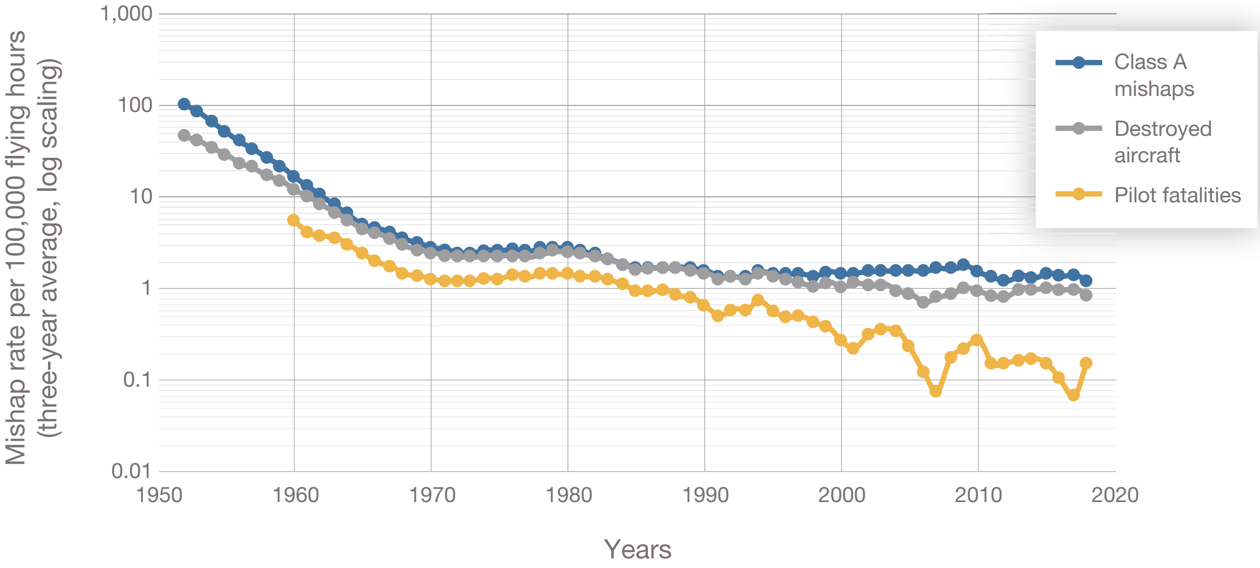
Trends in Mishap Rates by Aircraft Type

We can further break down the mishap rates by various characteristics of the aircraft, including whether it is fixed or rotary wing, by its mission area, and whether the aircraft has an onboard pilot or is remotely piloted. Table 2 shows how mishap rates have varied over time for each of the aircraft types associated with MDs shown in Table 1.

To understand whether mishap rates are changing in a statistically meaningful way over time, we performed a two-sided *t*-test for differences in the mean of the annual mishap rates in each decade relative to the previous decade for each aircraft type

FIGURE 1

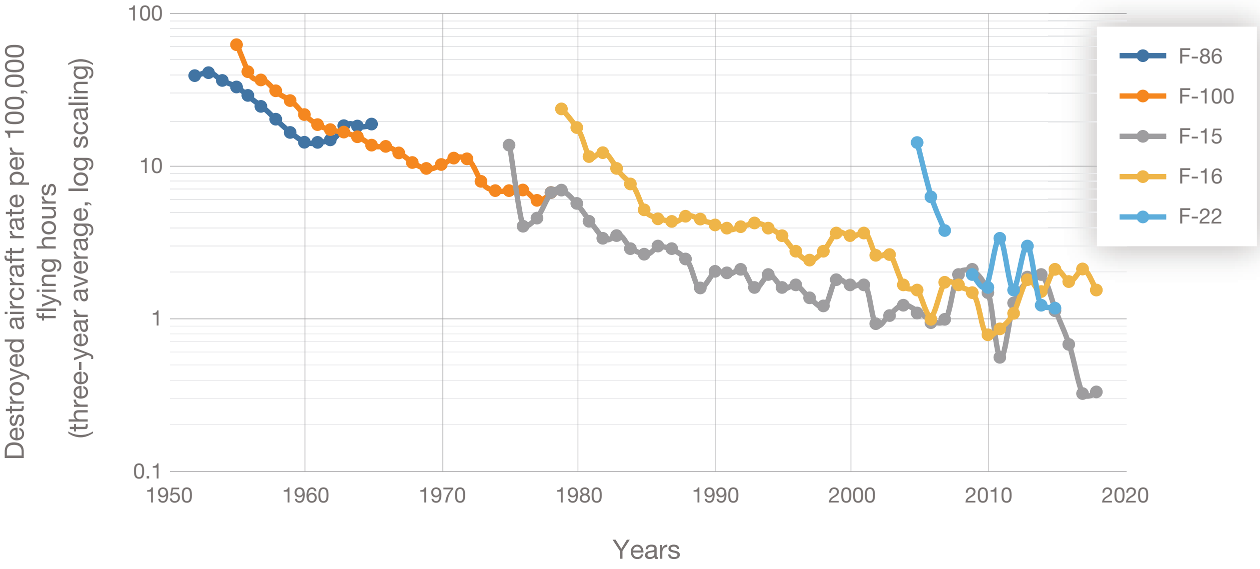
Trends in U.S. Air Force Aircraft Mishap Rates over Time



SOURCE: Authors' analysis of data accessed August 3, 2019, from Air Force Safety Center, undated.
NOTE: Each data point represents a three-year trailing average.

FIGURE 2

Destroyed Aircraft Rate over Time for Select Fighter Platforms



SOURCE: Authors' analysis of data accessed August 3, 2019, from Air Force Safety Center, undated.
NOTE: Each data point represents a three-year trailing average.

shown in Table 2. A statistically significant change in the mean is indicated by one asterisk or two asterisks, reflecting a 95- and a 99-percent statistical significance, respectively.[12] To help interpret direction, we highlight statistically significant reductions in mishap rates in blue text and statistically significant increases in mishap rates in red text.

TABLE 2

Mishap Rates by Aircraft Type over Time

Period	Bomber	Fighter	Helicopter	ISR	Mobility	RPA	Trainer	All Aircraft
Class A Mishap Rate (per 100,000 flying hours)								
1950s	10.1	54.2	NA	NA	4.3	NA	9.7	42.0
1960s	3.2	15.3**	6.0	5.0	1.1	NA	2.4	5.2**
1970s	1.6**	6.8**	4.4	2.6	0.7**	NA	1.3**	2.6**
1980s	1.2	3.9**	3.2	2.4	0.5*	NA	0.7*	1.8**
1990s	1.6	3.0*	2.7	2.7	0.3*	61.8	0.3*	1.4**
2000s	3.0	2.0**	4.8	2.4	0.7**	11.6	0.5	1.6
2010–2018	2.2	1.8	1.9	0.5**	0.5	3.1**	0.2*	1.3*
Destroyed Aircraft Rate (per 100,000 flying hours)								
1950s	6.3	30.2	NA	NA	1.6	NA	8.3	23.6
1960s	2.9	12.6**	3.8	5.0	0.7	NA	2.2	4.3**
1970s	1.4**	6.3**	3.1	2.2	0.4*	NA	1.2**	2.3**
1980s	1.0	3.8**	2.5	2.1	0.3	NA	0.7*	1.7**
1990s	0.7	2.9**	2.4	1.6	0.2*	44.1	0.3*	1.2**
2000s	0.8	1.5**	1.7	0.4	0.1	8.4	0.5	0.9**
2010–2018	0.5	1.1	1.3	0.3	0.1	2.8*	0.2*	0.9
Pilot Fatality Rate (per 100,000 flying hours)								
1950s	NA	NA	NA	NA	NA	NA	NA	NA
1960s	2.7	4.7	2.0	1.9	1.1	NA	0.6	2.2
1970s	1.3*	2.8**	2.0	1.6	0.9	NA	0.4	1.3*
1980s	1.0	1.6**	3.3	1.7	0.6	NA	0.3	1.0*
1990s	1.0	0.7**	1.8	1.4	0.3	0.0	0.1	0.5**
2000s	0.4	0.4	0.5	0.2	0.1*	0.0	0.2	0.2**
2010–2018	0.0	0.2	0.6	0.3	0.2	0.0	0.0	0.2

SOURCE: Authors' analysis of data accessed August 3, 2019, from Air Force Safety Center, undated.

NOTE: Student's *t*-test performed to test whether the mean annual mishap rate in each decade differs from those observed during the previous decade. The *t*-test assumes a two-tailed distribution, with potentially unequal variances in each decade. Statistically significant reductions and increases in mishap rates are shown in blue (95-percent statistical significance) and red (99-percent statistical significance).

* = The sample means are different with a 95-percent statistical significance.

** = The sample means are different with a 99-percent statistical significance.

NA = not available or not reliably reported (mishap data are either not reliably reported [e.g., pilot fatalities during the 1950s] or available because the aircraft type was not in widespread use during the period [e.g., RPA prior to the 1990s]).

The data presented in Table 2 offer further support for the observation that mishap rates have improved over time across aircraft types. However, the magnitude and statistical significance of the improvements from one decade to the next tend to vary and slow over time.[13] Furthermore, there are meaningful differences in the rates experienced across aircraft types in any given decade. In particular, fighters, bombers, helicopters, and, with their more recent introduction, RPA tend to experience greater mishap rates when compared with mobility, trainer, and ISR aircraft.

In the next section, we develop a statistical model of mishap rates that controls for and quantifies the effect of a variety of factors, including annual flying hours, the age of an MD, the aircraft type, and whether the aircraft has a single or multiengine design.

Statistical Analysis of Factors Influencing Mishap Rates

The data presented earlier in this report suggest that the Air Force has achieved meaningful improvements in its aircraft mishap rates over the past 70 years. In this section, we use statistical methods to disentangle and quantify factors that might be influencing mishap rates over time. We begin by discussing our statistical approach and then provide interpretation of the estimation results.

Statistical Approach

The data on mishap rates summarized earlier in the report are especially suitable for analysis using regression. Regression analysis allowed us to attribute observed variation in mishap rates to such factors as aircraft design features and the passage of time. We describe the technical details of our approach here.

Let n_{it} represent a count on the number of mishap events (either Class A mishaps, destroyed aircraft, or pilot fatalities) for aircraft MD i in year t. We model n_{it} as a random variable distributed according to a negative binomial distribution. Let μ_{it} represent the expected number of mishaps for MD i in year t.

In our first negative binomial regression specification, we allow μ_{it} to vary with the flying hours (f_{it}) MD i performs in year t, the design age (a_{it}) of MD i in year t, and an MD parameter α_i.[14] We have the design age enter the regression as a polynomial to allow the effect of design age to potentially vary over the life of an MD. The design age represents the time in years that has elapsed since the MD's first year of flight according to the Air Force Safety Center data. For aircraft that flew prior to 1950 (when the Air Force Safety Center began reporting data), we looked to open-source documents to obtain the year of first flight for those MDs.

Formally, we estimate μ_{it} using the following equation:

$$\log(\mu_{it}) = \alpha_i + \beta \cdot \log(f_{it}) + \gamma \cdot a_{it} + \eta \cdot a_{it}^2 \quad (1)$$

In addition to estimating the parameters α_i,[15] β, γ, and η, we estimate a scale parameter, θ, associated with the negative binomial distribution.[16]

To allow for additional insights, we also estimate a second version of the model where α_i varies parametrically by the aircraft types shown in Table 1, the MD vintage, and whether the aircraft is a single or multiengine aircraft. Formally, in our second specification, we substitute the following equation into Equation 1:

$$\begin{aligned} \alpha_i = {} & \Sigma_m \phi_m \cdot \mathit{Aircraft\ Type}_{mi} + \\ & \pi \cdot \mathit{Design\ Vintage}_i + \\ & \delta \cdot \mathit{Multiengine}_i \end{aligned} \quad (2)$$

where

- ϕ_m, π, and δ are coefficients to be estimated
- m is an index on aircraft types equal to bomber, fighter, helicopter, ISR, mobility, RPA, and trainer
- $\mathit{Aircraft\ Type}_{mi}$ is a dummy variable equal to 1 if MD i's aircraft type is m and 0 otherwise
- $\mathit{Design\ Vintage}_i$ represents the first year in which MD i was flown
- $\mathit{Multiengine}_i$ is a dummy variable equal to 1 if MD i has multiple engines and 0 if it is a single-engine aircraft.

Estimates

Table 3 shows the coefficient estimates for each mishap metric under both specifications described above. Notice that, for each of the three mishap rates, specification 1 has a higher log-likelihood value and smaller dispersion parameter, θ, suggesting

TABLE 3

Estimation Results

	Class A Mishaps		Destroyed Aircraft		Pilot Fatalities	
Specification	(1)	(2)	(1)	(2)	(1)	(2)
log(annual flying hours) (β)	0.7125**	0.7305**	0.7580**	0.8067**	0.6785**	0.8085**
	(0.0228)	(0.0218)	(0.0242)	(0.0225)	(0.0476)	(0.0388)
Design age (γ)	-0.1206**	−0.1032**	−0.0976**	−0.0783**	−0.0524**	−0.0493**
	(0.0062)	(0.0072)	(0.0064)	(0.0075)	(0.0109)	(0.0117)
Design age squared (η)	0.0014**	0.0011**	0.0009**	0.0006**	0.0000	0.0000
	(0.0001)	(0.0001)	(0.0001)	(0.0002)	(0.0002)	(0.0002)
MD dummies (α_i)	Included, not shown	—	Included, not shown	—	Included, not shown	—
Bomber aircraft (ϕ_{Bomber})	—	83.2649**	—	106.0351**	—	105.9987**
		(5.4155)		(5.5987)		(9.4811)
Fighter aircraft ($\phi_{Fighter}$)	—	84.0698**	—	107.0849**	—	106.1663**
		(5.4401)		(5.5674)		(9.5397)
Helicopter ($\phi_{Helicopter}$)	—	83.0739**	—	105.9602**	—	105.9855**
		(5.4323)		(5.6228)		(9.5225)
ISR aircraft (ϕ_{ISR})	—	82.5646**	—	105.6072**	—	105.6094**
		(5.4538)		(5.6504)		(9.9557)
Mobility aircraft ($\phi_{Mobility}$)	—	82.0461**	—	104.4188**	—	105.0266**
		(5.4357)		(5.6151)		(9.5156)
RPA (ϕ_{RPA})	—	84.7233**	—	108.2618**	—	—
		(5.5364)		(5.7315)		
Trainer aircraft ($\phi_{Trainer}$)	—	82.2361**	—	105.4501**	—	104.4259**
		(5.4422)		(5.6202)		(9.5213)
Design vintage (π)	—	−0.0452**	—	−0.0576**	—	−0.0579**
		(0.0027)		(0.0029)		(0.0048)
Multiengine aircraft (δ)	—	−0.4464**	—	−0.3999**	—	−0.0133
		(0.0673)		(0.0625)		(0.1140)
Dispersion scale parameter (θ)	0.1084	0.3588	0.0465	0.1999	0.4170	0.7547
Observations	1,819	1,819	1,819	1,819	1,785	1,785
Log-likelihood	29,631.99	29,344.34	15,497.17	15,291.24	922.06	834.04
Akaike information criterion	4,860.82	5,344.12	3,943.82	4,263.67	3,096.64	3,182.68

NOTE: RPA aircraft excluded from pilot fatality regression because of lack of onboard pilot. Standard errors presented in parentheses.
— = Variable not included. * = 95-percent statistical significance level. ** = 99-percent statistical significance level

specification 1 fits the data better. However, the coefficients unique to specification 2 (ϕ_m, π, and δ parameters) have interesting interpretations and can be used to estimate mishaps rates for MDs that may be contemplated in the future or are not included in our data.

We interpret some of the coefficient estimates shown in Table 3.

Flying Hours

If mishaps scale proportionally with flying hours, the β coefficient will equal 1. In fact, the regressions suggest that mishaps scale less than proportionally with flying hours. For example, according to specification 1, a 10-percent increase in flying hours is expected to increase Class A mishaps by approximately 7 percent [$= 1.1^{\beta} - 1.0 = 1.1^{0.7125} - 1.0$]. Results for all six regressions suggest that a 10-percent increase in flying hours would increase mishaps rates by 7 or 8 percent, all else equal.[17]

Design Age

One might expect that, as an aircraft design ages, the aircraft will be more prone to mishaps. The fighter data shown in Figure 2 suggest that aircraft mishap rates tend to decline (improve) as an aircraft design gets older. The coefficient estimates shown in Table 3 supports this finding but suggest that the rate of decline gets smaller over time for Class A mishaps and destroyed aircraft. Pilot fatalities, on the other hand, tend to decline at a constant rate, regardless of the design age. To see this, note that the regressions shown in Table 3 allow mishap rates to change at different rates with the design age. Specifically, the annual rate of change in the mishap rate can be calculated as $\gamma + \eta \cdot a_i$ (shown in Figure 3). As an example, Class A mishap rates will decline at a rate of approximately 12 percent and 10 percent in the initial design year (e.g., when $a_{it} = 0$) according to specification 1 and 2, respectively. After an aircraft design age reaches 50 years old, Class A mishaps are expected to decline at an annual rate of approximately 5 percent under both specifications [$= -0.1206 + 0.0014 \cdot 50 \approx -01032 + 0.0011 \cdot 50$].[18] Because the η parameter equals 0 for both pilot fatality regressions, we estimate the annual rate of change in pilot fatalities to decrease by approximately 5 percent [$= -0.0524 \approx -0.0493$] regardless of an aircraft's MD age, according to both regressions.[19]

Mission Design Characteristics

We next discuss the estimates associated with the MD coefficients estimated from the second regression specification for each of the mishap metrics.

Aircraft Type

Aircraft that operate in different mission areas (e.g., bomber, fighter, ISR, mobility, trainer) or with different technologies (e.g., fixed wing versus rotary wing; manned aircraft versus RPA) can require fundamentally different aircraft designs and can be used in much different ways. The ϕ_m coefficients provide an estimate of the inherent differences in the likelihood of mishaps for different types of aircraft. Mobility and trainer aircraft have the lowest aircraft type coefficient, suggesting that they are less likely than other types of aircraft to experience mishaps, all else equal. RPA and fighters have the greatest likelihood of experiencing a Class A mishap or destroyed aircraft using the coefficients.[20] Also, fighters have the highest likelihood of experiencing a pilot fatality. It is important to note, however, that RPA do not put onboard pilots and crew at risk. Because pilot fatalities are not possible for RPA, the RPA are not included in the pilot fatality regressions.

Design Vintage

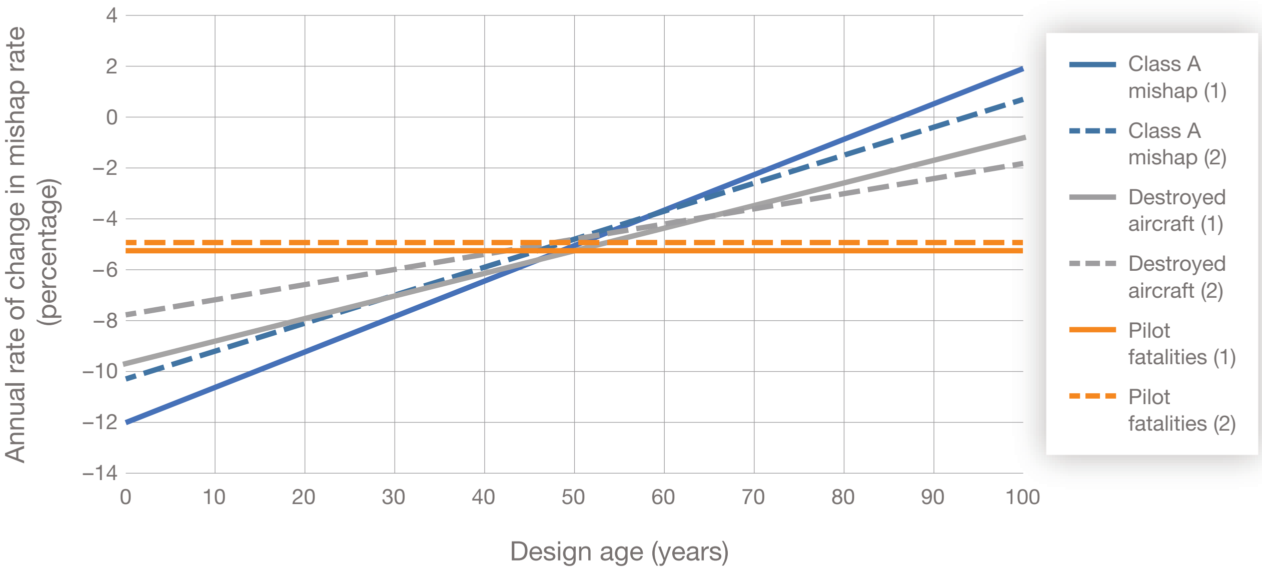
Given the functional form of specification 2, the coefficient π on the design vintage variable can be interpreted as an annual rate of change in the mishap rate dependent on the year in which the MD first flew. The estimates of π indicate that a 5- to 6-percent expected reduction in mishap rates occurs with each year of increase in the design vintage. Taken together, the estimate of π and the design age coefficients (γ,η) suggest that mishaps are generally declining over time for new and existing designs.

Single-Engine Versus Multiengine Aircraft

We find that single-engine aircraft are more likely to experience some types of mishaps than multiengine aircraft. Specifically, we estimate that multiengine aircraft relative to single-engine aircraft are, on

FIGURE 3

Annual Rate of Change in Mishap Rates at Different Design Ages



NOTE: The annual rate of change in mishap rates at different design ages a_{it} is calculated as $\gamma + \eta \cdot a_{it}$ from the coefficient estimates shown in Table 3.1. The regression specification number is shown in parentheses next to each mishap metric in the legend.

average, 36 percent less likely [= *exp*(−0.4464) – 1] to be involved in a Class A mishap and 33 percent less likely [= *exp*(−0.3999) – 1] to be destroyed in flight, all else equal. Single-engine versus multiengine aircraft was not found to have a statistically significant effect on pilot fatalities.[21]

Conclusions

This analysis has explored long-term trends in Air Force aircraft mishaps rates. To address the changing composition and utilization of aircraft in the fleet over time, we applied statistical models that allowed us to isolate trends and factors contributing to mishap rates. Key findings from this analysis are summarized as follows.

- **The trends in mishap rates suggest that major improvements in flight safety have been achieved, with the greatest rate of improvement occurring in the 1950s and 1960s.** As an indication of this, during the 1950s, there were more than 23.6 aircraft lost on average (excluding combat losses) per 100,000 flying hours. That rate has fallen to 2.3 aircraft lost per 100,000 flying hours during the 1970s and fewer than one aircraft lost per 100,000 flying hours during the 2010–2018 period. Similar improvements in rates of Class A mishaps have been observed. Pilot fatalities, however, have shown a more persistent rate of improvement over the 1960 to 2018 time frame.
- **As an aircraft MD ages, mishap rates tend to improve, although the annual rate of improvement lowers over an MD's life for Class A mishaps and destroyed aircraft.** In the case of Class A mishaps and destroyed aircraft, the annual rate of improvement is most pronounced early in the MD's life and decreases over time. In the case of pilot fatalities, the annual rate of improvement remains constant over the life of an MD. The long-run improvement in mishap rates may stem from a variety of factors, including the retirement and replacement of more accident-prone aircraft (e.g., replacement of C-130E/H with C-130Js), modifications to enhance aircraft reliability and safety, and general improvements in piloting, maintenance, and testing

practices that accrue from greater experience with an aircraft design or in general over time. Although our findings do not support the conclusion that aging aircraft are currently contributing to increasing mishap rates, these findings should be updated and monitored in the future as aircraft in use continue to age outside ranges observed today.[22]

- **Aircraft introduced in more recent years tend to exhibit lower mishap rates.** We estimate that a 5- to 6-percent reduction in mishap rates occurs with each year of increase in an MD's release. This improvement may stem from advancements in safety integrated into newer aircraft designs; more-reliable parts and components integrated into newer aircraft designs; and general changes in policies, practices, and procedures that allow aircraft to operate with fewer mishaps over time.
- **Multiengine aircraft tend to experience fewer Class A mishaps and destroyed aircraft when compared with single-engine aircraft, all else equal.**[23] We do not find, however, a significant statistical difference in pilot fatality rates for multiengine versus single-engine aircraft.
- **There are meaningful differences in mishap rates across aircraft types over time.** For example, when first introduced in the 1990s, RPA were as likely as fighter aircraft from the 1950s to be destroyed in flight. RPA mishap rates have improved significantly since then and are approaching destroyed aircraft rates comparable to fighter aircraft in operation today. RPA have the benefit of not experiencing any pilot (or crew) fatalities. In general, we find mobility and trainer aircraft to experience the lowest mishap rates.

Future research in this area might consider trends in the causes of mishaps (e.g., operator error, failure of systems and electronic parts, quality defects, environmental factors, and design-related problems) to understand the relative importance of different drivers. Readily available data currently do not support this type of analysis over long periods and may only be obtained from conducting detailed case studies of the mishap experience observed for select types of aircraft. Additionally, the development of better measures of the effectiveness of different steps taken to reduce aircraft accidents over time could be pursued using statistical models, such as those developed here.

Notes

[1] Public Law 115-232, John S. McCain National Defense Authorization Act for Fiscal Year 2019, August 13, 2018.

[2] The data reported by the Air Force Safety Center are summarized by aircraft mission design (MD). An MD often represents a collection of many different MD series aircraft. For example, the F-16 MD includes the F-16A, F-16B, F-16C, and F-16D MDs.

[3] Air Force Safety Center, *Air Force System Safety Handbook*, Kirtland Air Force Base, N.M., revised July 2000, p. vi.

[4] For a discussion of mishap reporting, see Air Force Instruction 91-204, *Safety Investigation and Hazard Reporting*, Washington, D.C.: Department of the Air Force, updated July 30, 2019. In addition to reporting the three mishap events discussed here, the Air Force Safety Center also publishes data on Class B mishaps, total fatalities, and flying hours by aircraft MD. We note that rates of Class B mishaps and total fatalities tend to vary more from year to year. We leave investigation of these mishap events for future research.

[5] To supplement the Air Force Safety Center data, information on the year of first flight and whether the aircraft MD is a single- or multiengine aircraft was compiled from Air Force fact sheets and other open-source documents. This information is used in the statistical analysis presented on p. 7.

[6] See, for example, William R. Ercoline, Carita A. DeVilbiss, and Terrence J. Lyons, “Trends in U.S. Air Force Spatial Disorientation Accidents: 1958–1992,” *Proceedings of SPIE’s International Symposium on Optical Engineering and Photonics in Aerospace Sensing*, Vol. 2218, June 10, 1994; and Liam P. Sarsfield, William Stanley, Cynthia C. Lebow, Emile Ettedgui, and Garth Henning, *Safety in the Skies: Personnel and Parties in NTSB Aviation Accident Investigations-Master Volume*, Santa Monica, Calif.: RAND Corporation, MR-1122/1-ICJ, 2000.

[7] A three-year trailing average (e.g., average of years *t*, *t*-1, and *t*-2) was applied to smooth out year-to-year fluctuations that make identification of longer-term trends difficult.

[8] Ercoline DeVilbiss, and Lyons (1994) report a decline in Class A mishaps for U.S. Air Force aircraft from 5.36 per 100,000 flying hours during the 1958–1972 period to 2.22 per 100,000 flying hours over the 1972–1992 period. They further note, however, that the subset of Class A mishaps associated with spatial disorientation over that period remained relatively constant.

[9] The improvement in mishap rates over time for military aircraft has been noted in other studies. For example, the U.S. Government Accountability Office found in 1996 that the Class A aviation mishap rate had improved significantly over the previous two decades for all three military Services (U.S. Government Accountability Office, *Military Aircraft Safety: Significant Improvements Since 1975*, Washington, D.C., GAO/NSIAD-96-69BR, February 1, 1996).

[10] For example, the F-16 System Program Office indicated at the end of 2019 that a new Automatic Ground Collision Avoidance System had saved eight aircraft and nine lives to date (Rachel S. Cohen, “USAF Sees No Widespread Safety Issues with F-16s Despite Recent Crashes,” *Air Force Magazine*, November 6, 2019).

[11] The U.S. Government Accountability Office has noted specific efforts by the U.S. Air Force and other military services to (1) improve the tracking and follow-through of safety recommendations (e.g., establishment of centralized database of open recommendations and production of status reports), (2) enhance the dissemination of safety information (e.g., changes to manuals and procedures, publication of safety newsletters and safety messages), and (3) undertake special initiatives targeted at improving aviation safety (e.g., convening of special panels to review specific aviation safety incidents or issues) (U.S. Government Accountability Office, 1996).

[12] If the average mishap rate shown in Table 2 for an aircraft type is lower (higher) than the previous decade, the *t*-test indicates whether the decline (increase) is statistically significant.

[13] There is only one instance where a statistically significance increase in mishap rates was observed relative to the prior decade (shown in bold red text). In all other cases, a statistically significant change from one decade to the next reflected a decrease in a mishap rate (shown in bold blue text). The statistically significant increase occurred between the 1990s and 2000s for Class A mishaps for mobility aircraft. In this instance, the rate increased from an average of 0.3 to 0.7 Class A mishaps per 100,000 flying hours from the 1990s to 2000s. The Class A mishap rate for mobility aircraft subsequently declined to 0.5 per 100,000 flying hours during the 2010–2018 period.

[14] A negative binomial regression is similar to standard multiple regression except that the dependent variable is an observed count taking on nonnegative integers (e.g., 0, 1, 2, . . .) that is assumed to follow the negative binomial distribution. The negative binomial regression is a generalization of Poisson regression in that the variance of n_{it} need not equal to the mean μ_{it} made by the Poisson model (John P. Hoffmann, *Regression Models for Categorical, Count, and Related Variables: An Applied Approach*, Oakland, Calif.: University of California Press, 2016).

[15] In this specification, there will be different α_i parameters estimated for each MD. In the case of the Class A mishap and destroyed aircraft regressions, there will be 55 different parameters estimated—one coefficient for each of the MDs shown in Table 1. For the pilot fatality regression, we exclude the three RPA aircraft, so 52 α_i parameters are estimated. For readability, we do not report the α_i parameter estimates in our regression coefficient tables, although we note when they are included in the regression.

[16] The θ parameter does not change the expected number of mishaps, but it does affect the estimated variance of the expected mishap counts. For a discussion on how to interpret the θ parameter, see Hoffmann, 2016.

[17] In sensitivity analysis, we reran the regressions, treating flying hours as an offset variable with fixed coefficient equal to 1. This restriction did not change the statistical significance or sign of any statistically significant variables in the six regressions shown in Table 3.

[18] The point at which mishap rates start to increase with design age can be calculated as $-\gamma/\eta$. Given the coefficient estimates for Class A mishaps, that point occurs at 86 [= 0.1206 + 0.0014] and 94 [= 0.1032/0.0011] years in specifications 1 and 2, respectively. The destroyed aircraft rate is not expected to increase with design age until design age reaches 108 [=/0.0009] and 131 [= 0.0783/0.0006] \years according to specifications 1 and 2, respectively. These change points are outside the age range at

which we observe any MDs flying today. The pilot fatality rate is not expected to ever increase with age according to both specifications 1 and 2 because the η parameter is estimated as 0 [$\eta = 0.0000$] in both regressions.

[19] Terence J. Lyons and William Nace, "Aircraft Crash Rates and Cumulative Hours: USAF Data for 25 Airframes, 1950–2006," A*viation, Space, and Environmental Medicine*, Vol. 78, No. 10, October 2007. Lyons and Nace found a negative relationship between Class A mishap rates and cumulative flying hours, supporting the notions that aircraft become less accident prone over time and with use. Their study further supports the finding that the risk of crashes declines (rather than increases) with aircraft age.

[20] For example, a fighter aircraft is 7.6 times [= *exp*(84.0698)/*exp*(82.046)] more likely than a mobility aircraft to experience a Class A mishap, all else equal.

[21] In an excursion, we found that single-engine versus multiengine aircraft tend to have a larger impact on Class A and destroyed aircraft rates when we limit our regression to include only fighter aircraft. Specifically, we found that multiengine fighters are 69 percent less likely to experience a Class A mishap [= *exp*(0.5270) – 1] and 63 percent less likely to be destroyed [= *exp*(0.4830) – 1] than single-engine fighters, all else equal. The effect of single-engine versus multiengine fighter aircraft was, however, not found to be statistically significant for pilot fatalities, consistent with the findings shown in Table 3, which pools data across all types of aircraft.

[22] However, other consequences of aging aircraft have been noted. For example, RAND research has noted an increase in maintenance cost and a reduction in availability with aircraft age in U.S. Air Force aircraft (see Raymond A. Pyles, *Aging Aircraft: USAF Workload and Material Consumption Life Cycle Patterns*, Santa Monica, Calif.: RAND Corporation, MR-1641-AF, 2003).

[23] The performance and systems redundancy of multiengine aircraft may offer certain safety advantages relative to single-engine aircraft. For example, many multiengine aircraft are capable of taking off, flying, and landing when one engine fails.

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About This Report

The aging of certain fleets and increasing complexity of newer military aircraft have led some in the U.S. government to worry that the U.S. Air Force's fleet is likely to be more prone to incidents that result in a loss of aircraft or, worse, life. These concerns were elevated following a March 15, 2018, HH-60 loss in Iraq that resulted in seven fatalities and a May 2, 2018, WC-130 loss in Savannah, Georgia, that resulted in nine fatalities and contributed to Congress establishing the National Commission on Military Aviation Safety as part of the 2019 National Defense Authorization Act.

To support the commission's work, RAND Project AIR FORCE researchers assembled and analyzed data on mishap rates published by the Air Force Safety Center for 55 different types of U.S. Air Force aircraft in operation from 1950 to 2018. The analysis focuses on three types of mishap events: Class A mishaps, pilot fatalities, and destroyed aircraft.

This report summarizes the findings of this analysis. It should be of interest to analysts and policymakers interested in trends in U.S. Air Force aircraft mishaps.

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