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An Examination of Commercial Aviation Accidents and Incidents Related to Integrated Vehicle Health Management

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Abstract

The Integrated Vehicle Health Management (IVHM) Project is one of the four projects within the National Aeronautics and Space Administration's (NASA) Aviation Safety Program (AvSafe). The IVHM Project conducts research to develop validated tools and technologies for automated detection, diagnosis, and prognosis that enable mitigation of adverse events during flight. Adverse events include those that arise from system, subsystem, or component failure, faults, and malfunctions due to damage, degradation, or environmental hazards that occur during flight. Determining the causal factors and adverse events related to IVHM technologies will help in the formulation of research requirements and establish a list of example adverse conditions against which IVHM technologies can be evaluated. This paper documents the results of an examination of the most recent statistical/prognostic accident and incident data that is available from the Aviation Safety Information Analysis and Sharing (ASIAS) System to determine the causal factors of system/component failures and/or malfunctions in U.S. commercial aviation accidents and incidents.

Nomenclature

AIDS	Accident/Incident Data System
AvSafe	Aviation Safety Program
ASIAS	Aviation Safety Information Analysis and Sharing
ASRS	Aviation Safety Reporting System
FAA	Federal Aviation Administration
FMC	Flight Management Computer
FMS	Flight Management System
GPWS	Ground Proximity Warning System
NTSB	National Transportation Safety Board
ILS	Instrument Landing System
ILS	Inertial Navigation System
IVHM	Integrated Vehicle Health Management
NASA	National Aeronautics and Space Administration
JPDO	Joint Planning and Development Office
SCFM	System/Component Failure/Malfunction
TCAS	Traffic Collision Avoidance System

TM	Technical Memorandum
VHF	Very High Frequency
VOR	VHF Omni-directional Radio

Introduction

The need for integrated vehicle health management research for the purpose of improving aviation safety has been affirmed by leaders in the aviation community. The "Decadal Survey of Civil Aeronautics: Foundation for the Future", (Ref. 1) cites integrated vehicle health management as being one of a group of the highest research and technology challenges for NASA aeronautics. The Joint Planning and Development Office's "National Aviation Safety Strategic Plan" which defines national goals, objectives, and strategies for aviation safety improvements cites the improvement of vehicle systems health management as one of its recommended research strategies. (Ref. 2) The National Institute of Aerospace's "Aviation Plan for American Leadership" report (Ref. 3) which identifies research and technology challenges for improving aviation safety recommends research in vehicle "health reliability and management". Because of this well documented need for IVHM research, NASA initiated the IVHM Project.

NASA's IVHM Project conducts research to develop validated tools and technologies for automated detection, diagnosis, and prognosis that enable mitigation of adverse events during flight. (Ref. 4) Adverse events include those that arise from system, subsystem, or component failures, faults, and malfunctions due to damage, degradation, or environmental hazards that occur during flight. Determining the causal factors and adverse events that drive the need for IVHM technologies will assist in the formulation of research requirements. With limited funding available for IVHM research, it is important to identify those research areas that will have the most impact in addressing IVHM related causal factors and adverse events. The purpose of this study was to review statistical data to interpret and extract information about causal factors in aircraft incidents and accidents which are related to key research areas in the IVHM Project.

Technical Approach

Two separate analyses are presented in this paper. The first analysis examines the publicly available National Transportation Safety Board (NTSB) and Federal Aviation Administration (FAA) accident and incident data. The second analysis is an examination of the Aviation Safety Reporting System (ASRS) incident reports. All of these data sources can be accessed using the Aviation Safety Information Analysis and Sharing (ASIAS) System. (Ref. 5) The focus of both analyses was the determination of the causal factors of incidents and accidents associated with failures and/or malfunctions associated with the various systems and/or components of commercial aircraft.

In these analyses, "commercial" is defined per the FAA's Federal Aviation Regulation (FAR) 121, Scheduled Part 135, and Non-Scheduled Part 135 flight operations (Ref. 6). Part 121 operations applies to major airlines and cargo carriers that fly large transport-category aircraft while part 135 applies to commercial aircraft air carriers commonly referred to as commuter airlines. Prior to March 1997, Part 121 operations included aircraft with 30 or more seats. In March 1997, the definition of Part 121 operations changed and now includes those aircraft with ten or more seats. Scheduled operation refers to "any common carriage passenger-carrying operation for compensation or hire conducted by an air carrier or commercial operator for which the certificate holder or its representative offers in advance the departure location, departure time, and arrival location. A non-scheduled operation refers to "any operation for compensation or hire in which the departure time, departure location, and arrival location are specifically negotiated with the customer".

Non-impact fires were included as a type of malfunction, even when the cause of the fire was not specified.

The safety risk is based on both accidents and incidents. Accidents and incidents have been defined per the NTSB definition as follows: (Ref. 7)

Accident—An occurrence associated with the operation of an aircraft, which takes place between the time any person boards the aircraft with the intention of flight and all such persons have disembarked, and in which any person suffers death or serious injury, or in which the aircraft receives substantial damage.
Incident—An occurrence other than an accident, associated with the operation of an aircraft, which affects or could affect the safety of operations.

NTSB and FAA Accident/Incident Data Analyses

These analyses looked at the safety risk associated with failures or malfunctions of various systems or components of commercial aircraft during the period 1988 to 2003. The source for accident data was the NTSB Aviation Accident and Incident Data System, while the source for incident data was the FAA's Accident/Incident Data System (AIDS). Although both databases contain accident and incident data, the FAA has primary investigative responsibility for incidents and the NTSB is the authority for accident investigation. The NTSB database contains information collected during an NTSB investigation of an accident or incident involving civil aircraft within the United States, its territories and possessions, and in international waters. AIDS contains data records for general aviation and commercial air carrier incidents since 1978. The information contained in AIDS is gathered from several sources including incident reports on FAA Form 8020-5. Data for total flight hours per year were obtained from tables published by the NTSB, which are based on data from the FAA. The abbreviation SCFM will be used throughout this paper to mean System/Component Failure/Malfunctions.

TABLE 1.—SUMMARY OF SCFM EVENTS BY OPERATION CATEGORY

Type of events	Operation			
	Part 121	Scheduled Part 135	Non-Scheduled Part 135	Part 121 and 135 combined
Total flight hours	232,868,640	25,050,928	46,350,000	304,269,568
Total accidents	600	213	1070	1883
Accidents with SCFM	109 (18%)	33 (16%)	228 (21%)	370 (20%)
SCFM accidents per million flight hours	0.47	1.32	4.92	1.22
Fatal accidents	60 (10%)	49 (23%)	278 (26%)	387 (21%)
Fatal accidents with SCFM	16 (27%)	5 (10%)	47 (17%)	68 (18%)
Total fatalities	2151	328	664	3143
Fatalities in accidents with SCFM	777 (36%)	52 (16%)	109 (16%)	938 (30%)
Total incidents	7497	2218	2081	11,796
Incidents with SCFM	4957 (66%)	1557 (70%)	1218 (58%)	7,732 (66%)
SCFM incidents per million flight hours	21.29	62.15	26.28	25.4

A summary of the SCFM events can be found in Table 1. For the three operational categories examined, between 16 percent and 21 percent of commercial accidents during the 1988-2003 period involved a SCFM. Scheduled Part 135 accidents had the lowest proportion of accidents (16 percent), fatal accidents (10 percent) and total fatalities (328) associated with SCFM. In Part 121 flights, 18 percent of the accidents, 27 percent of the fatal accidents and 36 percent of fatalities were associated with SCFM. In Non-Scheduled Part 135 flights, 21 percent of the accidents, 17 percent of the fatal accidents and 16 percent of the fatalities were associated with SCFM. There is at least one fatality in 18 percent of all SCFM accidents.

Between 58 and 70 percent of all incidents were caused by SCFM of system or component. Despite having the lowest percentage of SCFM accidents among the three flight operation categories, Scheduled Part 135 flights had the highest percentage of SCFM incidents. Non-Scheduled Part 135 flights had the highest percentage of accidents and the lowest percentage of incidents related to SCFM.

In Part 121 flights, 21 SCFM occurred for each one million flight hours; the rate was even higher among part 135 flights.

For each accident and incident, the system affected by the SCFM was determined (Tables 2 and 3). In some events multiple systems were affected, and in these cases the first system affected was selected. For example, if an electrical malfunction preceded an engine fire, that event was categorized under Electrical. A large percentage of accidents with SCFM occurred due to failures or malfunctions in the engine system (33 to 49 percent) and landing gear system (21 to 30 percent). A large percentage of incidents with SCFM occur due to failures in the engine system (28 to 31 percent) and landing gear system (20 to 46 percent).

TABLE 2.—ACCIDENTS WITH A SYSTEM AFFECTED BY SCFM BY OPERATION CATEGORY

System	Operation category			
	Part 121	Scheduled Part 135	Non-scheduled Part 135	Part 121 and 135 combined
Total accidents	109	33	228	370
Engine	36 (33%)	12 (36%)	111 (49%)	159 (43%)
Landing gear	23 (21%)	10 (30%)	64 (28%)	97 (26%)
Flight control	10 (9%)	3 (9%)	9 (4%)	22 (6%)
Electrical	8 (7%)	1 (3%)	12 (5%)	21 (6%)
Fuel	4 (4%)	3 (9%)	13 (6%)	20 (5%)
Hydraulic	9 (8%)	2 (6%)	7 (3%)	18 (5%)
Structure	5 (5%)	1 (3%)	7 (3%)	13 (4%)
Other	8 (7%)	1 (3%)	4 (2%)	13 (4%)
Instrumentation/ communication/ navigation	5 (5%)	0 (0%)	0 (0%)	5 (1%)
Unknown	1 (1%)	0 (0%)	1 (0%)	2 (0%)

TABLE 3.—INCIDENTS WITH A SYSTEM AFFECTED BY SCFM BY OPERATION CATEGORY

System	Operation category			
	Part 121	Scheduled Part 135	Non-scheduled Part 135	Part 121 and 135 combined
Total incidents	4957	1557	1218	7732
Engine	1384 (28%)	486 (31%)	349 (29%)	2219 (29%)
Landing gear	990 (20%)	509 (33%)	558 (46%)	2057 (27%)
Other	615 (12%)	135 (9%)	47 (4%)	797 (10%)
Hydraulic	414 (8%)	57 (4%)	45 (4%)	516 (7%)
Flight control	431 (9%)	43 (3%)	28 (2%)	502 (6%)
Fuel	215 (4%)	80 (5%)	54 (4%)	349 (4%)
Structure	214 (4%)	80 (5%)	49 (4.0%)	343 (4%)
Comfort systems	246 (5%)	54 (4%)	20 (2%)	320 (4%)
Electrical	191 (4%)	64 (4%)	47 (4%)	302 (4%)
Pressurization	174 (4%)	15 (1%)	8 (1%)	197 (2%)
Instrumentation/ communication/ navigation	83 (2%)	34 (2%)	13 (1%)	130 (2%)

The NTSB database includes causal factors for each accident. The SCFM accidents presented in Table 2 were further grouped into four system sub-categories: engine or fuel, flight control or structural, landing gear or hydraulic, and other. The most frequent causal factors of the SCFM accidents that are linked to these four system sub-categories are presented in Tables 4 though 6. The entire list of causal factors is too extensive for presentation in this paper. Some of the causal factors specify the problem with the component (corroded, fractured, separated, etc.) and others address errors by individuals (maintenance personnel) or groups of people (manufacturer, the company or operator) or regulatory deficiencies (the FAA). Most events have more than one causal factor. Each table includes the number of accidents within the particular group of systems; the percentages given are based on the number of accidents, not on the number of causal factors. The entire listing of causes and failures can be found in the NASA Technical Memorandum (TM): Causal Factors and Adverse Events of Aviation Accidents and Incidents Related to Integrated Vehicle Health Management (Ref. 8).

Of all the engine or fuel SCFM (Table 4) in commercial aircraft, 38 percent were related to maintenance errors. Some part of the engine or fuel system was said to have failed in 35 percent of the accidents and fatigue was noted in 23 percent of the accidents.

Maintenance errors were involved in 46 percent of flight control or structural SCFM in commercial aircraft accidents (Table 5). Component failure was cited in 29 percent of the accidents. In 23 percent of the accidents a component separated.

TABLE 4.—THE MOST FREQUENT CAUSES OF ENGINE OR FUEL SCFM ACCIDENTS BY OPERATION CATEGORY

Cause of failure/malfunction	Operation category			
	Part 121	Scheduled Part 135	Non-Scheduled Part 135	Part 121 and 135 combined
Total engine or fuel SCFM accidents	40	15	124	179
Maintenance related	17 (42%)	3 (20%)	49 (40%)	69 (38%)
Component failure	18 (45%)	5 (33%)	39 (31%)	62 (35%)
Component fatigue	8 (20%)	3 (20%)	30 (24%)	41 (23%)
Component separated	6 (15%)	3 (20%)	16 (13%)	25 (14%)
Component fractured	3 (8%)	1 (7%)	16 (13%)	20 (11%)
Manufacturing/Design	9 (22%)	3 (20%)	8 (6%)	20 (11%)
Component disconnected	3 (6%)	1 (7%)	15 (12%)	19 (11%)
Oil deprivation	1 (2%)	1 (7%)	13 (10%)	15 (8%)

TABLE 5.—THE MOST FREQUENT CAUSES OF FLIGHT CONTROL OR STRUCTURAL SCFM EVENTS BY OPERATION CATEGORY

Cause of failure/malfunction	Operation category			
	Part 121	Scheduled Part 135	Non-Scheduled Part 135	Part 121 and 135 combined
Total flight control or structural SCFM accidents	15	4	16	35
Maintenance related	8 (53%)	2 (50%)	6 (38%)	16 (46%)
Component failure	3 (20%)	2 (50%)	5 (31%)	10 (29%)
Component separated	4 (27%)	1 (25%)	3 (19%)	8 (23%)
Manufacturing/Design	6 (40%)	0 (0%)	1 (6%)	7 (20%)
Component jammed	2 (13%)	1 (25%)	4 (25%)	7 (20%)
Component inoperative	2 (13%)	0 (0%)	3 (19%)	5 (14%)

Maintenance errors were involved in 28 percent of landing gear or hydraulic system SCFM commercial accidents (Table 6). A component was said to have failed in 48 percent of the accidents. A component showed fatigue in 18 percent of the accidents and there was a loss of hydraulic fluid in 15 percent of the accidents.

Table 7 shows the most frequent causes of SCFM accidents in the other category. Maintenance errors were cited in 32 percent of the accidents, electrical failure was involved in 17 percent of the accidents and 15 percent of the accidents cited wire chafing and arcing as a cause.

Of interest is that the most frequent causal factors cited were maintenance errors in 35 percent of the SCFM accidents, (Table 8), followed by component failure in 34 percent of the accidents, and component fatigue in 17 percent of accidents.

TABLE 6.—THE MOST FREQUENT CAUSES OF LANDING GEAR OR HYDRAULIC SCFM EVENTS BY OPERATION CATEGORY

Cause of failure/Malfunction	Operation category			
	Part 121	Scheduled Part 135	Non-Scheduled Part 135	Part 121 and 135 Combined
Total landing gear or Hydraulic System SCFM accidents	32	12	71	115
Component failure	18 (56%)	3 (25%)	34 (48%)	55 (48%)
Maintenance related	8 (25%)	4 (33%)	20 (28%)	32 (28%)
Component fatigue	7 (22%)	2 (17%)	12 (17%)	21 (18%)
Hydraulic fluid loss	8 (25%)	3 (25%)	6 (8%)	17 (15%)

TABLE 7.—THE MOST FREQUENT CAUSES OF OTHER* SCFM EVENTS BY OPERATION CATEGORY

Cause of failure/Malfunction	Operation category			
	Part 121	Scheduled Part 135	Non-Scheduled Part 135	Part 121 and 135 Combined
Total other* SCFM accidents	22	2	17	41
Maintenance related	9 (41%)	1 (50%)	3 (18%)	13 (32%)
Electrical failure	1 (4%)	0 (0%)	6 (35%)	7 (17%)
Wiring chafed/arcing	3 (14%)	1 (50%)	2 (12%)	6 (15%)
*Other includes Electrical, Instrumentation/Communication/Navigation, Anti-ice/De-ice system, APU, Cargo Fire, Galley, Heating, Oxygen, Pressurization, Warning Systems, Vacuum Pump and Unknown				

TABLE 8.—THE MOST FREQUENT CAUSES OF SCFM BY OPERATION CATEGORY

Cause of failure/Malfunction	Operation category			
	Part 121	Scheduled Part 135	Non-Scheduled Part 135	Part 121 and 135 combined
Total SCFM accidents	109 (29%)	33 (9%)	228 (62%)	370
Maintenance related	42 (32%)	10 (8%)	78 (60%)	130 (35%)
Component failure	39 (31%)	10 (8%)	78 (61%)	127 (34%)
Component fatigue	15 (24%)	5 (8%)	42 (68%)	62 (17%)

Further analysis of SCFM accidents compared the severity in the four system categories. Two types of severity were analyzed: fatalities and aircraft damage. Table 9 compares the four system groups' fatal accidents and fatality rates. Table 10 compares the four system groups' aircraft damage sustained as a result of the accident. Although the Landing Gear or Hydraulic System category has 115 total accidents, only one was a fatal accident with five fatalities. In contrast, the Engine or Fuel System category has 179 total accidents of which 44 were fatal accidents (25 percent) with 276 fatalities. The Flight Control or Structure Systems category has 35 accidents, yet twelve were fatal accidents (34 percent) with 297 fatalities. Accidents involving SCFM of the Engine or Fuel System or the Flight Control or Structure Systems were more likely to result in destroyed aircraft (27 and 29 percent) than the Landing Gear or Hydraulics System Group Category (1 percent). Even though Flight Control or Structure SCFM accidents were less frequent than Landing Gear or Hydraulic System SCFM, the outcomes were far worse.

The consequence of the SCFM in each of the four system groups is shown in Table 11. In Part 121 and Scheduled Part 135 accidents, the flight control or structural SCFM were the most likely group to result in in-flight loss of control. Landing gear or hydraulic SCFM were the most likely type to occur with the aircraft on the ground, regardless of operation category. With an engine or fuel system SCFM, Part 121 flights were most likely to make an uneventful landing, while Part 135 flights were most likely to make a complicated landing.

TABLE 9.—ACCIDENT FATALITY CHARACTERISTICS BY SCFM SYSTEM GROUP AND BY OPERATION CATEGORY

System group	Fatality characteristics	Operation			
		Part 121	Scheduled Part 135	Non-Scheduled Part 135	Part 121 and 135 combined
Engine or fuel system	Total accidents	40	15	124	179
	Fatal accidents	4 (10%)	3 (20%)	37 (30%)	44 (25%)
	Total fatalities	151	33	92	276
Flight control or structure	Total accidents	15	4	16	35
	Fatal accidents	7 (47%)	1 (25%)	4 (25%)	12 (34%)
	Total fatalities	279	14	4	297
Landing gear or Hydraulic	Total accidents	32	12	71	115
	Fatal accidents	0 (0%)	1 (8%)	0 (0%)	1 (1%)
	Total fatalities	0	5	0	5
Instrument/Communication/ Navigation, Electrical, Other, Unknown	Total accidents	22	2	17	41
	Fatal accidents	5 (23%)	0 (0%)	6 (35%)	11 (27%)
	Total fatalities	347	0	13	360

TABLE 10.—ACCIDENT AIRCRAFT DAMAGE SEVERITY BY SCFM SYSTEM GROUP AND BY OPERATION CATEGORY

System group	Aircraft damage	Operation			
		Part 121	Scheduled Part 135	Non-scheduled Part 135	Part 121 and 135 combined
Engine or fuel system	Total accidents	40	15	124	179
	Destroyed	5 (12.5%)	3 (20.0%)	41 (33.1%)	49 (27%)
	Substantial damage	29 (72.5%)	11 (73.3%)	83 (66.9%)	123 (69%)
	Minor damage	1 (2.5%)	1 (6.7%)	0	2 (1%)
	No damage	5 (12.5%)	0	0	5 (3%)
Flight control or structure	Total accidents	15	4	16	35
	Destroyed	5 (33.3%)	1 (25.0%)	4 (25.0%)	10 (29%)
	Substantial damage	10 (67.7%)	2 (50.0%)	12 (75.0%)	24 (68%)
	Minor damage	0	1 (25.0%)	0	1 (3%)
	No damage	0	0	0	0 (0%)
Landing gear or hydraulics	Total accidents	32	12	71	115
	Destroyed	0	1 (8.3%)	0	1 (1%)
	Substantial damage	25 (78.1%)	11 (91.7%)	71 (100%)	107 (93%)
	Minor damage	4 (12.5%)	0	0	4 (3%)
	No damage	3 (9.4%)	0	0	3 (3%)
Electrical, instrumentation, communication, navigation, other, unknown	Total accidents	22	2	17	41
	Destroyed	7 (31.8%)	0	6 (35.3%)	13 (32%)
	Substantial damage	4 (18.2%)	2 (100%)	11 (64.7%)	17 (41%)
	Minor damage	4 (18.2%)	0	0	4 (10%)
	No damage	7 (31.8%)	0	0	7 (17%)

TABLE 11.—CONSEQUENCE OF SCFM BY SYSTEM GROUP AND BY OPERATION CATEGORY

System group	Consequence of event	Operation			
		Part 121	Scheduled Part 135	Non-scheduled Part 135	Part 121 and 135 combined
Engine or fuel system	Total accidents	40	15	124	179
	On ground at time of event	11 (28%)	2 (13%)	4 (3%)	17 (9%)
	Uneventful landing	18 (45%)	1 (7%)	7 (6%)	26 (14%)
	In-flight loss of control	3 (8%)	2 (13%)	17 (14%)	22 (12%)
	Complicated landing	8 (20%)	10 (67%)	96 (77%)	114 (64%)
Flight control or structure	Total accidents	15	4	16	35
	On ground at time of event	1 (7%)	0	1 (6%)	2 (6%)
	Uneventful landing	5 (33%)	2 (50%)	3 (19%)	10 (29%)
	In-flight loss of control	5 (33%)	1 (25%)	3 (19%)	9 (26%)
	Complicated landing	4 (27%)	1 (25%)	9 (56%)	14 (40%)
Landing gear or hydraulics	Total accidents	32	12	71	115
	On ground at time of event	20 (62%)	4 (33%)	21 (30%)	45 (39%)
	Uneventful landing	0	1 (8%)	0	1 (1%)
	In-flight loss of control	1 (3%)	1 (8%)	0	2 (2%)
	Complicated landing	11 (34%)	6 (50%)	50 (70%)	67 (58%)
Electrical, instrumentation, communication, navigation, other, unknown	Total accidents	22	2	17	41
	On ground at time of event	7 (32%)	0	1 (6%)	8 (20%)
	Uneventful landing	9 (41%)	0	3 (18%)	12 (29%)
	In-flight loss of control	4 (18%)	0	6 (35%)	10 (24%)
	Complicated landing	2 (9%)	2 (100%)	7 (41%)	11 (27%)

Aviation Safety Reporting System Incident Analysis

The Aviation Safety Reporting System (ASRS) is a voluntary, non-punitive, self reporting system administered by NASA Ames Research Center that includes incident reports submitted by members of the flight crew and other people working in the aviation industry. The ASRS reports do not represent an unbiased sample of aviation incidents, and the results presented here should not be considered statistically representative, but rather informational in nature. Data used in this analysis are for the period January 1993 through March 2008. While the ASRS online database includes incidents starting in 1988, information on the FAR Part Flight Operations is available only beginning in 1993. Since other flight operations, such as Part 91 (general aviation), may provide substantially different data compared with Parts 121 and 135, it was decided to use only those years for which the FAR Part Flight Operations are known. During this time period there were 60,380 incident reports for Part 121 operation and 6,151 incident reports for Part 135 operations resulting in a total of 66,531 reports for commercial aircraft. Each

ASRS incident report lists the primary problem (or cause), and, if applicable, the component involved. While this categorization is performed by the experts at ASRS, the analysis presented in this paper further categorized those components into groups based on aircraft subsystems.

ASRS identifies the most significant factor of the incident and includes it under the category "Primary Problem." Of the 13,390 incident reports listed as having "Aircraft" as the primary problem or cause, 12,395 can be attributed to "Equipment Problems" as shown in Table 12. During some incidents, multiple components failed in succession. Separately and combined, equipment problems account for approximately 93 percent of incidents whose primary factor was "Aircraft" for both FAR Parts 121 and 135. Subcategories from within this primary problem are presented in Table 13.

To provide an alternative approach to research, the SCFMs were further grouped by aircraft system. Then the components were ranked in order of frequency within the new subcategories. It must be noted than some incidents had more than one type of aircraft system failure, therefore the total of the Aircraft System SCFMs is actually greater than the Equipment Problem total shown in Table 12. Shown in Table 13, the top four systems cause 65 percent of all aircraft equipment failures during incidents. Those systems are Avionics, Propulsions Systems, Landing Gear, and Environmental Controls System. The top eight systems cause 88 percent of all aircraft SCFM during incidents. The top eight systems are expanded to include Control Surfaces, Structures, Electrical Systems, and the Hydraulic System.

TABLE 12.—SYSTEM AFFECTED BY SCFM BY OPERATION CATEGORY

Subcategory	Incident frequency of operation		
	Part 121	Part 135	Part 121 and 135 combined
Equipment problem	11268	1127	12395
Non-adherence	164	31	195
Airspace violation	5	0	5
Altitude deviation	203	11	214
Cabin event	44	1	45
Conflict	77	10	87
Excursion	2	1	3
Ground encounter	4	0	4
Incursion	2	1	3
Inflight encounter	62	9	71
Maintenance problem	15	0	15
Other anomaly	325	20	345
Other spatial deviation	8	0	8
Total	12179	1211	13390

TABLE 13.—FREQUENCIES OF SCFM GROUPED BY SYSTEM

Aircraft system	Frequency of failure/ malfunction
Avionics	3208
Propulsion system	2424
Landing gear	1378
Environmental control system	1247
Control surfaces	996
Electrical	669
Hydraulics	657
Structures	605
Fuel System	278
F & E- furnishings and equipment	263
Oil system	246
Brakes	196
Anti-Icing	110
Miscellaneous	438
Total	12715

Avionics

While hardware features have extensive background research and testing of failures, avionics failures may be harder to predict and test. Information given by United Airlines in reference to Boeing 777 aircraft indicates that health monitoring significantly reduces mechanical problems, but increases software problems (Ref. 9). More research is needed to insure that mechanical problems are not replaced by software problems. Because of the extremely high frequency of failures for avionics, along with the complexity of the system, further subcategories were developed for this study.

Avionics failures were sorted into the subcategories in Table 14 and the distribution of failures is illuminating. While some subcategories, like Weather Systems, are negligibly small, others are very significant. Monitoring mainly includes indicators of health of individual systems such as landing gear or engine temperature, and it is nearly twice as large as any other subcategory. Included in Table 15 are the most frequent specific component failures of the avionics system. These failures account for 62 percent of all avionics failures.

TABLE 14.—FREQUENCY OF SCFM FOR AVIONICS SUBCATEGORY

Avionics subcategories	Frequency of SCFM
Monitoring	1174
Navigation system	561
Air flight control	451
Communications	344
Aircraft management	337
Collision avoidance system	309
Weather systems	32
Total	3208

TABLE 15.—FREQUENCY OF SPECIFIC AVIONICS COMPONENT SCFM

Component	Subcategory	Frequency of SCFM
FMS/FMC	Navigation	267
Autopilot	Air flight control	241
Indicating and warning - landing gear	Monitoring	142
GPWS	Collision avoidance systems	120
VHF	Communications	103
Traffic Collision Avoidance System (TCAS)	Collision avoidance systems	96
Fire/Overheat warning	Aircraft management	95
ILS/VOR	Navigation	94
Cargo compartment fire/Overheat warning	Monitoring	86
Door warning system	Aircraft management	83
Fuel quantity-pressure indication	Monitoring	81
Transponder	Communications	79
Power plant fire/Overheat warning	Monitoring	77
Auto throttle/Speed control	Monitoring	72
Air/Ground communication	Communications	68
Oil pressure indication	Monitoring	65
Air data computer	Aircraft management	57
TCAS equipment	Collision avoidance systems	55
INS (Inertial navigation system)	Air flight control	54
Altimeter	Monitoring	52
Total		1987

Propulsion Systems

The propulsion systems category was also large and complex, so subcategories were developed to ease the analysis of its SCFMs. The Unspecified Engine subcategory contains the "turbine engine" and "engine" components illustrating the lack of uniformity of information detail provided in the ASRS incident reports. Some reports contain a great deal of detail, while others are very nonspecific. Many of the SCFMs of the propulsion system stated no more detail than "engine failure." Table 16 shows the frequency of the propulsion sub-category SCFMs. Included in Table 17 are the most frequent specific component failures of the Propulsion System. These failures account for 60 percent of all Propulsion System failures. The two components with the greatest number of failures are the "Engine" and "Turbine Engine" components, which are fairly vague categories. The rest of the propulsion failures were actually remarkably specific and diverse, so unlike avionics, individual components did not have high rates of failure. Without "engine" and "turbine engine," most of the propulsion components do not fail a significant amount of times. Specific engine components failures are not always clearly reported in ASRS.

Landing Gear

The landing gear system also contributed to a significant number of failures. Its component problems were less varied than those of avionics or propulsion. The most problematic component was the gear-extend/retract mechanism followed by the main gear tires. There were several other important components that bear further consideration in Table 18. These failures account for 75 percent of all landing gear failures.

TABLE 16.—FREQUENCY OF SCFM FOR PROPULSION SYSTEMS SUBCATEGORY

Propulsion subcategory	Frequency of failure/ malfunction
Unspecified engine	1011
Power plant	376
Auxiliary systems	329
Propeller engine system	199
Compressor	135
Turbine	129
Exhaust/Nozzle	86
Nacelle/Cowling	67
Turbofan system	57
Engine starting	33
Combustor	2
Total	2424

TABLE 17.—FREQUENCY OF SPECIFIC PROPULSION SYSTEM SCFM

Component	Subcategory	Frequency of failure/ malfunction
Turbine engine	Unspecified engine	752
Engine	Unspecified engine	259
Power plant lubrication system	Power plant	91
Compressor	Compressor	73
Throttle/Power level	Power plant	69
Power plant fuel control	Power plant	55
Circuit breaker/Fuse/ Thermocouple	Power plant	54
Cowling	Nacelle/Cowling	50
Turbine assembly	Turbine	48
Total		1451

TABLE 18.—FREQUENCY OF SPECIFIC LANDING GEAR SYSTEM SCFM

Component	Frequency of failure/malfunction
Gear extend/Retract mechanism	174
Main gear tire	165
Nose gear	128
Landing gear indicating system	98
Antiskid system	90
Nosewheel steering	90
Leading edge slat	77
Generator drive	76
Main gear	68
Main gear door	58
Total	1024

TABLE 19.—FREQUENCY OF SPECIFIC ENVIRONMENTAL CONTROLS SCFM

Component	Frequency of failure/malfunction
Pressurization system	351
Air conditioning and pressurization	192
Pressurization control system	162
Air conditioning distribution system	130
Aircraft cooling system	76
AC generator/Alternator	71
AC generation	68
Total	1050

Environmental Controls

The environmental control system had the fourth highest impact on the incidents reported from 1993 to 2008. Like the landing gear system, the environmental control system was less varied. A few components contributed to most of the total of 1247 SCFM. The pressurization system, air conditioning and pressurization components accounted for a large portion of the SCFM. The top failures in Table 19 account for 84 percent of environmental controls failures.

Results/Key Findings

NSTB Accident/FAA Incident Data Analyses

Between 1988 and 2003, twenty percent of all U.S. commercial aircraft accidents involved SCFM, and 18 percent of those accidents included at least one fatality. In addition, 66 percent of incidents during the same time period consisted of a SCFM.

Of the 370 accidents affected by SCFM, 48 percent involved the engine or fuel systems, 31 percent involved the landing gear or hydraulic systems, 9 percent involve flight control or structural systems, and 11 percent involved other aircraft systems. A total of 35 percent of all SCFM accidents had been caused by maintenance errors. The next most frequent causes of SCFM accidents in the research time period were component failure, 34 percent, and component fatigue, 17 percent.

Aircraft destruction followed SCFM in twenty percent accidents. One possible contributing factor is that in-flight loss of control followed only about 12 percent of the SCFM. Among Part 121 accidents, 65 percent of the SCFM either occurred while the aircraft was on the ground or resulted in an uneventful landing, whereas 69 percent of the Part 135 SCFM resulted in a complicated landing.

In general, SCFM of either the landing gear or hydraulic systems result in less severe outcomes (fewer fatalities and less aircraft destruction) than other systems. This may be in part because these SCFM were the most likely type to occur while the aircraft was on the ground. Similarly, SCFM of either the structure or flight control systems result in more severe outcomes, perhaps because these were more likely to lead to in-flight loss of control.

ASRS Incident Data Analysis

Of the 66,531 commercial incident reports contained in the ASRS system for the time period 1993 to March 2008, 20 percent or 13,390 incidents were grouped in the "Aircraft" Primary Problem category. During some incidents, multiple components failed in succession. Separately and combined, equipment problems (12, 395 incidents) accounted for approximately 93 percent of incidents whose primary factor was "Aircraft" for both FAR Parts 121 and 135. The most frequent systems cited in the equipment problems subcategory were: avionics (26 percent), propulsion systems (20 percent), landing gear (11 percent), and environmental control systems (10 percent).

Of Avionics systems SCFM, the most common subsystem cited was the monitoring subcategory with 1174 SCFM. Monitoring includes indicators of the health of individual systems and components such as the landing gear or engine temperature. Avionics and software failures are among the most frequent factors in incidents reported to ASRS, validating the importance of the performance, robustness, and reliability of software used in IVHM. Unfortunately, often the propulsion system SCFM were not clearly defined in the reports. The most frequently cited propulsion system component to have a SCFM was "turbine engine".

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14. ABSTRACT
The Integrated Vehicle Health Management (IVHM) Project is one of the four projects within the National Aeronautics and Space Administration's (NASA) Aviation Safety Program (AvSafe). The IVHM Project conducts research to develop validated tools and technologies for automated detection, diagnosis, and prognosis that enable mitigation of adverse events during flight. Adverse events include those that arise from system, subsystem, or component failure, faults, and malfunctions due to damage, degradation, or environmental hazards that occur during flight. Determining the causal factors and adverse events related to IVHM technologies will help in the formulation of research requirements and establish a list of example adverse conditions against which IVHM technologies can be evaluated. This paper documents the results of an examination of the most recent statistical/prognostic accident and incident data that is available from the Aviation Safety Information Analysis and Sharing (ASIAS) System to determine the causal factors of system/component failures and/or malfunctions in U.S. commercial aviation accidents and incidents.

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