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Human Factors and Propulsion Failures in U.S. General Aviation Accidents: What a Decade of NTSB Findings Implies for Electric Training Aircraft

Jules Oliver Roa and Mehdy Emad Araim

Department of Civil and Geomatics Engineering, California State University, Fresno, 2320 E. San Ramon Ave., Fresno, CA 93740, USA

ABSTRACT

Battery-electric training aircraft are entering U.S. flight schools without the fuel, induction, ignition, exhaust and lubrication systems used in piston aircraft. The extent to which this architecture eliminates, changes or introduces accident mechanisms has not been assessed against recent accident data. Every U.S. 14 CFR Part 91 accident from 2015 through 2025 in the National Transportation Safety Board (NTSB) database (12,052 accidents, 2,038 fatal) was examined, counts were normalized by FAA survey hours, and the 10,970 accidents with coded findings for 2015–2024 were classified by human-factors and propulsion-related finding groups. The accident rate fell from 5.47 to 4.13 per 100,000 hours and the fatal-accident rate from 1.04 to 0.64. Poisson trends give declines of about 3% and 4% per year. Personnel findings appear in 79% of accidents and pilot aircraft-control findings in 53%, rising to 60% on instructional flights. A propulsion or fuel finding is present in 22% of accidents. An elimination-and-substitution screen shows that 8.3% of accidents carry a finding naming a component absent from an electric powertrain. A further 11.4% involve components that persist in electric form. Fuel exhaustion and starvation have energy-management counterparts, while internal engine failure has counterparts in motor and inverter failure, at rates not estimated here. The other four accidents in five, and most fatal accidents, involve aircraft control, decision making, weather and terrain, and they require continued attention to human factors regardless of propulsion type.

Keywords: General aviation safety, NTSB findings, Human factors, Electric aircraft, Flight training, Loss of engine power

INTRODUCTION

General aviation (GA) produces most of the accidents and fatalities in U.S. civil aviation, and flight training is one of its largest exposures. For fiscal year 2024, the Federal Aviation Administration (FAA) reported 0.68 fatal GA accidents per 100,000 flight hours, the lowest value since it began tracking the metric, with 195 fatal accidents and 337 fatalities (Federal Aviation Administration, 2025). That figure covers all general aviation operations on a fiscal-year basis against about 29 million hours, close to the survey's general aviation plus on-demand Part 135 total. It is not directly comparable

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with the calendar-year Part 91 rates on general aviation use hours reported below, although the two are of the same magnitude. Analyses based on the Human Factors Analysis and Classification System (HFACS) attribute most accidents in general and commercial aviation to skill-based, decision and perceptual errors of the pilot (Wiegmann and Shappell, 2003; Wiegmann et al., 2005), more often among less experienced pilots (Li et al., 2001; Boyd, 2017). Propulsion malfunction and fuel mismanagement form the second major family of causes and account for most of the loss-of-engine-power events that precede forced landings (National Transportation Safety Board, 2017; AOPA Air Safety Institute, 2024).

At the same time, the training fleet is beginning to change. The Pipistrel Velis Electro received the first type certificate for an electric airplane from the European Union Aviation Safety Agency in 2020 (European Union Aviation Safety Agency, 2025), and in 2024 the FAA granted an exemption that allows U.S. flight schools to operate it as a light-sport aircraft for flight training (Thurber, 2024). Electric trainers differ from the piston aircraft that dominate GA in ways that matter for accident causation. They have no fuel system, carburetor or fuel injection, magnetos, exhaust or oil system, and the motor has a single rotating assembly (Rendón et al., 2021). Energy, however, is limited. It is stored in a lithium-ion battery whose thermal behavior is a known hazard (Wang et al., 2012) and managed through a state-of-charge display rather than fuel gauges and a mixture control. Earlier work on urban air mobility, the pilot pipeline and electric aircraft adoption (Maxwell and Roa, 2021; Roa, 2022), together with broader assessments of all-electric aircraft (Schäfer et al., 2019), argued that these aircraft could lower training costs and ease the pilot pipeline. The safety argument, though, has so far rested on design reasoning rather than accident data.

This paper quantifies the distribution of human-factors and propulsion-related findings in U.S. GA accidents over the last decade and maps those findings onto failure mechanisms that battery-electric propulsion eliminates, replaces or retains. It asks how accident counts and rates, overall and for instructional flights, changed from 2015 to 2025; which coded findings appear most often in these accidents and in their fatal and instructional subsets; and what share of accidents involves a propulsion or fuel finding that an electric trainer would remove, replace with an analog, or leave unchanged. The analysis provides a data-based reference for flight schools, insurers and regulators preparing the safety case for electric training fleets.

DATA AND METHODS

Accident records come from the NTSB aviation accident database, bulk release of 1 October 2026 (National Transportation Safety Board, 2026). The study set comprises all events classified as accidents, located in the United States, with the aircraft operated under 14 CFR Part 91 and an event date between 1 January 2015 and 31 December 2025: 12,052 accidents involving 12,179 aircraft. For the 127 multi-aircraft events, only the first aircraft record was retained. Airplanes account for 88.5% of the accidents, single-engine aircraft for 87.6%, amateur-built aircraft for 15.9%, personal flying for 72.2% and instructional flying for 16.3%.

Causal information comes from the findings table, in which investigators code each condition in a hierarchical taxonomy of category (aircraft, personnel issues, environmental issues, organizational issues, not determined), subcategory, section, subsection and modifier, for example Aircraft–Aircraft power plant–Engine (reciprocating)–Reciprocating engine cylinder section–Failure. For reports completed through 2019, most findings also carry a flag with three states: cause, factor, or finding (a condition the investigator recorded but did not deem contributory). The NTSB phased the flag out by report-completion date beginning in 2019, and findings in reports completed after the transition are listed without it and are treated here as contributory (National Transportation Safety Board, 2026). Plain findings are 17% of the 2015–2018 findings, mostly environmental conditions. The primary series keeps cause, factor and unflagged findings and drops plain findings, yielding an average of 2.8 findings per accident both before and after the transition. The all-codes result is reported as a sensitivity check. Because investigations take time to close, 95% of the 2024 accidents carried findings at the release date, but only 75% of the 2024 fatal accidents and 65% of the 2025 accidents did. Open cases cluster among fatal and power-loss events. The causal analysis therefore uses 2015–2024 (10,970 accidents with findings, 1,849 fatal, 1,797 instructional), and 2025 counts are reported as preliminary.

Exposure comes from the FAA General Aviation and Part 135 Activity Survey for calendar year 2024, whose historical tables give hours flown by actual use for each year since 2013 (Federal Aviation Administration, 2026). The denominator is the general aviation use total, which excludes on-demand Part 135 hours but still includes a small volume of non-Part 91 activity such as agricultural and external-load work whose accidents are not in the numerator, so the Part 91 rates are biased slightly downward. Instructional rates use instructional hours from the same table. Trends in annual counts for 2015–2024 were tested with Poisson regression of the count on calendar year with the logarithm of hours as an offset, which yields a rate ratio per year. The all-accident, fatal and instructional counts were overdispersed (Pearson dispersion 2.7, 1.8 and 1.9 on 8 degrees of freedom), so their standard errors were multiplied by the square root of the dispersion (quasi-Poisson) and intervals were formed with the normal critical value. The instructional-fatal series was not overdispersed (0.6) and its interval is unscaled. Survey hours were treated as fixed, so the intervals do not include the sampling error of the exposure estimates, about 1.4% for total hours and larger for instructional hours (Federal Aviation Administration, 2026).

Propulsion and fuel findings were grouped by section, subsection and modifier of the taxonomy into sixteen groups, listed with the results below. Each group was assigned one of three outcomes for a battery-electric trainer by comparing the failed component or condition with the certified architecture of the Velis Electro and the design provisions of the applicable electric-propulsion standards (ASTM International, 2021; European Union Aviation Safety Agency, 2021). A group is eliminated when the component does not exist on an electric aircraft and has no functional equivalent: carburetor, fuel injection and engine fuel pump; ignition; exhaust, turbocharger, starting and accessory systems; airframe fuel storage, lines, valves, filters, caps and vents;

fuel contamination and wrong fuel; and carburetor icing conditions. A group is analog when the function persists in a different form: internal engine failure becomes motor or inverter failure, the oil system becomes a cooling system, fuel quantity indication and fuel pumps become charge indication and high-voltage distribution, and fuel exhaustion, starvation and fuel planning become energy-state misjudgment and charge planning. A group is retained when the component is unchanged or expanded: propeller, engine controls and electrical power system. Power-plant and fuel-system findings whose modifier is unknown or not determined form a separate undetermined group, excluded from the unions, because since 2020 the NTSB has coded unexplained engine failures this way rather than under the not-determined category. The screen counts accidents with at least one contributory finding that names a component or condition absent from an electric powertrain. The screen measures the proportion of accidents containing such findings; it does not estimate accidents prevented or model the failure probabilities of replacement components or newly introduced hazards. Power-loss events were identified from the sequence-of-events table as any occurrence coded loss of engine power (total or partial), fuel exhaustion, fuel starvation, fuel related, fuel contamination or powerplant system or component malfunction. The NTSB codes these as separate occurrences, and the loss-of-engine-power codes alone omit about 821 accidents, most of them fuel exhaustion and starvation events coded since 2019. Each power-loss accident was classified by its contributory findings, with overlap allowed, as fuel exhaustion, starvation or planning; carburetor icing; fuel-system component failure or contamination; determined mechanical engine failure; or undetermined (a finding in the not-determined category, or a power-plant or fuel-system finding with an unknown modifier). For the figure, each accident is assigned to one class by precedence in that order.

RESULTS

Accident Counts, Rates and Trends

Table 1 and Figure 1 summarize the decade. Annual Part 91 accidents fell from 1,126 in 2015 to 1,024 in 2024 while GA hours rose from 20.6 to 24.8 million, so the accident rate declined from 5.47 to 4.13 per 100,000 hours. Fatal accidents fell from 215 to 159 and the fatal-accident rate from 1.04 to 0.64. The Poisson trend gives a rate ratio of 0.970 per year for all accidents (quasi-Poisson 95% CI 0.960–0.980), 0.962 for fatal accidents (0.942–0.982) and 0.953 for instructional accidents (0.932–0.974), or declines of about 3%, 4% and 5% per year. The instructional-fatal trend (0.955, 0.906–1.007) is not significant. Instructional exposure grew by 75% (against 21% for all GA hours) and its accident rate fell from 3.03 to 2.25 per 100,000 hours. Because surveyed instructional hours jumped by 29% in 2023, the trend over 2015–2022 alone is weaker and only marginally significant (0.970, 0.940–1.000). The 2025 figures (1,025 accidents, 149 fatal) are preliminary. The fatal count is near final, but the total is likely to rise as late reports are filed.

Table 1: Part 91 accidents in the United States, 2015–2025, hours flown (FAA survey, general aviation use and instructional use) and rates per 100,000 hours; instructional rates use instructional hours. *2025 preliminary; survey hours not yet published.

Year	Accidents	Fatal	Instructional	Instr. Fatal	GA Hours (M)	Instr. Hours (M)	Rate	Fatal Rate	Instr. Rate
2015	1,126	215	141	14	20.6	4.65	5.47	1.04	3.03
2016	1,171	184	180	17	21.3	4.89	5.49	0.86	3.68
2017	1,140	187	192	20	21.7	5.07	5.25	0.86	3.78
2018	1,194	203	199	15	21.7	5.68	5.51	0.94	3.50
2019	1,139	215	189	14	21.8	6.42	5.22	0.99	2.95
2020	1,007	179	151	12	19.5	5.50	5.18	0.92	2.75
2021	1,064	191	180	17	22.0	6.12	4.84	0.87	2.94
2022	1,109	183	188	20	22.5	6.38	4.92	0.81	2.95
2023	1,053	173	197	21	24.9	8.26	4.22	0.69	2.39
2024	1,024	159	183	15	24.8	8.14	4.13	0.64	2.25
2025*	1,025	149	167	12	—	—	—	—	—

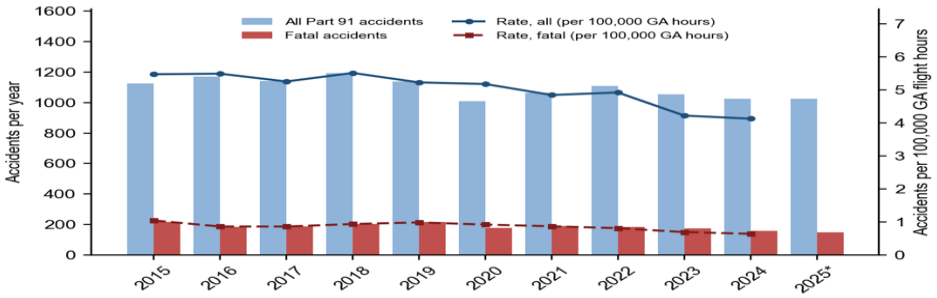


Figure 1: Annual Part 91 accidents and fatal accidents (bars) and rates per 100,000 general aviation flight hours (lines), 2015–2025 (rates through 2024; 2025 counts preliminary).

Causal Structure of the Accidents

Table 2 gives the share of accidents in 2015–2024 with at least one contributory finding in each category and in the most frequent sections. Personnel findings appear in 79.4% of all accidents and 87.1% of fatal accidents. Aircraft findings appear in 81.8%, but most of them describe the outcome of the pilot's handling rather than a mechanical failure. The single largest aircraft section, performance and control parameters (airspeed, angle of attack, descent rate, directional control), is present in 52.6% of accidents and accompanies a pilot aircraft-control finding in 80% of those cases. The pilot's use of equipment and aircraft control is the most frequent human-factors section (53.1% of all accidents, 60.4% of instructional accidents), followed by information processing and decision making (16.0%),

incorrect or delayed action (12.4%) and attention and monitoring (7.2%). Fatal accidents look different: decision making (28.9% against 16.0% of all accidents), ceiling, visibility and precipitation (13.9% against 2.9%), perception, orientation and illusion (11.5% against 2.5%), experience and qualifications (8.3% against 2.5%) and impairment (6.9% against 1.4%) are each 1.8 to 4.9 times as frequent among fatal accidents as among all accidents, and 2 to 23 times as frequent as among non-fatal accidents. Instructional accidents, by contrast, are dominated by aircraft-control and action findings (23.2% for action, almost twice the overall value of 12.4%) and by landing-phase events (42% of instructional defining events against 35% overall), led by loss of control on the ground and hard landings. Across the decade the personnel share moved within about five percentage points and the aircraft share within about seven, while the environmental share rose from 17%–24% in 2015–2018 to 32%–37% from 2019 and the not-determined share fell from 12% to 3%. Both shifts coincide with the change in coding practice and should not be read as changes in the fleet or the weather.

Table 2: Share of Part 91 accidents (2015–2024, N = 10,970) with at least one contributory finding in each category or section; fatal (N = 1,849), non-fatal (N = 9,121) and instructional (N = 1,797) subsets.

Category / Section	Accidents	% of all	% of Fatal	% of Non-Fatal	% of Instructional
Personnel issues (any)	8,710	79.4%	87.1%	77.8%	80.6%
Pilot use of equipment/aircraft control	5,826	53.1%	57.0%	52.3%	60.4%
Information processing/decision	1,757	16.0%	28.9%	13.4%	11.4%
Action (incorrect/delayed)	1,364	12.4%	11.6%	12.6%	23.2%
Attention/monitoring	790	7.2%	8.5%	6.9%	11.0%
Planning/preparation (incl. fuel planning)	563	5.1%	6.5%	4.8%	2.5%
Perception/orientation/illusion	279	2.5%	11.5%	0.7%	0.8%
Experience/qualifications	277	2.5%	8.3%	1.3%	1.6%
Impairment/incapacitation	159	1.4%	6.9%	0.4%	0.3%
Aircraft (any)	8,971	81.8%	76.5%	82.9%	83.2%
Aircraft performance/control parameters	5,768	52.6%	58.4%	51.4%	58.9%
Environmental issues (any)	3,161	28.8%	33.4%	27.9%	22.1%
Wind	906	8.3%	3.3%	9.3%	5.8%
Ceiling/visibility/precipitation	313	2.9%	13.9%	0.6%	0.3%
Not determined	930	8.5%	13.8%	7.4%	6.2%

Propulsion and Fuel Findings

Table 3 gives the propulsion and fuel groups. A propulsion or fuel finding (excluding the propeller, the electrical system and turbine engines) is present in 2,406 accidents, 21.9% of the total, in 18.2% of fatal accidents and in 17.6% of instructional accidents. The largest group is fuel exhaustion and starvation

(750 accidents, 6.8%), coded under fluids-fuel with any modifier other than fluid condition, fluid type or unknown. Fluid level (424 findings) and fluid management (330) account for 670 of these accidents, and the remaining 80 carry inspection, servicing, incorrect-use or unspecified modifiers. Fuel contamination (114 findings) and wrong fuel (7) are a separate, much smaller group (1.1%). Other prominent groups include determined internal engine failures, pilot fuel planning and airframe fuel-system components. Power-plant or fuel-system findings whose cause could not be determined appear in 2.3% of accidents.

A power-loss occurrence is coded in the sequence of events of 2,730 accidents (24.9% of the base), including 374 fatal and 347 instructional accidents. Of these, 750 (27%) carry a fuel exhaustion, starvation or planning finding, 551 (20%) a fuel-system component or contamination finding, 217 (8%) carburetor icing, 746 (27%) a determined mechanical engine finding and 619 (23%) an undetermined finding; 336 accidents carry findings in more than one class and 196 carry none of them (Figure 2). The share of accidents with a power-loss occurrence moved between 22% and 28% a year with no clear trend. Occurrences coded specifically as loss of engine power fell from 256 in 2015 to 102 in 2024 while occurrences coded as fuel exhaustion or starvation without a loss-of-power code rose from 55 to 104, so the apparent decline in loss-of-power events reflects a change in occurrence coding, not fleet reliability, and is not treated as evidence of a trend.

Table 3: Propulsion and fuel finding groups, 2015–2024 (contributory findings): accidents with at least one finding in the group, shares of all, fatal and instructional accidents, and outcome of the group on a battery-electric trainer.

Finding Group	Accidents	% of all	% of Fatal	% of Instructional	Electric Trainer
Fuel exhaustion and starvation (fluid level/management)	750	6.8%	5.0%	4.5%	Analog (energy state)
Reciprocating engine internal failure (determined)	526	4.8%	4.0%	4.3%	Analog (motor, inverter)
Fuel planning (pilot)	339	3.1%	1.8%	1.5%	Analog (charge planning)
Airframe fuel storage, lines, valves, filters, caps, vents	278	2.5%	3.0%	1.9%	Eliminated
Carburetor icing conditions (environment)	225	2.1%	1.3%	2.1%	Eliminated
Carburetor, fuel injection, engine fuel pump	195	1.8%	1.5%	1.9%	Eliminated
Fuel contamination and wrong fuel (fluid condition/type)	121	1.1%	0.9%	1.1%	Eliminated
Power plant, general/ unspecified (determined)	103	0.9%	1.0%	0.9%	Analog
Ignition system (magnetos, plugs, wiring)	101	0.9%	0.9%	0.8%	Eliminated

(Continued)

Table 3: Continued.

Finding Group	Accidents	% of all	% of Fatal	% of Instructional	Electric Trainer
Exhaust, turbocharger, starting, accessories	75	0.7%	1.1%	0.4%	Eliminated
Airframe fuel quantity indication and fuel pumps	62	0.6%	0.6%	0.5%	Analog (charge indication)
Engine controls (power lever, mixture)	57	0.5%	0.2%	0.6%	Retained
Engine oil system	25	0.2%	0.2%	0.2%	Analog (cooling)
Propeller/rotor system	161	1.5%	2.1%	1.7%	Retained
Electrical power system	90	0.8%	0.6%	0.6%	Retained (expanded)
Undetermined power-plant or fuel-system finding	251	2.3%	2.2%	1.5%	Undetermined
Any propulsion or fuel finding (excl. propeller, electrical, turbine)	2,406	21.9%	18.2%	17.6%	—
Union of eliminated groups	911	8.3%	7.7%	7.4%	—
Union of analog groups	1,425	13.0%	10.4%	9.9%	—
Union of eliminated and analog groups	2,159	19.7%	16.6%	16.0%	—
Eliminated, lenient (adds oil system, fuel indication and pumps)	979	8.9%	8.3%	8.1%	—

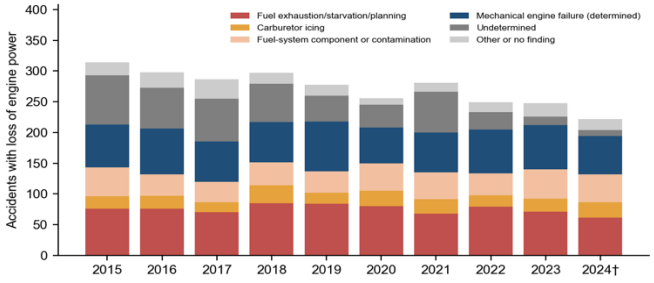


Figure 2: Accidents with a power-loss occurrence by year and by the class of contributory finding (precedence: fuel exhaustion/starvation/planning, carburetor icing, fuel-system component, mechanical, undetermined), 2015–2024; †2024 investigations partly open.

Elimination-and-Substitution Screen

The last five rows of Table 3 apply the screen. Groups with no electric counterpart account for 911 accidents, 8.3% of all accidents, 7.7% of fatal

accidents and 7.4% of instructional accidents. The lenient classification, which also counts the oil system, fuel quantity indication and fuel pumps as eliminated, gives 8.9%, and using all coded findings instead of contributory findings gives 8.7%. Groups that an electric trainer replaces with an analog account for 1,425 accidents (13.0%, 10.4% of fatal, 9.9% of instructional). Because 177 accidents carry findings in both sets, the two together cover 2,159 accidents, 19.7% of the base and 16.6% of fatal accidents, so the analog groups add 11.4% beyond the eliminated groups. The eliminated-group and combined eliminated-and-analog shares, respectively, are slightly higher in the fleets an electric trainer would replace: 8.8% and 21.1% among the 7,164 accidents of certified single-engine airplanes, and 8.9% and 22.6% among the 1,973 accidents of common trainer types (Cessna 150, 152 and 172, Piper PA-28, Diamond DA20 and DA40, Cirrus SR20). Among the 827 instructional accidents of those types they are 6.8% and 16.3%. If every undetermined power-plant finding (2.3%) were of an eliminated type, the eliminated share would rise to 10.3%. If the 476 power-loss accidents (4.3%) whose only causal finding is undetermined, mostly coded as not determined before 2020, were also of that type, it would reach about 13%. Under these alternative assumptions about undetermined cases, the eliminated-group share ranges from approximately 8% to 13%.

Of the remaining four in five accidents, about one in ten still involves propulsion through undetermined findings, retained components such as the propeller, or power-loss occurrences without a determined propulsion finding. The rest involve aircraft handling, decision making, weather and terrain, or carry no determined finding (8.5%). These risks remain relevant to electric aircraft.

The 765 accidents (7.0%) with exhaustion, starvation or fuel-planning findings mostly describe pilot decisions rather than component failures, and comparable energy-management risks remain unless training and cockpit design address them.

The mechanical reliability gain is plausible but not yet quantified. Determined internal failures of reciprocating engines (4.8% of accidents) give way to motor and inverter failures whose in-service rates for certified aircraft are not yet public, and batteries introduce thermal-runaway and high-voltage hazards (Wang et al., 2012; European Union Aviation Safety Agency, 2021).

The instructional subset matters because flight training is where electric aircraft fly first. Propulsion and fuel findings are less frequent on instructional flights (17.6%) than overall (21.9%), carburetor icing is as frequent, and aircraft-control and action findings are much more frequent. The eliminated finding groups therefore occur in a smaller proportion of instructional accidents than of Part 91 accidents overall, while the risks of training itself (directional control on landing, stall and loss of control in the pattern, hard landings and runway excursions) remain. The short endurance of current electric trainers, about 50 minutes plus reserve (European Union Aviation Safety Agency, 2025), also concentrates instruction in the traffic pattern, where these events occur.

DISCUSSION

The elimination-and-substitution screen supports a measured safety argument for electric training aircraft. These results agree with the long-standing finding that mechanical failure is a secondary cause of GA accidents compared with pilot performance (Li et al., 2001; Wiegmann et al., 2005; Boyd, 2017). Approximately 28% of accidents have some propulsion link, although this proportion does not establish the reduction achievable through a change in propulsion.

For flight schools and curricula, the implications are direct. Energy-state management should be taught as rigorously as fuel management, with explicit decision thresholds for departure charge, diversion energy and pattern work. Schools should teach and drill procedures for battery thermal events, which have no analog in the piston syllabus, and report electric-specific occurrences to voluntary safety programs. Whatever the aircraft, the dominant risks of training remain the focus: aircraft control on takeoff and landing, and decision making in the pattern.

For regulators and insurers, the tables above are a baseline against which the electric fleet can be judged once it has flown enough hours, preferably in instructional flying, where the 2024 rate per hour was 46% below the overall rate.

The data have limitations. At the release date, coded findings were available for 95% of 2024 accidents and 75% of 2024 fatal accidents; incomplete investigations may therefore affect the findings distribution for the most recent year. The NTSB phased out the cause-or-factor flag from 2019 and began coding unexplained engine failures under the power-plant sections, so comparisons of individual groups across 2020 are affected by coding practice even after plain findings are removed. Exposure hours come from a sample survey (standard error about 1.4% for total hours, more for use categories), purpose-of-flight codes depend on investigator judgment, and no exposure data exist yet for certified electric aircraft.

CONCLUSION

Over the study period (2015-2024), Part 91 accident and fatal–accident rates declined by approximately 3% and 4% per year, respectively, while personnel findings were present in 79.4% of accidents. Propulsion and fuel findings are present in about 22% of Part 91 accidents and 18% of instructional accidents. Finding groups associated with components absent from battery-electric trainers occur in about 8% of accidents; groups with electric analogs occur in a further 11%, for a combined 20%. For the other four accidents in five, and the great majority of fatal accidents, changing propulsion alone does not resolve the underlying safety concerns; continued attention to aircraft control, decision making and weather judgment remains essential. The safety case for electric training aircraft should rest on these numbers and on the new hazards the technology brings.

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