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Commercial Aircraft Integrated Vehicle Health Management Study

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Summary

The National Transportation Safety Board (NTSB) and Federal Aviation Administration (FAA) accident and incident data were examined for three types of operations (i.e., Federal Aviation Regulation (FAR) Part 121, Part 135 Scheduled, and Part 135 Nonscheduled) for the years 1988 to 2003. In this time period, between 15 and 22 percent of commercial accidents and between 58 and 70 percent of commercial incidents involved a failure or malfunction of some system or component. Accidents involving system/component failures/malfunctions (SCFM) were most likely to result in substantial aircraft damage. Less than 25 percent of SCFM incidents in Part 121 or Scheduled Part 135 resulted in any damage, but more than 50 percent of Nonscheduled Part 135 SCFM incidents resulted in some aircraft damage.

Engine and landing gear failures or malfunctions dominate both accidents and incidents, with those two systems accounting for between 48 and 77 percent of all SCFM accidents and incidents. Among Part 121 accidents and incidents, failures and malfunctions have been more frequent in the engine than in landing gear, but among Part 135 incidents, landing gear malfunctions occurred more often. No other system accounted for more than 10 percent of the failure and/or malfunction accidents or incidents.

The Integrated Vehicle Health Management (IVHM) technology research plan mapped the Joint Planning and Development Office's Research and Development Plan (R&D) as well as the National Aviation Safety Strategic Plan (NASSP). The R&D cites two applied research areas that relate to IVHM, while the NASSP contains five objectives, nine strategies, and twelve tasks that impact IVHM technologies research.

Future directions in aviation technology as related to IVHM were identified via the review of papers from three conferences and have been compiled in the technology areas of propulsion, aeronautics, and aircraft.

Current and future directions of IVHM-related technologies were identified through the survey of literature, Joint Strike Fighter (JSF) Program prognostic health management system documents, Air Force Research Laboratory (AFRL) advanced sensor development for health monitoring documents, and Boeing IVHM-technology-focused documents. The resulting technologies were classified into 8 categories with a total of 34 current or emerging IVHM technologies.

1.0 Introduction

1.1 Purpose of Study

NASA's Integrated Vehicle Health Management (IVHM) Project is one of four projects within the Agency's Aviation Safety Program (AvSafe) in the Aeronautics Research Mission Directorate (ARMD). The IVHM Project, which was updated August 14, 2008, conducts research to develop validated tools and technologies for automated detection, diagnosis, and prognosis to mitigate adverse events during flight. Adverse events include those that arise from system, subsystem, or component faults or failures due to damage, degradation, or environmental hazards that occur during flight (Ref. 1).

The purpose of this study is to review statistical data and literature from academia, industry, and other Government agencies to establish requirements for future work in detection, diagnosis, prognosis, and mitigation for IVHM-related hardware and software. This study is considered a "waypoint" with the following expected outcomes (Ref. 1):

(1) Report and document the incidents and accidents related to IVHM utilizing the most current statistical and prognostic data available from the Aviation Safety Information Analysis and Sharing (ASIAS) Project.
(2) Document and use data such as true and false positive rates for detection and diagnosis from the Joint Strike Fighter (JSF) Program and other relevant programs.
(3) Complete a focused assessment of the potential impact of Joint Planning and Development Office (JPDO) Research and Development Plan (R&D)/Next Generation Air Transportation System (NextGen) plans on IVHM.
(4) Document reports by subject matter experts on future directions in IVHM research areas.
(5) Assess future directions in aviation technology as related to IVHM topics through a report documenting the trends according to at least three conferences.

The results of this study are considered a "key decision point" to establish future requirements for the project.

1.2 Overview of Study Contents

The expected outcomes for this study are addressed in sequential order. Outcome 1 is addressed first and contains statistical analyses of accident and incident data; these analyses have been conducted by NASA researchers for this "key decision point." Outcome 2 is summarized by the plan of the JSF Program for future IVHM data collecting. Outcome 3 is focused on a summary of aviation priority lists including information from the JDPO. Future trends in IVHM-related technologies address Outcome 4, while future directions in aviation technology, Outcome 5, follow. Finally, discussion and the conclusions are provided.

2.0 NASA Statistical Analyses

The first expected outcome of this study is a report that documents the results of an examination of the most recent statistical and/or prognostic incident and accident data that is available to determine the significance of system or component failures and/or malfunctions in U.S. commercial aviation accidents and incidents. This section contains the results of a statistical analysis that has been conducted by NASA to address this expected outcome.

2.1 NASA Analysis of National Transportation Safety Board and Federal Aviation Administration Accident and Incident Data

A statistical analysis was conducted to examine the safety risk associated with failures or malfunctions of the various systems or components of commercial aircraft during 1988 to 2003. In this analysis, "commercial" is defined as Part 121, Scheduled Part 135 and Nonscheduled Part 135 flights. 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 10 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 nonscheduled 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" (Ref. 2).

Nonimpact 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, which are defined as follows (Ref. 3):

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

The source for accident data is the National Transportation Safety Board (NTSB) Aviation Accident and Incident Data System, while the source for incident data is the Federal Aviation Administration (FAA) Accident/Incident Data System. Although both databases contain both accident and incident data, the FAA has primary investigative responsibility for incidents, and the NTSB is the authority for accident investigation.

Data for total flight hours per year were obtained from tables published by the NTSB, which they created based on data from the FAA. The abbreviation SCFM will be used throughout this report to mean system/component failure/malfunction.

A summary of the SCFM events can be found in Table I. Between 15 and 22 percent of commercial accidents during 1988 to 2003 involved a failure or malfunction of some system or component. The lowest proportion of accidents, fatal accidents, and total fatalities associated with SCFM was among Scheduled Part 135 accidents (10 to 16 percent). In Part 121 flights, SCFM accounted for 18 percent of all accidents, 27 percent of fatal accidents, and 36 percent of fatalities. In Nonscheduled Part 135 flights, SCFM accounted for 21 percent of all accidents, 17 percent of fatal accidents, and 17 percent of all fatalities. Roughly 15 to 20 percent of all SCFM accidents included at least one fatality.

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

In Part 121 flights, 21 failures or malfunctions occurred for each 1 million flight hours; the rate was even higher among Part 135 flights.

TABLE I.—SUMMARY OF SCFM EVENTS BY OPERATION CATEGORY

Type of event	Operation		
	Part 121	Scheduled Part 135	Nonscheduled Part 135
Total flight hours	232,868,640	25,050,928	46,350,000
Total accidents	600	213	1070
Accidents with SCFM	109 (18.2%)	33 (15.5%)	228 (21.3%)
SCFM accidents per million flight hours	0.468	1.317	4.919
Fatal accidents	60	49	278
Fatal accidents with SCFM	16 (26.7%)	5 (10.2%)	47 (16.9%)
Total fatalities	2151	328	664
Fatalities in accidents with SCFM	777 (36.1%)	52 (15.9%)	109 (16.4%)
Total incidents	7497	2218	2081
Incidents with SCFM	4957 (66.1%)	1557 (70.2%)	1218 (58.5%)
SCFM incidents per million flight hours	21.29	62.15	26.28

Each flight operation category has a different phase of flight in which failures or malfunctions are most likely to occur (see Table II). In Part 121, SCFM is most likely to occur during takeoff (23 percent), whereas in Scheduled Part 135, takeoff (24 percent) runs a close second to the landing phase (27 percent), and in Nonscheduled Part 135, SCFM occurs less often in both takeoff (20 percent) and landing (22 percent) phases than in cruise flight (31 percent). Among Scheduled Part 135 accidents, the landing and takeoff phases accounted for more than half of the failures or malfunctions. In Part 121, the largest percentage of SCFM occurred during takeoff (23 percent), but 17.5 percent of the SCFM occurred while the aircraft was standing or during taxi, which is more than 10 percentage points higher than in Part 135.

A large percentage (26 to 32 percent) of incidents, on the other hand, occurred during cruise flight, regardless of the flight category. In Part 121 and Scheduled Part 135 incidents, the takeoff phase was the second most common phase for failures or malfunctions, but in Nonscheduled Part 135 incidents, nearly as many SCFM incidents occurred during the landing phase as in cruise flight.

TABLE II.—PHASE OF FLIGHT FOR SCFM EVENTS BY OPERATION CATEGORY

Accidents or incidents	Phase of flight	Operation		
		Part 121	Scheduled Part 135	Nonscheduled Part 135
Accidents	Total accidents	109	33	228
	Standing	9 (8.3%)	1 (3.0%)	0
	Taxi	10 (9.2%)	1 (3.0%)	8 (3.5%)
	Takeoff	25 (22.9%)	8 (24.2%)	45 (19.7%)
	Climb	15 (13.8%)	3 (9.1%)	21 (9.2%)
	Cruise	13 (11.9%)	4 (12.1%)	70 (30.7%)
	Descent	6 (5.5%)	5 (15.2%)	6 (2.6%)
	Approach	12 (11.0%)	2 (6.1%)	28 (12.3%)
	Landing	19 (17.4%)	9 (27.3%)	50 (21.9%)
Incidents	Total incidents	4957	1557	1218
	Standing	58 (1.2%)	14 (0.9%)	11 (0.9%)
	Taxi	293 (5.9%)	93 (6.0%)	70 (5.8%)
	Takeoff	941 (19.0%)	320 (20.6%)	126 (10.3%)
	Climb	807 (16.3%)	206 (13.2%)	117 (9.6%)
	Cruise	1568 (31.6%)	408 (26.2%)	360 (29.6%)
	Descent	363 (7.3%)	106 (6.8%)	70 (5.7%)
	Approach	580 (11.7%)	219 (14.1%)	104 (8.5%)
	Landing	331 (6.7%)	189 (12.1%)	355 (29.1%)
	Unknown	16 (0.3%)	2 (0.1%)	5 (0.4%)

Accidents involving SCFM were most likely to result in substantial aircraft damage (see Table III). However, it was not possible to determine from these data whether the most damage was done by the malfunction itself (e.g., an uncontained engine failure) or by some later event in the landing sequence (e.g., a hard landing, wing strike, or collision with terrain during an off-airport landing).

Less than 25 percent of SCFM incidents in Part 121 or Scheduled Part 135 resulted in any damage, but more than 50 percent of Nonscheduled Part 135 SCFM incidents resulted in some aircraft damage.

TABLE III.—AIRCRAFT DAMAGE IN SCFM EVENTS BY OPERATION CATEGORY

Accidents or incidents	Aircraft damage	Operation		
		Part 121	Scheduled Part 135	Nonscheduled Part 135
Accidents	Total accidents	109	33	228
	Destroyed	17 (15.6%)	5 (15.2%)	51 (22.4%)
	Substantial damage	68 (62.4%)	26 (78.8%)	177 (77.6%)
	Minor damage	9 (8.3%)	2 (6.1%)	0
	No damage	15 (13.8%)	0	0
Incidents	Total incidents	4957	1557	1218
	Destroyed	0	0	2 (0.2%)
	Substantial damage	37 (0.7%)	3 (0.2%)	8 (0.7%)
	Minor damage	1081 (21.8%)	364 (23.4%)	638 (52.4%)
	No damage	3822 (77.1%)	1186 (76.2%)	568 (46.6%)
	Unknown	17 (0.3%)	4 (0.3%)	2 (0.2%)

The consequences of the failures or malfunctions were categorized into four groups (see Table IV). Some accidents occurred while the aircraft was on the ground (standing, taxi, takeoff roll, or landing roll), and no other occurrences except aircraft evacuation were noted. In other events, an uneventful landing or aborted takeoff was made with no further damaging occurrence. Loss of control with resulting ground collision followed some malfunctions. In some cases (particularly with autopilot malfunctions), control was regained and an emergency landing was made. In the final group, a precautionary landing was attempted, but was complicated by some other event that could not be characterized as in-flight loss of control. These events included hard landings, overruns, wing strikes, collisions with trees while maneuvering for landing, and encounters with unsuitable terrain during off-airport landings.

The lack of detailed information in the incident database made it impossible to create this type of table for the incident data.

TABLE IV.—CONSEQUENCES OF SCFM EVENTS BY OPERATION CATEGORY

Consequence of event	Operation		
	Part 121	Scheduled Part 135	Nonscheduled Part 135
Total SCFM accidents	109	33	228
On ground at time of event	39 (35.8%)	6 (18.2%)	27 (11.8%)
Uneventful landing	32 (29.4%)	4 (12.1%)	13 (5.7%)
In-flight loss of control	13 (11.9%)	4 (12.1%)	26 (11.4%)
Complicated	25 (22.9%)	19 (57.6%)	162 (71.1%)

In Part 121 accidents, 65 percent of the failures or malfunctions either occurred while the aircraft was on the ground or resulted in an uneventful landing. In Part 135 accidents, 58 to 71 percent of the failures or malfunctions resulted in a complicated landing. In-flight loss of control after or as a consequence of the SCFM occurred in about 12 percent of the SCFM events, regardless of flight category.

For each accident and incident, the system affected by the malfunction or failure was determined (see Table V). 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.

TABLE V.—SYSTEM AFFECTED BY FAILURE OR MALFUNCTION BY OPERATION CATEGORY

Accidents or incidents	System	Part 121	Scheduled Part 135	Nonscheduled Part 135
Accidents	Total accidents	109	33	228
	Electrical	8 (7.3%)	1 (3.0%)	12 (5.3%)
	Engine	36 (33.0%)	12 (36.4%)	111 (48.7%)
	Flight control	10 (9.2%)	3 (9.1%)	9 (3.9%)
	Fuel	4 (3.7%)	3 (9.1%)	13 (5.7%)
	Hydraulic	9 (8.3%)	2 (6.1%)	7 (3.1%)
	Instrumentation/communication/navigation	5 (4.6%)	0 (0.0%)	0 (0.0%)
	Landing gear	23 (21.1%)	10 (30.3%)	64 (28.1%)
	Structure	5 (4.6%)	1 (3.0%)	7 (3.1%)
	Other	8 (7.3%)	1 (3.0%)	4 (1.8%)
	Unknown	1 (0.9%)	0 (0.0%)	1 (0.4%)
Incidents	Total incidents	4957	1557	1218
	Electrical	191 (3.9%)	64 (4.1%)	47 (3.9%)
	Engine	1384 (27.9%)	486 (31.2%)	349 (28.7%)
	Comfort systems	246 (5.0%)	54 (3.5%)	20 (1.6%)
	Flight control	431 (8.7%)	43 (2.8%)	28 (2.3%)
	Fuel	215 (4.3%)	80 (5.1%)	54 (4.4%)
	Hydraulic	414 (8.4%)	57 (3.7%)	45 (3.7%)
	Instrumentation/communication/navigation	83 (1.7%)	34 (2.2%)	13 (1.1%)
	Landing gear	990 (20.0%)	509 (32.7%)	558 (45.8%)
	Pressurization	174 (3.5%)	15 (1.0%)	8 (0.7%)
	Structure	214 (4.3%)	80 (5.1%)	49 (4.0%)
	Other	615 (12.4%)	135 (8.7%)	47 (3.9%)

Engine and landing gear failures/malfunctions dominate both accidents and incidents, with those two systems accounting for between 48 and 77 percent of all SCFM accidents and incidents. Among accidents and Part 121 incidents, failures and malfunctions have been more frequent in the engine than in landing gear, but among Part 135 incidents, landing gear malfunctions occurred more often. No other system accounted for more than 10 percent of the failure/malfunction accidents or incidents.

The eight "other" systems in Part 121 accidents were as follows: two auxiliary power unit (APU) malfunctions with fire, two cargo fires, a galley elevator malfunction, the latch failure of a galley door, a pressurization system malfunction, and an oxygen system leak. A false stall warning was the "other" system malfunction in Scheduled Part 135, and in Nonscheduled Part 135 the "other" systems were a vacuum pump, a heater, the anti-ice/de-ice system, and the pressurization system.

For the purpose of further examination, the systems were divided into four groups: engine or fuel system, flight control or structure, landing gear or hydraulics, and everything else.

Tables VI to VIII detail the specific component (when included in the accident report) that was said to have failed, fractured, separated, etc. Compilation of this data was dependent upon the phrasing used in the NTSB report. It must be noted that some reports included more details than others, impacting the compilation of this data. Also note that some accidents are listed multiple times if multiple malfunctions occurred.

TABLE VI.—SPECIFIC COMPONENTS OF ENGINE OR FUEL SYSTEM FAILURE/MALFUNCTION EVENTS BY OPERATION CATEGORY

Specific parts or components in the failure/malfunction	Operation		
	Part 121	Scheduled Part 135	Nonscheduled Part 135
Total engine or fuel SCFM accidents	40	15	124
Accessory drive shaft/gear	1 (2.5%)		3 (2.4%)
Beta control linkage	1 (2.5%)		
Bleed air duct	1 (2.5%)		
Compressor blade		1 (6.7%)	
Compressor disk	5 (12.5%)		
Compressor impeller		1 (6.7%)	
Compressor stator vane	1 (7.5%)		
Connecting rod	1 (2.5%)		12 (9.7%)
Connecting rod bolt/cap/pin		1 (6.7%)	5 (4.0%)
Coupling shaft			1 (0.8%)
Crankshaft			17 (13.7%)
Crankshaft gear bolt/pin			2 (1.6%)
Crankcase			4 (3.2%)
Engine bull gear	1 (2.5%)		
Engine bearing	3 (7.5%)		5 (4.0%)
Engine cowling/latch		1 (6.7%)	
Exhaust cam shaft			1 (0.8%)
Engine cylinder		1 (6.7%)	13 (10.5%)
Engine cylinder intake valve			3 (2.4%)
Exhaust manifold collector			1 (0.8%)
Exhaust push rod			1 (0.8%)
Exhaust rocker arm			1 (0.8%)
Exhaust stack			1 (0.8%)
Exhaust valve			1 (0.8%)
Fuel leak	2 (5.0%)	1 (6.7%)	3 (2.4%)
Fuel control	1 (2.5%)		1 (0.8%)
Fuel filter	1 (2.5%)		
Fuel injection control linkage			3 (2.4%)
Fuel line		1 (6.7%)	2 (1.6%)
Fuel pump	1 (2.5%)		4 (3.2%)
Fuel pump drive shaft	1 (2.5%)		1 (0.8%)
Fuel tank			1 (0.8%)
Fuel tank float valves		1 (6.7%)	
Gas producer turbine		1 (6.7%)	
Ignition system	1 (2.5%)	1 (6.7%)	3 (2.4%)
Induction air ducting			2 (1.6%)
Magneto			8 (6.5%)
Mixture control linkage			3 (2.4%)
Loss of oil pressure	1 (2.5%)		3 (2.4%)
Oil line			2 (1.6%)
Oil pump			1 (0.8%)
Oil filter gasket			3 (2.4%)
Oil deprivation	1 (2.5%)	1 (6.7%)	13 (10.5%)
Oil magnetic plug	1 (2.5%)		
Piston		1 (6.7%)	8 (6.5%)
Power turbine		1 (6.7%)	
Propeller blade		1 (6.7%)	6 (4.8%)
Propeller control unit		1 (6.7%)	1 (0.8%)
Propeller erosion shield	1 (2.5%)		
Propeller feathering system			1 (0.8%)
Propeller governor control linkage		2 (13.2%)	1 (0.8%)

TABLE VI.—Continued.

Specific parts or components in the failure/malfunction	Operation		
	Part 121	Scheduled Part 135	Nonscheduled Part 135
Propeller hub assembly	1 (5.0%)		2 (1.6%)
Propeller section			2 (1.6%)
Spark plug			5 (4.0%)
Throttle control			7 (5.6%)
Thrust reverser	2 (5.0%)		1 (0.8%)
Timing gear			1 (0.8%)
Torsional vibration damper			1 (0.8%)
Turbine air seal	1 (2.5%)		
Turbine antirotation nozzle lock	1 (2.5%)		
Turbine blade	3 (7.5%)		
Turbine disk	2 (5.0%)		
Turbine hub	1 (2.5%)		
Turbine seal	1 (2.5%)		
Turbocharger			2 (1.6%)
Miscellaneous clamp/bolt/seal	3 (7.5%)		2 (1.6%)
Wiring	1 (2.5%)		1 (0.8%)
Unknown	3 (7.5%)		7 (5.6%)

TABLE VII.—SPECIFIC COMPONENTS OF FLIGHT CONTROL OR STRUCTURAL FAILURE/MALFUNCTION EVENTS BY OPERATION CATEGORY

Specific parts or components in the failure/malfunction	Operation		
	Part 121	Scheduled Part 135	Nonscheduled Part 135
Total flight control or structural SCFM accidents	15	4	16
Control yoke		1 (25.0%)	
Door locking pin or latch			2 (12.5%)
Engine cowling			2 (12.5%)
Elevator controls	1 (6.7%)		1 (6.3%)
Elevator servo tab			2 (12.5%)
Elevator trim/tab control	1 (6.7%)	1 (25.0%)	2 (12.5%)
Fuselage skin or structure	2 (13.3%)		
Horizontal stabilizer		1 (25.0%)	1 (6.3%)
Inadequate lubrication	1 (6.7%)		
Jackscrew assembly	1 (6.7%)		
Rudder	2 (13.3%)		1 (6.3%)
Flaps	3 (20.0%)		2 (12.5%)
Slats	2 (13.3%)		
Taxi light support bracket	1 (6.7%)		
Window panel		1 (25.0%)	1 (6.3%)
Wing rib or spar			2 (12.5%)
Screws or bolts	2 (13.3%)	1 (25.0%)	
Unknown	3 (20.0%)		

TABLE VIII.—SPECIFIC COMPONENTS OF LANDING GEAR OR HYDRAULIC FAILURE/MALFUNCTION EVENTS BY OPERATION CATEGORY

Specific parts or components in the failure/malfunction	Operation		
	Part 121	Scheduled Part 135	Nonscheduled Part 135
Total landing gear or hydraulic system SCFM accidents	32	12	71
Brakes	2 (6.3%)		8 (11.3%)
Brake steering control unit	1 (3.1%)		
Gear indication system	1 (3.1%)		3 (4.2%)
Gear switch	1 (3.1%)		5 (7.0%)
Hydraulic actuator			1 (1.4%)
Hydraulic check valve	1 (3.1%)		
Hydraulic fluid loss	8 (25.0%)	3 (25.0%)	6 (8.5%)
Hydraulic line	3 (9.4%)	1 (8.3%)	3 (4.2%)
Hydraulic pump	1 (3.1%)		
Hydraulic seal			1 (1.4%)
Hydraulic shutoff valve	1 (3.1%)		
Center gear lower drag brace	1 (3.1%)		
Main gear axle			1 (1.4%)
Main gear bellcrank assembly			3 (4.2%)
Main gear door		2 (16.7%)	2 (2.8%)
Main gear drag brace	1 (3.1%)		
Main gear forward trunnion bearing support fitting	1 (3.1%)		
Main gear drag link			1 (1.4%)
Main gear extension/retraction assembly	1 (3.1%)	1 (8.3%)	9 (1.4%)
Main gear locking mechanism			2 (2.8%)
Main gear outer cylinder	2 (6.3%)		
Main gear pivot link			1 (1.4%)
Main gear pivot shaft			1 (1.4%)
Main gear scissor assembly	2 (6.3%)		6 (12.7%)
Main gear shaft roll pin			1 (1.4%)
Main gear side brace	1 (3.1%)		1 (1.4%)
Main gear spring			1 (1.4%)
Main gear strut	3 (9.4%)		10 (14.1%)
Main gear trunnion		1 (8.3%)	
Main gear unspecified	1 (3.1%)		2 (2.8%)
Miscellaneous bolt	1 (3.1%)	1 (8.3%)	2 (2.8%)
Nose gear actuator		2 (16.7%)	
Nose gear fork assembly			1 (1.4%)
Nose gear link assembly	1 (3.1%)		1 (1.4%)
Nose gear locking mechanism	1 (3.1%)		1 (1.4%)
Nose gear retraction cylinder			1 (1.4%)
Nose gear seals		1 (8.3%)	
Nose gear selector valve			1 (1.4%)
Nose gear steering system			1 (1.4%)
Nose gear strut	1 (3.1%)		
Nose gear upper lock link	2 (6.3%)		
Tail-wheel assembly			1 (1.4%)
Wheel assembly	1 (3.1%)		1 (1.4%)

Table IX shows the number of fatal accidents and total fatalities in each group of the accidents. In Part 121 accidents, the flight control or structural failures/malfunctions were the least common but the most deadly. Landing gear or hydraulic malfunctions were very rarely fatal, regardless of flight operation. In Nonscheduled Part 135 accidents, the percentages of fatal events were somewhat similar in the three groups other than landing gear, but lowest in-flight SCFM.

TABLE IX.—EVENT CHARACTERISTICS BY FAILURE/MALFUNCTION SYSTEM GROUP AND BY OPERATION CATEGORY

System group	Event characteristics	Operation		
		Part 121	Scheduled Part 135	Nonscheduled Part 135
Engine or fuel system	Total accidents	40	15	124
	Fatal accidents	4 (10.0%)	3 (20.0%)	37 (29.8%)
	Total fatalities	151	33	92
Flight control or structure	Total accidents	15	4	16
	Fatal accidents	7 (46.7%)	1 (25.0%)	4 (25.0%)
	Total fatalities	279	14	4
Landing gear or hydraulic	Total accidents	32	12	71
	Fatal accidents	0	1 (8.3%)	0
	Total fatalities	0	5	0
Instrument, communication, navigation, electrical, other, or unknown	Total accidents	22	2	17
	Fatal accidents	5 (22.7%)	0	6 (35.3%)
	Total fatalities	347	0	13

Table X shows the level of aircraft damage in each group of the accidents. Landing gear or hydraulic malfunctions very rarely resulted in aircraft destruction. Of the other three groups, the flight control or structural failures/malfunctions were the most likely group to result in aircraft destruction among Part 121 and Scheduled Part 135, but the least likely group to result in aircraft destruction in Nonscheduled Part 135.

TABLE X.—AIRCRAFT DAMAGE BY FAILURE/MALFUNCTION SYSTEM GROUP AND BY OPERATION CATEGORY

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

Table XI shows the consequence of the event in each group of the accidents. In Part 121 and Scheduled Part 135 accidents, the flight control or structural failures/malfunctions were the most likely group to result in in-flight loss of control. Landing gear or hydraulic malfunctions were the most likely type to occur with the aircraft on the ground, regardless of operation category. With an engine or fuel system malfunction or failure, Part 121 flights were most likely to make an uneventful landing, while Part 135 flights were most likely to make a complicated landing.

TABLE XI.—EVENT CONSEQUENCE BY FAILURE/MALFUNCTION SYSTEM GROUP AND BY OPERATION CATEGORY

System group	Consequence of event	Operation		
		Part 121	Scheduled Part 135	Nonscheduled Part 135
Engine or fuel system	Total accidents	40	15	124
	On ground at time of event	11 (27.5%)	2 (13.3%)	4 (3.2%)
	Uneventful landing	18 (45.0%)	1 (6.7%)	7 (5.6%)
	In-flight loss of control	3 (7.5%)	2 (13.3%)	17 (13.7%)
	Complicated landing	8 (20.0%)	10 (66.7%)	96 (77.4%)
Flight control or structure	Total accidents	15	4	16
	On ground at time of event	1 (6.7%)	0	1 (6.3%)
	Uneventful landing	5 (33.3%)	2 (50.0%)	3 (18.7%)
	In-flight loss of control	5 (33.3%)	1 (25.0%)	3 (18.7%)
	Complicated landing	4 (26.7%)	1 (25.0%)	9 (56.3%)
Landing gear or hydraulics	Total accidents	32	12	71
	On ground at time of event	20 (62.5%)	4 (33.3%)	21 (29.6%)
	Uneventful landing	0	1 (8.3%)	0
	In-flight loss of control	1 (3.1%)	1 (8.3%)	0
	Complicated landing	11 (34.4%)	6 (50.0%)	50 (70.4%)
Electrical, instrumentation, communication, navigation, other, or unknown	Total accidents	22	2	17
	On ground at time of event	7 (31.8%)	0	1 (5.9%)
	Uneventful landing	9 (40.9%)	0	3 (17.6%)
	In-flight loss of control	4 (18.2%)	0	6 (35.3%)
	Complicated landing	2 (9.1%)	2 (100%)	7 (41.2%)

Around 15 to 20 percent of commercial aircraft accidents between 1988 and 2003 involved malfunctions or failures of some aircraft system or component, and roughly 15 to 20 percent of those accidents included at least one fatality. In addition, 60 to 70 percent of incidents during the same time period consisted of a system/component failure/malfunction. In Part 121 flights, 21 failures or malfunctions occurred for each 1 million flight hours; the rate was even higher among Part 135 flights.

Among Nonscheduled Part 135 flights, SCFM accidents occurred most frequently during cruise flight (31 percent), followed by the landing (22 percent) and takeoff (20 percent) phases. Among Scheduled Part 135 accidents, the landing and takeoff phases accounted for more than half of the failures or malfunctions. In Part 121, the largest percentage of SCFM occurred during takeoff (23 percent), but 17.5 percent of the SCFM occurred while the aircraft was standing or during taxi, which is more than 10 percentage points higher than in Part 135. The largest percentage of incidents occurred during cruise flight, regardless of the operation category (26 to 32 percent).

Less than 25 percent of the SCFM accidents resulted in destruction of the aircraft. 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 failures or malfunctions either occurred while the aircraft was on the ground or resulted in an uneventful landing, whereas 69 percent of the Part 135 failures or malfunctions resulted in a complicated landing.

Engine and landing gear failures/malfunctions dominate both accidents and incidents, with those two systems accounting for between 48 and 77 percent of all SCFM accidents and incidents. Among accidents and Part 121 incidents, failures and malfunctions have been more frequent in the engine than in landing gear, but among Part 135 incidents, landing gear malfunctions occurred more often. No other system accounted for more than 10 percent of the failure/malfunction accidents or incidents.

In general, failures or malfunctions 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 malfunctions were the most likely type to occur while the aircraft was on the ground. Similarly, failures or malfunctions of either the structure or flight control systems result in more severe outcomes, perhaps because these malfunctions were more likely to lead to in-flight loss of control.

3.0 Joint Strike Fighter Program

One of the tasks of systems analysis was to use and document data such as true and false positive rates for detection and diagnosis technologies from JSF and other relevant programs with a goal of finding useful synergies between the programs. A representative from the IVHM Project systems analysis team participated in a prognostics and health management Small Business Innovation Research (SBIR) consortium to discuss progress of various technologies supported by JSF (Ref. 4). The systems analysis team has the responsibility to provide critical information to the IVHM management team regarding new technology trends as they pertain to the stated goal of the IVHM Project (Ref. 1). Representatives from the Army, Navy, Air Force, and related SBIR companies were also in attendance. Unfortunately, their research has not progressed far enough to have relevant true and false positive data. However, they have documented how this data will be collected and analyzed once they reach that point in the development of their technologies. As technologies are evaluated for their reliability in detection and diagnosis, a panel will score each individual test event based on a series of criteria and assign a code to the test event based on the outcome (Ref. 5). This code will document whether the detection or diagnosis was correct, a false alarm, or another outcome. This process is outlined in a charter document for the Joint Reliability and Maintainability Evaluation Team (JRMET) and Test Data Scoring Board (TDSB).

4.0 Joint Planning and Development Office

4.1 Joint Planning and Development Office's National Research and Development Plan

The first version of the R&D for the Next Generation Air Transportation System (NextGen) was released by the FAA's JPDO on August 31, 2007 (Ref. 6). The R&D responds to a request from the Office of Management and Budget (OMB) to provide a "research and development plan that details the requirements for needed technologies and identifies the responsibilities of each JPDO member agency (Departments of Transportation, Defense, Commerce, Homeland Security, and NASA)" (Ref. 6). The focus of this first R&D is the fiscal years 2009 to 2013. In the R&D, basic research is defined as systematic study directed toward fuller knowledge or understanding of the fundamental aspects of phenomena and of observable facts without specific applications toward processes or products in mind. Applied research is defined as systematic study for gaining knowledge or understanding necessary to determine the means by which a recognized and specific need may be met. Finally, development is defined as systematic application of knowledge or understanding directed toward the production of useful materials, devices, and systems or methods, including design, development, and improvement of prototypes and new processes to meet specific requirements.

The research is to focus on procedures, technologies, and automated recovery capabilities to address the most significant safety issues: loss of control, weather encounters, and mechanical failures. Specifically the following safer systems outcomes are identified

- Improvement in safety of aircraft, ground systems, and operations
- Reduction in rate of accidents resulting from human error
- Extension of the airworthiness of aircraft where safety is not compromised

The IVHM-related R&D safer systems objective is to "Introduce advanced aircraft and ground systems to improve health monitoring and mitigate hazards." Table XII shows the research and development needs identified in the R&D related to the above safer systems objective that will impact IVHM research plans (Ref. 6).

TABLE XII.—R–1280 APPLIED RESEARCH ON SYSTEMS HEALTH MANAGEMENT

R–1280	Complete applied research on system health management to support alternative NextGen equipage decisions
Lead agency	NASA
Supporting agencies	None
Required completion date	2015
Supported operational improvement (OIs)	OI–3008
Agency alignment	Agency R&D is aligned.
Agency programs	NASA/ARMD/AvSafe/IVHM FAA–NextGen Research, Engineering and Development

The objective of the R&D is to "Continuously measure and assess safety through prognostic trend analysis, coupled with an integrated means of predicting and mitigating risks before incidents or accidents occur," which is under the outcome related to identifying proactively safety risks. Table XIII shows the research needs identified in the R&D related to the objective above that will impact IVHM research plans (Ref. 6).

TABLE XIII.—R–0200 APPLIED RESEARCH ON VULNERABILITY DISCOVERY

R–0020	Complete applied research on vulnerability discovery to support an alternatives selection decision for the NextGen Aviation Safety Information Analysis and Sharing (ASIAS) capability
Lead agency	NASA
Supporting agencies	FAA
Required completion date	2009
Supported operational improvement (OI)	OI–3004
Agency alignment	Agency R&D is aligned.
Agency program	NASA/ARMD/AvSafe/IVHM FAA–NextGen System Development–1A13

4.2 Joint Planning and Development Office Safety Working Group's National Aviation Safety Strategic Plan

An assessment of the potential impact of the JPDO is continued here through an assessment of the National Aviation Safety Strategic Plan (NASSP) developed by the JPDO Safety Working Group. The purpose of the Safety Working Group is to establish a comprehensive proactive safety management approach including a shared national aviation safety data reporting and analysis system, and a comprehensive national-level aviation safety management framework. The NASSP is meant to be a "living" document and will be updated annually. The NASSP defines national goals, objectives, and strategies for aviation safety improvements. The plan's workareas provide the basis by which JPDO member departments and agencies will plan their aviation safety resources and by which the OMB will align budgets relative to aviation safety. The NASSP was developed and vetted by the JPDO partner departments and agencies. At the time of this writing, the current version was Version 7 dated August 4, 2008 (Ref. 7).

The NASSP is organized in three goal areas: safer practices, safer systems, and safer worldwide. The first two goals are being addressed by IVHM Project research tasks. The first goal, safer practices, emphasizes safety through standards, regulations, and procedures including comprehensive safety information monitoring, sharing, and analysis for proactive solutions.

The IVHM-related objectives of the Safer Practices Goal are

- Provide consistent safety management approaches that are implemented throughout government and industry: seeks to improve safety risk management by identifying hazards and analyzing the risk those hazards pose.

- Provide enhanced monitoring and safety analysis of the Air Transportation System: focuses on actively managing risk in the aviation system through a continuous process that monitors and analyzes data for safety risk.
- Provide enhanced methods for system safety, design certainty, operational procedures, and training and includes complex system validation and verification processes.

Table XIV summarizes a mapping of the IVHM Project's research to the Safer Practices Goal, objectives, and strategies.

TABLE XIV.—THE NASSP'S SAFER PRACTICES GOAL, OBJECTIVES, STRATEGIES, AND TASKS RELATED TO NASA IVHM PROJECT RESEARCH

NASSP Objective	NASSP Strategy	Task	Related NASA IVHM Research
1A) Provide consistent safety management approaches that are implemented throughout government and industry	1A3) Improve safety risk management	1A3.2) Increase the effectiveness of fault management by improving the detection and diagnostic capabilities to increase fault management	IVHM 3.1 Detection IVHM 3.2 Diagnosis
1B) Provide enhanced monitoring and safety analysis of the Air Transportation System (ATS)	1B1) Increase data analysis for safety risk management (go beyond traditional causal factor monitoring; use proactive methods to identify incident and accident precursors)		IVHM 4.3 Discovery in Aeronautics Systems Health (DASHlink) Collaborative Web site
	1B2) Increase Data Analysis for Safety Risk Management	1B2.3) Identify and develop tools, methods, and process	IVHM 1.3 Advanced analytics and complex systems
	1B3) Develop prognostic methods to assess risks		IVHM 3.3 Prognosis
	1B4) Increase confidence in analytical results by validating the analytic techniques and the reliability of results		IVHM 1.4 Verification and Validation
1C) Provide enhanced methods for system safety, design certainty, operational procedures, and training	1C2) Advance complex system validation and verification methods in support of their certification for operational use	1C2.1) Improve complex systems requirements documentation, communications, and validation methods for NextGen	IVHM 1.4 Verification and Validation
		1C2.2) Improve software, hardware, operational procedure, and system verification methods for complex systems	IVHM 1.4 Verification and Validation

The second goal, safer systems, emphasizes implementation of safety-enhancing technologies that will improve safety through human-centered interfaces and improvements for airborne and ground-based systems. Included within this goal area is vehicle and ground systems health management.

The IVHM-related objectives of the Safer Systems Goal are

- Provide risk-reducing system interfaces: seeks to ensure the availability of information required to drive interface concepts.

- Provide safety enhancements for airborne systems: focuses on improving the reliability and airworthiness of aircraft and improving vehicle systems health management through advanced monitoring systems and decision aids.

Table XV summarizes a mapping of the IHVM Project's research to the Safer Systems Goal, objectives, and strategies.

TABLE XV.—THE NASSP'S SAFER SYSTEMS GOAL, OBJECTIVES, STRATEGIES, AND TASKS RELATED TO NASA IVHM PROJECT RESEARCH

NASSP Objective	NASSP Strategy	Task	Related NASA IVHM Research
2A) Provide risk-reducing system interfaces	2A1) Ensure the availability and accessibility of required information	2A1.2) Perform sensor/data analysis of information required to drive interface concepts	IVHM 1.1 Advanced Sensors and Materials
		2A1.4) Develop sensors and presentation/interface concepts	IVHM 1.1 Advanced Sensors and Materials
		2A1.5) Perform real-world reliability testing and validation of sensors and information	IVHM 4.1 Evaluation of Multidisciplinary IVHM Technologies, Tools, and Techniques
2B) Provide safety enhancements for airborne systems	2B1) Improve the reliability and airworthiness of aircraft	2B1.1) Advance the science of materials, structures, and aircraft systems	IVHM 1.1 Advanced Sensors and Materials IVHM 1.2 Modeling
		2B1.2) Develop prognostic health management (PHM) system concepts for identifying and mitigating system anomalies and identify advanced sensors, integrated sensors, and embedded sensors	IVHM 1.1 Advanced Sensors and Materials IVHM 3.1.1 Baseline assessment of detection capabilities IVHM 3.2.1 Baseline assessment of diagnosis capabilities IVHM 3.3.1 Baseline assessment of prognosis capabilities IVHM 3.4.1 Establish minimum performance criteria of candidate mitigation strategies
		2B1.4) Perform flight testing in relevant environment	IVHM 4.1.2 Flight test of detection, diagnosis, and prognosis technologies for selected adverse event types.
	2B2) Improve vehicle systems health management through advanced monitoring systems and decision aids	2B2.1) Develop PHM systems' design requirements and goals for all aircraft types	IVHM 3.3 Prognosis IVHM 2.1 Aircraft Systems Health Management IVHM 2.2 Airframe Health Management IVHM 2.3 Propulsion Systems Health Management IVHM 2.4 Software Health Management
		2B2.2) Develop PHM system concepts for identifying and mitigating system anomalies and identify advanced sensors, integrated sensors, and embedded sensors	IVHM 3.1 Detection IVHM 3.2 Diagnosis IVHM 3.3 Prognosis IVHM 3.4 Mitigation IVHM 1.1 Advanced Sensors and Materials
		2B2.3) Perform simulation and/or model tests of PHM concepts (includes sensors) to verify concepts	IVHM 4.1 Evaluation of Multidisciplinary IVHM Technologies, Tools, and Techniques
		2B2.4) Perform flight testing in relevant environment	IVHM 4.1 Evaluation of Multidisciplinary IVHM Technologies, Tools, and Techniques

5.0 Future Directions in Aviation Technology as Related To IVHM

The fourth expected outcome of this study is a report providing input on future trends in aviation technology as documented by at least three conferences. This section contains the results of the literature survey conducted by NASA to address this expected outcome (Ref. 8). The data used in this report for identifying and documenting future directions in aviation technology were gathered primarily from the following four conferences.

- AIAA Aerospace Sciences Meeting and Exhibit
- AIAA Joint Propulsion Conference
- IEEE Aerospace Conference
- NASA Fundamental Aeronautics Program (FAP) Annual Meeting

Papers from the first three conferences have been reviewed across a 5-yr span (2004 to 2008). Topics from the last conference were reviewed for the past 2 yr only, since it has only convened since 2007. Some of the tracks selected for surveying include the topics of silent aircraft initiative, laser propulsion, microelectrolmechanical (MEMS) electrospray thrusters, plasma actuators, electric propulsion, and hypersonic flight.

The resulting technologies were classified according to three categories: Propulsion Technologies, Aeronautics Technologies, and Aircraft Technologies. A total of 21 identified technology trends have been compiled:

Propulsion Technologies

- Micropropulsion
- Plasma combustion and thrusters
- Electric propulsion
- Fusion propulsion
- Laser propulsion
- Spray combustion
- MEMS electrospray thruster
- Nuclear thermal propulsion

Aeronautics Technologies

- Low- and high-altitude airships
- Blended wing body aircraft
- Adaptive wing shape control
- Surface effect transports
- Unmanned aerovehicles
- Extreme short takeoff and landing vehicles (ESTOL)
- Supersonic cruise
- High-lift concepts

Aircraft Technologies

- Silent aircraft
- Distributed power systems for measurement and inspection technologies
- Multifunction structures
- Integrated wireless airplane systems
- Integrated thermal management

While surveying these resources, the aim was to document high-level future aviation trends and concepts. For the next phase of this project, we will define these technologies in detail. In addition, we plan to work with appropriate NASA personnel and other collaborators to further develop technical expertise in these areas in order to relate them to IVHM topics and assess their potential impact on the NASA ARMD IVHM Project.

6.0 Current and Future Directions of IVHM-Related Technologies

The fifth and final study outcome is addressed in this section, which details technology trends in research related to detection, diagnosis, prognosis, and mitigation for IVHM applications. The data used for identifying and organizing IVHM technologies and trends were gathered primarily from

- Survey results from literature
- JSF Prognostics Health Management System documents (Ref. 9)
- AFRL Advanced Sensor Development for Health Monitoring documents (Refs. 10 and 11)
- Boeing IVHM technologies focus area documents through the Space Act Agreement (SAA)

While surveying these resources, we aimed both at documenting the state of the art in current IVHM technologies, including those employed by major military and commercial platforms (JSF PHM program, the U.S. Air Force, and Boeing), and at identifying potential technologies for future aerospace applications.

The organizational scheme followed here, however, can be redefined depending on the future needs of both the IVHM Project and the broader IVHM community. In fact, similar studies in the literature have adopted varying organizational schemes for documenting future technologies and developing technology roadmaps. To give an example, Boeing organizes technology focus areas based on major subsystems and components of an aircraft and include new and emerging technologies listed under Propulsion IVHM, Environmental Control, Electronics IVHM, Electrical Power Systems, Batteries, Wiring, Landing Gear, Electromechanical Actuators, Hydraulic Actuators, Fuel Systems, and Generators. Similarly, JSF PHM and other relevant AFRL programs have their own organizational schemes for organizing IVHM-related technologies.

When identifying these technologies, a distinction between current and emerging technologies has not been made. Although this distinction can be made, the difference is subtle in light of all the documents reviewed. It often depends on the maturation level of a specific technology and the objectives of the program it is used in. A combined list of current and emerging technologies for IVHM has been provided.

The resulting technologies are classified according to 8 categories with a total of 34 current or emerging technology areas:

- Measurement and Inspection Technologies
  - Acoustic emission
  - Induced positron annihilation
  - Robust laser interferometer
  - Eddy current inspection
  - Thermography
  - Time domain reflectometry
  - Stress wave analysis
- Sensor Technologies
  - MEMS devices
  - Eddy current
  - Corrosion
  - Surface acoustic wave
  - Tomography
  - Fiber optics
  - Silicon carbide

- Solid state vacuum
- Thin film (ceramic)
- Piezoelectric materials
- Microwave blade tip
- Sensor Management Technologies
  - Distributed smart sensor network
  - Adaptive energy harvesting
- Detection Technologies
  - Piezoceramic crack
  - Foreign object damage (FOD)
- Component and Subsystem Monitoring Technologies
  - Gas path debris
  - Blade harmonics (vibration)
  - Wiring
  - Solder joint fatigue modeling and monitoring
- Diagnosis Technologies
  - Distributed and agent-based diagnostics
  - Fuzzy reasoning
- Prognosis Technologies
  - Actuator
  - Electronics
  - Bearing
  - Prognostic fusion
- Mitigation Technologies
  - Arc fault prevention
  - Selective fault reporting

For additional information regarding these technologies, including descriptions of the technology and literature references, see Reference 5.

7.0 Discussion and Conclusions

Around 15 to 20 percent of commercial aircraft accidents between 1988 and 2003 involved malfunctions or failures of some aircraft system or component, and roughly 15 to 20 percent of those accidents included at least one fatality. In addition, 60 to 70 percent of incidents during the same time period consisted of a SCFM.

Less than 25 percent of the SCFM accidents resulted in destruction of the aircraft. 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 failures or malfunctions either occurred while the aircraft was on the ground or resulted in an uneventful landing, whereas 69 percent of the Part 135 failures or malfunctions resulted in a complicated landing.

Engine and landing gear failures/malfunctions dominate both accidents and incidents, with those two systems accounting for between 48 and 77 percent of all SCFM accidents and incidents. Among accidents and Part 121 incidents, failures and malfunctions have been more frequent in the engine than in landing gear, but among Part 135 incidents, landing gear malfunctions occurred more often. No other system accounted for more than 10 percent of the failure/malfunction accidents or incidents.

In general, failures or malfunctions 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 malfunctions were the most likely type to occur while the aircraft was on the ground. Similarly, failures or malfunctions of either the structure or flight control systems result in more severe outcomes, perhaps because these malfunctions were more likely to lead to in-flight loss of control.

The IVHM Project research technologies were found to map to the Joint Planning and Development Office's National Research and Development Plan (R&D) as well as the Safety Working Group's National Aviation Safety Strategic Plan (NASSP). The IVHM Project is related to two R&D safer system applied research objectives: applied research on systems health management, and applied research on vulnerability discovery. All four levels of the IVHM Project's Technical Plan can be directly linked to five objectives contained within the safety systems and safety practices goals of the NASSP.

Future directions in Aviation Technology as related to IVHM were identified by reviewing papers from three conferences across a 5-year timespan. A total of 21 trend groups in propulsion, aeronautics, and aircraft categories were compiled.

Current and future directions of IVHM-related technologies were gathered through a survey of literature, Joint Strike Fighter Prognostics Health Management System documents, AFRL Advanced Sensor Development for Health Monitoring documents, and Boeing IVHM technology focus area documents. The resulting technologies were classified according to eight categories: measurement and inspection, sensors, sensor management, detection, component and subsystem monitoring, diagnosis, prognosis, and mitigation.

Appendix A.—Acronyms

AFRL	Air Force Research Laboratory
AIAA	American Institute of Aeronautics and Astronautics
APU	auxiliary power unit
ARMD	Aeronautics Research Mission Directorate
ASIAS	Aviation Safety Information Analysis and Sharing
AvSafe	Aviation Safety Program
ATS	Air Transportation System
DASHlink	Discovery in Aeronautics Systems Health Collaborative Web site
ESTOL	extreme short takeoff and landing
FAA	Federal Aviation Administration
FAP	Fundamental Aeronautics Program
FAR	Federal Aviation Regulation
FOD	foreign object damage
IEEE	Institute of Electrical and Electronic Engineers
IVHM	Integrated Vehicle Health Management
JPDO	Joint Planning and Development Office
JRMET	Joint Reliability and Maintainability Evaluation Team
JSF	Joint Strike Fighter
MEMS	microelectromechanical devices
NASA	National Aeronautics and Space Administration
NASSP	National Aviation Safety Strategic Plan
NextGen	Next Generation Air Transportation System
NTSB	National Transportation Safety Board
OI	operational improvement
OMB	Office of Management and Budget
PHM	prognostics health management
R&D	Research and Development Plan (JPDO)
SAA	Space Act Agreement
SBIR	Small Business Innovation Research
SCFM	system/component failure/malfunction
TDSB	Test Data Scoring Board

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14. ABSTRACT
Statistical data and literature from academia, industry, and other government agencies were reviewed and analyzed to establish requirements for future work in detection, diagnosis, prognosis, and mitigation for IVHM related hardware and software. Around 15 to 20 percent of commercial aircraft accidents between 1988 and 2003 involved malfunctions or failures of some aircraft system or component. Engine and landing gear failures/malfunctions dominate both accidents and incidents. The IVHM Project research technologies were found to map to the Joint Planning and Development Office's National Research and Development Plan (RDP) as well as the Safety Working Group's National Aviation Safety Strategic Plan (NASSP). Future directions in Aviation Technology as related to IVHM were identified by reviewing papers from three conferences across a five year time span. A total of twenty-one trend groups in propulsion, aeronautics and aircraft categories were compiled. Current and future directions of IVHM related technologies were gathered and classified according to eight categories: measurement and inspection, sensors, sensor management, detection, component and subsystem monitoring, diagnosis, prognosis, and mitigation.

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