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Aviation Trends Related to Atmospheric Environment Safety Technologies Project Technical Challenges

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Summary

Current and future aviation safety trends related to the National Aeronautics and Space Administration (NASA) Atmospheric Environment Safety Technologies (AEST) Project's three technical challenges (TCs) were assessed by examining accidents from the National Transportation Safety Board (NTSB) database, incidents from the Federal Aviation Administration (FAA) database, and literature from various industry and government sources. The three AEST TCs are engine icing characterization and simulation capability; airframe icing simulation and engineering tool capability; and atmospheric hazard sensing and mitigation (AHSM) technology capability.

The NTSB accident data was examined for fixed-wing airplanes operating under Federal Aviation Regulation (FAR) Parts 121, 135, and 91 from 1989 to 2008 for atmospheric conditions related to airframe icing, ice-crystal engine icing, turbulence, clear air turbulence (CAT), wake vortex, lightning, and low visibility (fog, low ceiling, clouds, precipitation, and low lighting). Less than 5 percent of all accidents were affected by icing conditions, although when icing was involved in Parts 91 and 135 scheduled operations, between 25 and 54 percent involved fatalities. No accidents involving ice crystal engine icing were found in the NTSB database. Accidents with turbulence were a cause or factor in 24 percent of Part 121 accidents. Turbulence accidents usually did not involve fatalities. CAT was found to be involved in 19 percent of all turbulence accidents. Less than 1 percent of all accidents involved either wake vortex or lightning, although this may increase in the future due to denser en route and terminal area operations for wake vortex and the introduction of new aircraft with composite structures for lightning. Low visibility was involved in between 6 and 23 percent of all accidents depending on operational category. Nearly one-third of all accidents are caused by the combined atmospheric conditions studied in this analysis. The accident rate for accidents involving any atmospheric condition causal factor

declined for Parts 91 and Part 135–NS, increased for Part 135–S, and remained steady for Part 121 operations.

The FAA Accident/Incident Data System (AIDS) database was examined for incidents that occurred during the years 1985 to 2006 related to airframe icing, ice crystal engine icing, turbulence, CAT, wake vortex, lightning, and low visibility for fixed-wing airplanes operating under FAR Part 121, 135, and 91. Engine icing was found to be involved in 14 of the incidents, 2 of which specifically cited as “ice crystals”. These incidents are often not thoroughly investigated and often lack sufficient detail. Less than 2 percent of the incidents were affected by airframe icing, and less than 3 percent involved turbulence. Low visibility was a factor in 27 percent of the incidents and has declined over the time period. Close to one-third of all incidents in Parts 121 and 135 operations were affected by the six atmospheric conditions examined in this study. Icing, turbulence, wake vortex, lightning, low lighting and low visibility and have declined over the time period of this study.

Five future aviation safety risk areas associated with the three AEST TCs were identified after an exhaustive survey of a variety of sources and include: approach and landing accident reduction, icing/ice detection, loss of control (LOC) in flight, super density operations, and runway safety. The focus of AEST research is on in-flight icing, both engine and airframe, as well as on investigations of other high-priority atmospheric hazards and sensor technologies required for their detection. The engine and airframe icing TCs will impact the future risk areas of icing/ice detection and LOC in flight. The third TC, AHSM technology capability, will impact the future risk areas of approach and landing reduction, icing/ice detection, LOC in flight, runway safety, and super density operations.

1.0 Introduction

NASA’s Aviation Safety Program (AvSP) includes three research projects. One of these, the Atmospheric Environment Safety Technologies (AEST) Project, focuses on three technical challenges (TCs) (Ref. 1):

- TC1: Engine icing characterization and simulation capability
- TC2: Airframe icing simulation and engineering tool capability
- TC3: Atmospheric hazard sensing and mitigation (AHSM) technology capability

This report analyzes aviation safety trends related to these AEST TCs by reviewing the most current statistical and prognostic data available including accident and incident data as well as literature from academia, industry, and other Government agencies. This study evaluates possible impacts of the TCs on historic and future aviation safety hazards and how aviation safety risk areas change over time. The following data and published research were examined:

- Accidents (using the National Transportation Safety Board (NTSB) Aviation Accident and Incident Data System)
- Incidents (using the Federal Aviation Administration (FAA) Accident/Incident Data System (AIDS) database)
- Industry and government data and published research sources:
 - Decadal Survey of Civil Aeronautics, National Research Council
 - National Aeronautics Research and Development Plan
 - National Transportation Safety Board Most Wanted Aviation Safety Improvements 2010
 - Joint Planning and Development Office Safety Working Group Issues Database

- Future Aviation Safety Teams Areas of Change
- Next Generation Air Transportation System (NextGen) Integrated Work Plan
- Commercial Aviation Safety Team's Safety Enhancements
- NextGen Implementation Plan
- Icing Protection Harmonization Working Group

2.0 Background

Public benefits derived from continued growth in passenger and cargo transport depend on intrinsic safety improvements on current and future air vehicles to operate in NextGen. The AvSP addresses this challenge by conducting cutting-edge, fundamental research to yield innovative algorithms, tools, concepts, and technologies from the discipline level up to subsystem and system levels. As part of the AvSP, the AEST Project focuses primarily on both engine and airframe in-flight icing. Research also includes investigations of other high-priority atmospheric hazards and sensor technologies for their detection. The AEST Project will investigate sources of risk and provide technology needed to help ensure safe flight in and around atmospheric hazards.

3.0 Technical Challenge Descriptions

The AEST Project focuses on the following three TCs:

- TC1: Engine icing characterization and simulation capability: Develop knowledge bases, analysis methods, and simulation tools to address engine icing, particularly ice crystal icing. The goal of TC1 is to eliminate turbofan engine interruptions, failures, and damage caused by flights into high ice crystal content clouds. Research will enable new engine icing protection systems and methods and provide a verified basis for engine icing certification requirements.
- TC2: Airframe icing simulation and engineering tool capability: Develop and demonstrate three-dimensional simulations and experimental methods for modeling of airframe ice accretion and related aerodynamic performance degradation in an icing environment that expands to include freezing drizzle and rain for current and future aircraft configurations. The goal of TC2 is to achieve acceptance of simulation tools for design and certification of swept-wing configurations over an expanded range of icing conditions. Research will develop technology that enables safe flight operations in a supercooled large droplet (SLD) environment; enables aircraft manufacturers to perform reliable icing assessments; and builds in effective icing mitigation approaches for current and future aircraft.
- TC3: AHSM technology capability: Improve and expand remote sensing and mitigation of hazardous atmospheric environments and phenomena. The goals of TC3 are to develop mature technologies for sensing and measuring icing, turbulence, and wake vortex hazards to provide real-time information to pilots and operators in the National Airspace System (NAS); address low visibility conditions for safer runway operations; and advance technologies for lightning-immune composite aircraft. Research performed under this TC will provide flight crews with a greater ability to avoid hazards, share available information available with other aircraft and ground-based systems, and reduce the vulnerability of aircraft to lightning and other hazards.

Research will be conducted in several associated subproject elements to address the three TCs shown in Figure 1.

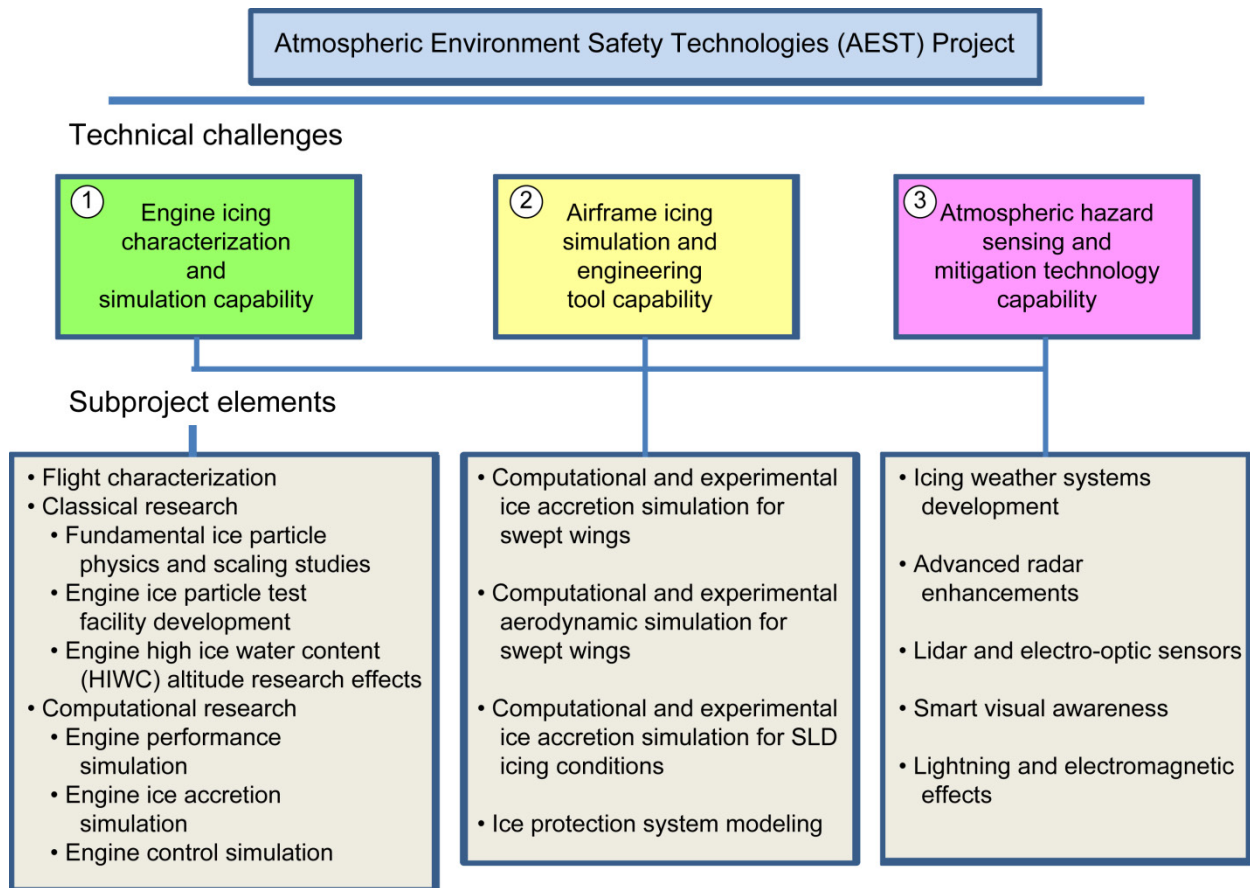


Figure 1.—AEST Project research framework.

4.0 National Transportation Safety Board Data Accident Analysis

The NTSB, an independent Federal agency, investigates every civil aviation accident in the United States and significant accidents in other transportation modes. The NTSB also conducts special investigations, provides safety studies, and issues safety recommendations to prevent future accidents. Reports produced by NTSB investigators provide details about accidents, analysis of factual information, conclusions and the probable cause, factors and findings of accidents, and related safety recommendations. Causes are the direct source of accidents while factors contribute to accidents. Each accident can have multiple causes and factors (Ref. 2). Findings are actions that occurred in conjunction with the accident, but were not determined to have contributed to the accident. For example, an aircraft might have flown in or near a thunderstorm with lightning, but the lightning had no impact on the flight or the accident. Similarly, the flight might have taken place during the night, but lack of visibility in the dark had no effect on the flight. Reports are located in the NTSB Aviation Accident and Incident Data System.

The NTSB data was searched for AEST TC-related accidents including the following atmospheric conditions that were cited as “causes” or “factors,” but not findings:

- Icing (ice, freezing rain, drizzle, and ice crystals)
- Turbulence (related to thunderstorm and clear air)

- Wake vortex
- Lightning
- Low lighting
- Low visibility (fog, low ceilings, clouds, below approach/landing minimums, haze, smoke, obscuration, and whiteout)

Federal Aviation Regulations (FARs) are FAA regulations that govern all aviation activities in the United States and are contained in Title 14 of the Code of Federal Regulations. FARs are organized into sections called parts depending on specific types of activity. Other parts regulate certification of pilots, schools, and aircraft and their operation (Ref. 3).

The NTSB database includes accident reports that involved airplanes, helicopters, hot air balloons, gliders, ultralight aircraft, etc., and operations conducted under the following operational categories:

- Part 91: General Aviation (small noncommercial aircraft)
- Part 121: Commercial Air Carriers (aircraft with 10 or more seats)
- Part 129: Foreign Air Carriers
- Part 135: Commuters and On-Demand Air Taxis (aircraft with fewer than 10 seats)
- Part 137: Agricultural Operations

Part 121 operations originally included aircraft with 30 or more seats. In March 1997 the definition changed to include aircraft with 10 or more seats. (Ref. 4).

The NTSB considers each event to be either an accident or an incident using the following definitions (Ref. 5):

- 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 disembark, 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.

Injuries or aircraft damage that occur when there was no intent for flight (high-speed taxi tests, aircraft movement around the airfield, maintenance run-ups, etc.) are, by definition, incidents.

All recorded accidents involving commercially built fixed-wing airplanes operating under FAR Parts 121, 135, and 91 regulations were included in this analysis, regardless of whether the investigations are preliminary or finalized, and whether or not the events occurred in the United States. Amateur-built and experimental aircraft, helicopters, ultralight aircraft, gliders, and balloons were excluded. The only sky diving accidents that were included were those caused by the aircraft, not the parachute or parachutist.

4.1 TC1: Engine Icing Characterization and Simulation Capability

A search of NTSB accident data did not yield propulsion system-related accidents that were impacted by ice crystals. There were accidents, however, that did involve carburetor and/or fuel system icing.

4.2 TC2: Airframe Icing Simulation and Engineering Tool Capability

The database was searched for any accident caused by in-flight icing conditions, freezing rain, or drizzle and with or without confirmed ice accretion. Accidents caused by inadequate preflight frost, ice, and snow removal were not included in this group. A summary of the accidents caused by in-flight icing conditions are found in Table 1. Two types of fatal accident percentages are of interest: the percentage of all fatal accidents caused by icing conditions and the percentage of accidents caused by icing conditions with a fatality. The numerators in these percentages are identical (fatal accidents caused by icing conditions) but the denominators are different.

Less than 5 percent of the accidents were related to icing conditions. Between 3 and 8 percent of fatal accidents and between 3 and 11 percent of fatalities were related to icing conditions. Percentages were highest in nonscheduled Part 135 (Part 135–NS) flights, except for the percentage of fatalities, which was highest among scheduled Part 135 (Part 135–S) flights. Although the percentage of accidents, fatal accidents, and fatalities that were related to icing conditions is low, the percentage of accidents related to icing conditions, in which there was at least one fatality, ranges from 25 percent for Part 135–S to 54 percent for Part 91.

Figure 2 displays the change in the accident rate (per million flight hours) for accidents that were related to icing conditions across four time periods. Rates have declined over time for every category of flight operations, except Part 135–S, which increased significantly between the 1994 to 1998 and the 1999 to 2003 time periods.

TABLE 1.—ICING-CONDITION-RELATED ACCIDENT DATA BY OPERATIONAL CATEGORY, 1989 TO 2008

Data category	Flight operation category			
	Part 121	Part 135–S	Part 135–NS	Part 91
Flight hours, total	317,999,117	24,446,927	61,751,000	507,516,000
Accidents, total	738	219	1202	26,922
Accidents per million flight hours	2.321	8.959	19.465	53.047
Accidents caused by icing conditions	5	8	54	321
Accidents caused by icing conditions per million flight hours	0.015	0.327	0.874	0.632
Accidents caused by icing conditions, percent	1% (5/738)	4% (8/219)	5% (54/1202)	1% (5214/26922)
Fatal accidents, total	67	48	307	5214
Fatal accidents caused by icing conditions	2	2	23	172
Fatal accidents caused by icing conditions, percent	3% (2/67)	4% (2/48)	8% (23/307)	3% (172/5214)
Accidents caused by icing conditions with a fatality, percent	40% (2/5)	25% (2/8)	43% (23/54)	54% (172/5214)
Fatalities, total	1956	309	745	10 109
Fatalities caused by icing conditions	70	35	27	395
Fatalities caused by icing conditions, percent	4% (70/1956)	11% (35/309)	4% (27/745)	4% (395/10109)

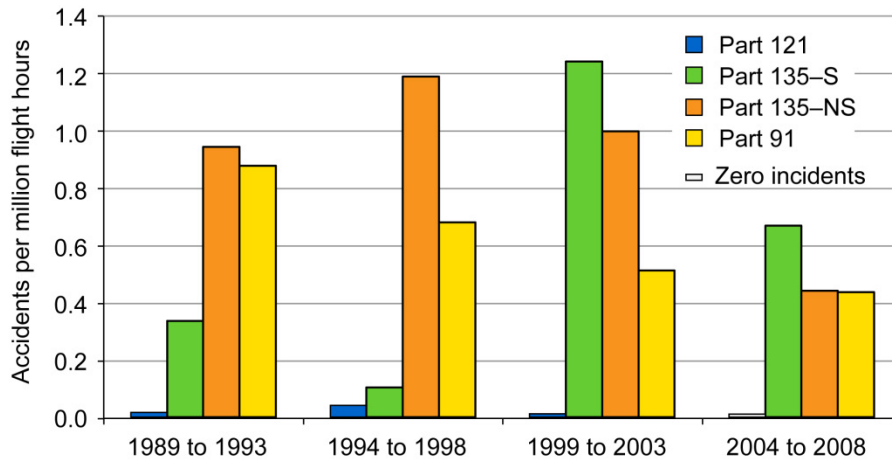


Figure 2.—Icing-related accident rate by operational category across four time periods.

4.3 TC3: Atmospheric Hazard Sensing Mitigation Technology Capability

The database was searched for accidents caused by turbulence, wake vortex, lightning, low lighting and low visibility conditions. Information on icing conditions is found in Section 4.2.

4.3.1 Turbulence

A summary of the accidents that were caused by in-flight turbulence are found in Table 2. Turbulence related to thunderstorms is included but not terrain-induced or wake vortex turbulence. There are two types of fatal accident percentages that are of interest: the percentage of all fatal accidents that included a condition (such as turbulence) and the percentage of accidents marked by that condition in which there was a fatality. The numerators are identical (e.g., fatal turbulence accidents) but the denominators are different. Twenty-four percent of Part 121 accidents, compared with less than 1 percent of accidents in other flight operations, were caused by turbulence. Less than 3 percent of fatal accidents and fatalities were caused by turbulence, regardless of flight operation. Turbulence was least likely to be a factor in Part 135-S accidents, and no fatalities were associated with turbulence in that flight category. Even in Part 121 the number of fatalities was very low. However, more than half of the Part 135-NS and Part 91 accidents that were affected by turbulence included at least one fatality.

Figure 3 displays the change in the accident rate related to turbulence across four time periods. Rates have declined over time for Parts 91 and 135-NS, while Part 135-S rates have increased. As shown in Table 2, the total number of accidents affected by turbulence was lowest in Part 135-S. Part 121 turbulence caused accident rates to increase during the 1994 to 2003 time period before decreasing during the 2004 to 2008 time period.

The AEST Project is particularly interested in reducing the risk of encounters with clear air turbulence (CAT). Figure 4 displays the change in the accident rate related to CAT across the four time periods. The rate for Part 135-S has increased dramatically in the most recent time period. Table 3 summarizes CAT-related accidents, which accounts for 19 percent of all turbulence-related accidents (64 of 344 turbulence-caused accidents). CAT was involved in 6 percent of all Part 121 accidents and was more likely to be a factor in Part 121 operations than Parts 135 or 91. Most CAT accidents did not involve a fatality.

TABLE 2.—TURBULENCE-RELATED-ACCIDENT DATA BY OPERATIONAL CATEGORY, 1989 TO 2008

Data Category	Flight operation category			
	Part 121	Part 135-S	Part 135-NS	Part 91
Flight hours, total	317,999,117	24,446,927	61,751,000	507,516,000
Accidents, total	738	219	1202	26,922
Accidents per million flight hours	2.321	8.959	19.465	53.047
Accidents caused by turbulence	180	2	9	153
Accidents caused by turbulence per million flight hours	0.566	0.082	0.146	0.301
Accidents caused by turbulence, percent	24% (180/738)	1% (2/219)	1% (9/1202)	1% (153/26922)
Fatal accidents, total	67	48	307	5214
Fatal accidents caused by turbulence	2	0	5	91
Fatal accidents caused by turbulence, percent	3% (2/67)	0% (0/48)	2% (5/307)	2% (91/5214)
Accidents caused by turbulence with a fatality, percent	1% (2/180)	0% (0/2)	56% (5/9)	60% (91/153)
Fatalities, total	1956	309	745	10,109
Fatalities caused by turbulence	2	0	8	201
Fatalities caused by turbulence, percent	0% (2/1956)	0% (0/309)	1% (8/745)	2% (201/10109)

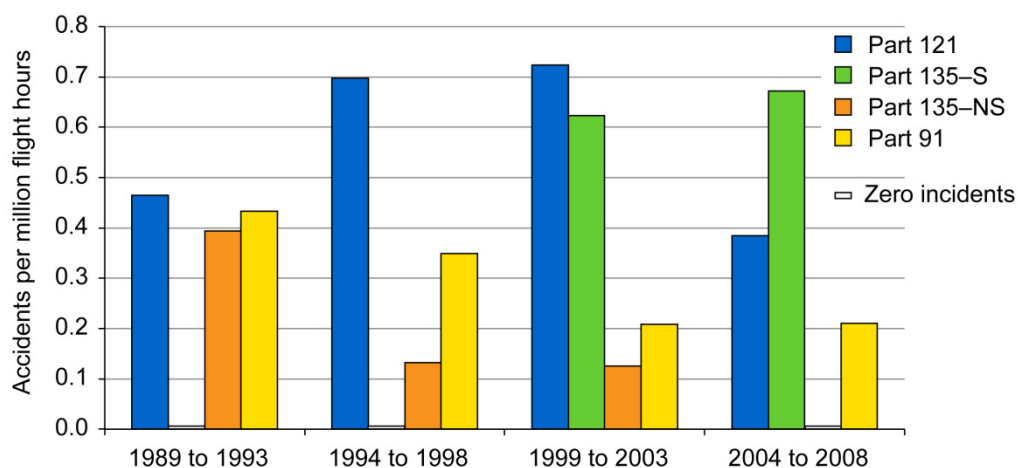


Figure 3.—Turbulence-related accident rate by operational category across four time periods.

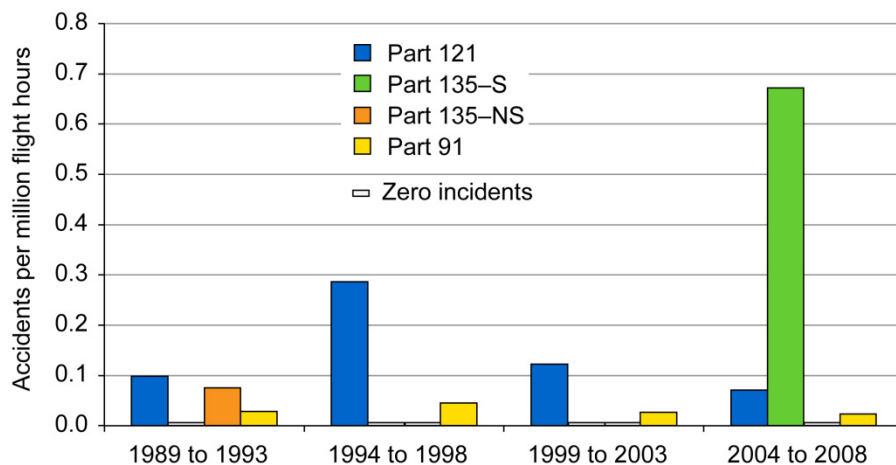


Figure 4.—Clear-air-turbulence-related accident rate by operational category across four time periods.

TABLE 3.—CLEAR-AIR-TURBULENCE-RELATED ACCIDENT DATA BY OPERATIONAL CATEGORY, 1989 TO 2008

Data category	Flight operation category			
	Part 121	Part 135-S	Part 135-NS	Part 91
Flight hours, total	317,999,117	24,446,927	61,751,000	507,516,000
Accidents, total	738	219	1,202	26,922
Accidents per million flight hours	2.321	8.959	19.465	53.047
Accidents caused by CAT ^a	45	1	1	17
Accidents caused by CAT per million flight hours	0.142	0.041	0.016	0.033
Accidents caused by CAT, percent	6% (45/738)	1% (1/219)	0% (1/1202)	0% (17/26922)
Fatal accidents, total	67	48	307	5214
Fatal accidents caused by CAT	1	0	1	3
Fatal accidents caused by CAT, percent	2% (1/67)	0% (0/48)	0% (1/307)	2% (17/5214)
Accidents caused by CAT, percent	2% (1/45)	0% (0/1)	100% (1/1)	18% (3/17)
Fatalities, total	1956	309	745	10,109
Fatalities caused by CAT	1	0	1	8
Fatalities caused by CAT, percent	0% (1/1956)	0% (0/309)	0% (1/745)	0% (8/10109)

^aClear air turbulence.

4.3.2 Wake Vortex

A summary of accidents caused by wake vortex are found in Table 4. These numbers include aircraft that were impacted by the wake vortex, not the aircraft that caused the wake vortex encounter. Jet blast or propeller wash from engine run-up or movements from a standing position were not included either. In general, less than 1 percent of all accidents, fatal accidents, and fatalities were related to wake vortex, except that 2 percent of fatal accidents in Part 135-S were associated with wake vortex. This single accident resulted in three fatalities. Two of the three Part 135-NS wake vortex accidents included at least one fatality (67 percent). Almost 12 percent of the Part 91 wake vortex accidents were fatal.

Figure 5 displays the change in the accident rate related to wake vortex across four time periods. Rates have remained fairly constant over time, except for Part 91, which has shown a consistent decline. Although the accident rate caused by wake vortex has been low and decreasing during this study, expected growth in the demand for air transportation will require denser en route and terminal area operations, resulting in an increase in likelihood of an encounter with a wake vortex.

TABLE 4.—WAKE VORTEX-RELATED ACCIDENT DATA BY OPERATIONAL CATEGORY, 1989 TO 2008

Data category	Flight operation category			
	Part 121	Part 135–S	Part 135–NS	Part 91
Flight hours, total	317,999,117	24,446,927	61,751,000	507,516,000
Accidents, total	738	219	1,202	26,922
Accidents per million flight hours	2.321	8.959	19.465	53.047
Accidents caused by wake vortex	5	1	3	61
Accidents caused by wake vortex per million flight hours	0.016	0.041	0.049	0.120
Accidents caused by vortex, percent	1% (5/738)	1% (1/219)	0% (3/1202)	0% (61/26922)
Fatal accidents, total	67	48	307	5214
Fatal accidents caused by wake vortex	0	1	2	7
Fatal accidents caused by wake vortex, percent	0% (0/67)	2% (1/48)	1% (2/307)	0% (7/5214)
Accidents caused by vortex with a fatality, percent	0% (0/5)	100% (1/1)	67% (2/3)	12% (7/61)
Fatalities, total	1956	309	745	10,109
Fatalities caused by wake vortex	0	3	6	15
Fatalities caused by wake vortex, percent	0% (0/1956)	1% (3/309)	1% (6/745)	0% (15/10109)

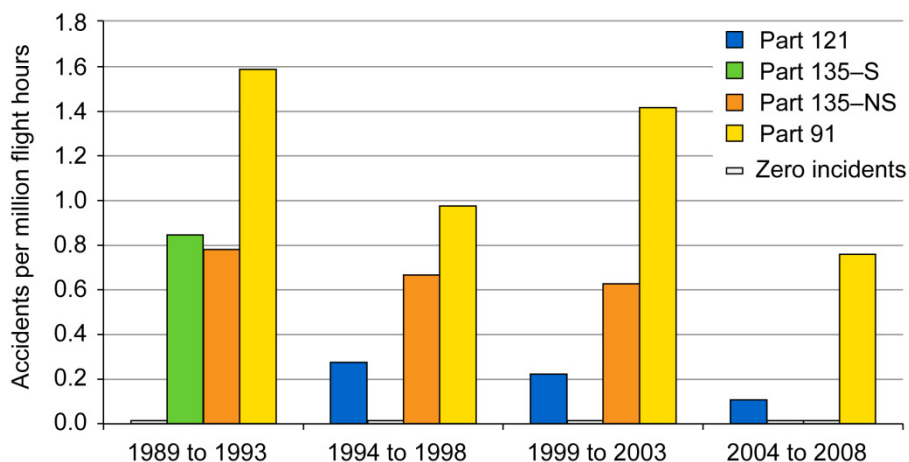


Figure 5.—Wake-vortex-related accident rate by operational category across four time periods.

4.3.3 Lightning Strikes

A summary of accidents caused by lightning are found in Table 5. In general, lightning was a cause or factor in less than one-half of 1 percent of all accidents, fatal accidents, and fatalities. The one exception was that 2 percent of the Part 121 fatal accidents were associated with lightning. This single accident in 1989 resulted in one fatality when lightning struck an aircraft in the ramp area, and a ground crew member was connected to the aircraft via headset. There were no lightning-related fatal accidents in Part 135, but 64 percent of the Part 91 lightning-related accidents were fatal.

Figure 6 displays the accident rate related to lightning across four time periods. With the exception of Part 135–S, rates have been fairly consistent over time.

TABLE 5.—LIGHTNING-RELATED ACCIDENT DATA BY OPERATIONAL CATEGORY, 1989 TO 2008

Data category	Flight operation category			
	Part 121	Part 135–S	Part 135–NS	Part 91
Flight hours, total	317,999,117	24,446,927	61,751,000	507,516,000
Accidents, total	738	219	1,202	26,922
Accidents per million flight hours	2.321	8.959	19.465	53.047
Accidents caused by lightning	3	0	2	14
Accidents caused by lightning per million flight hours	0.009	0.000	0.032	0.028
Accidents caused by lightning, percent	0% (3/738)	0% (0/219)	0% (2/1202)	0% (14/26922)
Fatal accidents, total	67	48	307	5214
Fatal accidents caused by lightning	1	0	0	9
Fatal accidents caused by lightning, percent	2% (1/67)	0% (0/48)	0% (0/307)	0% (9/5214)
Accidents caused by lightning with a fatality, percent	33% (1/3)	0% (0/0)	0% (0/2)	64% (9/14)
Fatalities, total	1956	309	745	10,109
Fatalities caused by lightning	1	0	0	19
Fatalities caused by lightning, percent	0% (1/1956)	0% (0/309)	0% (0/745)	0% (19/10109)

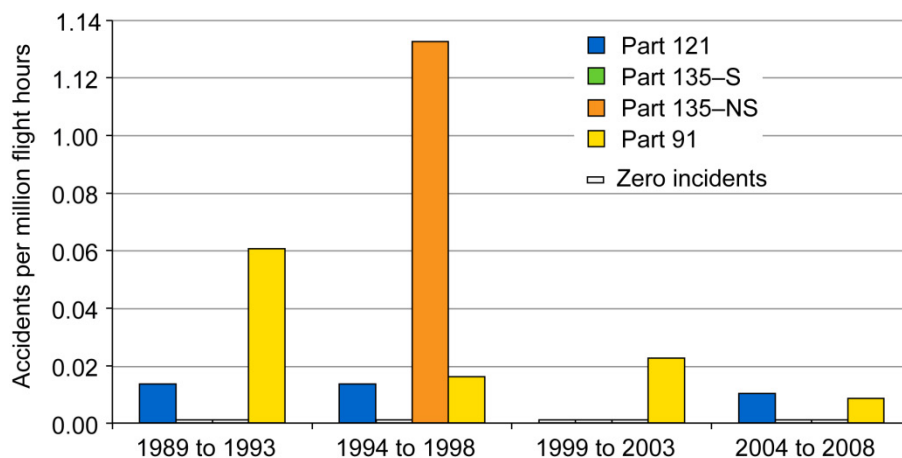


Figure 6.—Lightning-related accident rate by operational category across four time periods.

4.3.4 Low Visibility

In this report, low visibility refers to fog, low ceiling or clouds, below approach minimums, haze, smoke, obscuration, whiteout conditions, sand/dust storms, sun glare, precipitation, low lighting and unspecified visibility issues. “Visibility is the farthest distance at which an observer can distinguish objects. Ceiling is the altitude to the nearest cloud layer that obscures at least half of the sky” (Ref. 6). Low lighting conditions at dusk, dawn, and nighttime have a profound impact on safety. Low lighting conditions occur, for example, when the Moon is not present, there is extensive cloud cover, or manmade lighting (from around a city) is limited or nonexistent. Narratives from some accidents mention lack of visibility without being specific for example, instrument meteorological conditions (IMC) or some sort of precipitation, usually rain or snow.

A summary of the accidents that were related to low visibility are found in Table 6. The frequency of accidents caused by low visibility conditions varied across the four flight operation categories. In Part 121, low visibility caused 6 percent of all accidents and 6 percent of fatal accidents. In Part 91, low visibility caused 10 percent of accidents and 31 percent of fatal accidents. Part 135 flights were affected most by low visibility (19 to 23 percent of accidents and 37 to 40 percent of fatal accidents).

Figure 7 displays the change in the accident rate related to low visibility conditions across four time periods. The rate for Part 121 remained steady across the time periods, while Parts 91 and 135–NS rates declined.

TABLE 6.—LOW-VISIBILITY-RELATED ACCIDENT DATA BY OPERATIONAL CATEGORY, 1989 TO 2008

Data category	Flight operation category			
	Part 121	Part 135–S	Part 135–NS	Part 91
Flight hours, total	317,999,117	24,446,927	61,751,000	507,516,000
Accidents, total	738	219	1202	26,922
Accidents per million flight hours	2.321	8.959	19.465	53.047
Accidents caused by low visibility	41	51	227	2689
Accidents caused by low visibility per million flight hours	0.129	2.086	3.676	5.298
Accidents caused by low visibility, percent	6% (41/738)	23% (51/219)	19% (227/1202)	10% (2689/26922)
Fatal accidents, total	67	48	307	5214
Fatal accidents caused by low visibility	4	19	114	1606
Accidents caused by low visibility with a fatality, percent	6% (4/67)	40% (19/48)	37% (114/307)	31% (1606/5214)
Fatal accidents caused by low visibility, percent	10% (4/41)	37% (19/51)	50% (114/227)	60% (1606/2689)
Fatalities, total	1956	309	745	10,109
Fatalities caused by low visibility	22	92	279	3238
Fatalities caused by low visibility, percent	0% (1/1956)	0% (0/309)	34% (279/745)	32% (3238/10109)

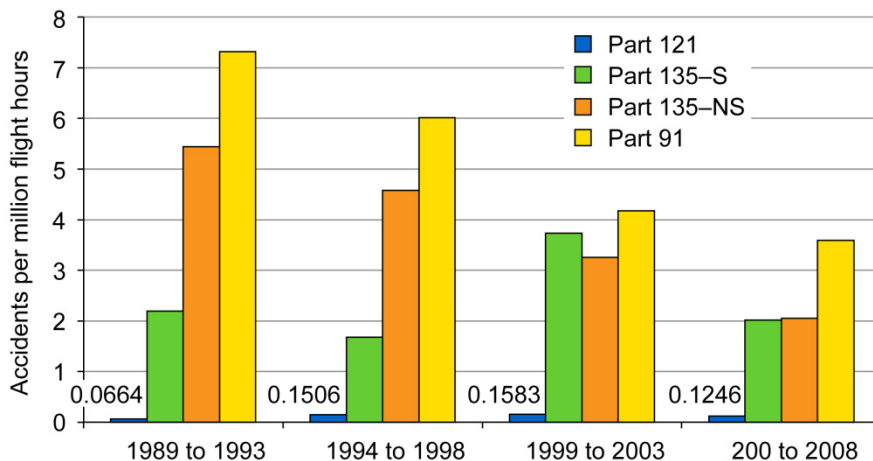


Figure 7.—Low-visibility-related accident rate by operational category across four time periods.

Accidents with low visibility as causes or factors were further sorted by the following types of low visibility to include

- Fog
- Low ceiling or clouds
- Precipitation
- Low lighting (dusk, dawn, or nighttime)
- Unspecified

Accidents caused by these types of low visibility conditions are summarized in Table 7. More than one condition might have affected particular accidents. In Parts 121, 135–NS and 91, the most likely low visibility condition was low lighting (39 to 80 percent). Low lighting was involved in 80 percent of Part 121 low-visibility-related accidents. In contrast, low ceiling and clouds were a cause in 42 to 53 percent of Parts 135 and 91 accidents, yet rarely a cause in Part 121 accidents.

4.3.5 All Six Atmospheric Conditions

A summary of accidents related to any of the atmospheric conditions previously discussed (icing, turbulence, CAT, wake vortex, lightning, and low visibility) are found in Table 8. Nearly one-third of Part 121 accidents had one or more of these six atmospheric conditions as a cause or factor, with only 4 percent involving a fatality. The lowest percentage of accidents caused by any of the atmospheric conditions was in Part 91, yet 58 percent involved fatalities.

Figure 8 displays the change in the accident rate related to the following atmospheric conditions across four time periods: icing, turbulence, CAT, wake vortex, lightning, and low visibility. Rates declined in every time period for Parts 91 and 135–NS, while Part 135–S operations increased. Part 121 operations remained somewhat steady over the time periods.

TABLE 7.—LOW VISIBILITY-RELATED ACCIDENT FREQUENCY BY TYPE
AND OPERATIONAL CATEGORY, 1989 TO 2008

Data category	Flight operation category			
	Part 121	Part 135-S	Part 135-NS	Part 91
Total	41	51	227	2689
Fog	4 (10%)	15 (29%)	58 (26%)	677 (25%)
Low ceiling/clouds	1 (2%)	27 (53%)	96 (42%)	1203 (45%)
Precipitation	7 (17%)	13 (25%)	45 (20%)	329 (12%)
Low lighting	33 (80%)	20 (39%)	116 (51%)	1427 (53%)
Unspecified	2 (5%)	13 (25%)	48 (21%)	382 (14%)

TABLE 8.—ATMOSPHERIC^a CONDITION-RELATED ACCIDENT DATA
BY OPERATIONAL CATEGORY, 1989 TO 2008

Data category	Flight operation category			
	Part 121	Part 135-S	Part 135-NS	Part 91
Flight hours, total	317,999,117	24,446,927	61,751,000	507,516,000
Accidents, total	738	219	1202	26,922
Accidents per million flight hours	2.321	8.959	19.465	53.047
Accidents caused by atmospheric conditions	234	61	279	3102
Accidents caused by atmospheric conditions per million flight hours	0.736	2.495	4.518	6.112
Accidents caused by atmospheric conditions, percent	32% (234/738)	28% (61/219)	23% (279/1202)	12% (3102/26922)
Fatal accidents, total	67	48	307	5214
Fatal accidents caused by atmospheric conditions	9	22	139	1783
Fatal accidents caused by atmospheric conditions, percent	13% (9/67)	46% (22/48)	45% (139/307)	34% (1783/5214)
Accidents caused by atmospheric conditions with a fatality, percent	4% (9/234)	36% (22/61)	50% (139/279)	58% (1783/3102)
Fatalities, total	1956	309	745	10,109
Accident fatalities caused by atmospheric conditions	95	130	312	3649
Fatalities caused by atmospheric conditions, percent	5% (95/1956)	42% (130/309)	42% (312/745)	36% (3649/10109)

^aIcing, turbulence, CAT, wake vortex, lightning, and low visibility combined.

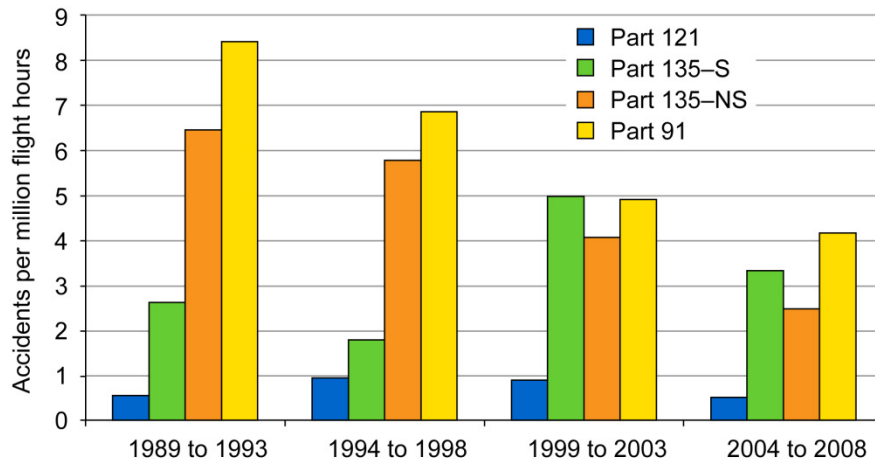


Figure 8.—Atmospheric-condition-related accident rate (icing, turbulence, CAT, wake vortex, lightning, and low visibility combined) by operational category across four time periods.

5.0 Federal Aviation Administration Incident Data Analysis

Each incident and accident is reported to the FAA by pilots, airport personnel, and private citizens although the NTSB does not investigate all incidents. The FAA maintains the Accident/Incident Data System (AIDS) database with the information contained in these reports and collected in their investigations.

A copy of the FAA’s AIDS database was obtained from the Aviation Safety Information Analysis and Sharing (ASIAS) System in October 2007—late enough in the year that nearly all incidents from 1985 to 2006 had been investigated.

FAA incident data are far less detailed than NTSB accident data. Weather and visibility conditions are mentioned without specifying causality. All mentions of fog, low ceilings, dusk or night flight, or less than one mile visibility were included in the low visibility results, as were those mentioned in the narratives of Visual Flight Rules (VFR) flight into IMC conditions and other unspecified, restricted visibility conditions. These unspecific visibility conditions are referred to as “unspecified” later in the report. Precipitation-related incidents were evaluated to determine whether the precipitation impacted the visibility or runway conditions.

Among the incidents in this analysis were some midair and ground collisions between multiple aircraft. The database includes an incident record for each aircraft involved, unless the aircraft was parked and unoccupied. In order to reduce the analysis data set to one record for each incident, incidents that involved multiple aircraft were reviewed and reports for passive aircraft (i.e., aircraft that was hit during the collision) were eliminated.

5.1 TC1: Engine Icing Characterization and Simulation Capability

A search of the FAA incident database showed that 38 incidents were caused by the propulsion system. Of the 38 incidents, 14 were caused by icing conditions or ice ingestion. Only two incidents specifically cited ice crystals in the propulsion system as a cause. Both of these incidents resulted in flameouts of all engines, cited a lack of training on the hazards of high-altitude ice crystals to turbine fan engines, and occurred in Florida. Of interest is a third incident that involved multiple-engine flameouts after passing through thunderstorms near Miami, Florida, but the report did not cite engine icing. Because a majority of the propulsion system-related incidents were not thoroughly investigated, clear causes of the

failures were not provided. Table 9 summarizes incidents that involved any form of engine icing. Most of the engine icing incidents occurred during Part 121 operations. Figure 9 provides the incident rate related to engine icing across four time periods.

5.2 TC2: Airframe Icing Simulation and Engineering Tool Capability

This section examines incidents that were related to in-flight icing conditions, freezing rain, or drizzle, with or without confirmed ice accretion. Incidents caused by inadequate preflight frost, ice, or snow removal were not included in this group. A summary of the incidents that were affected by in-flight icing conditions is found in Table 10. Less than 1 percent of incidents were affected by icing conditions. Figure 10 displays the incident rate related to icing conditions across four time periods. Rates have declined over time for each flight operations category except for Part 135–S. Rates for 2004 to 2008 are underestimated because they do not include 2 years of incident data.

TABLE 9.—ENGINE-ICING-RELATED INCIDENT DATA BY OPERATIONAL CATEGORY, 1989 TO 2006

Data category	Flight operation category			
	Part 121	Part 135–S	Part 135–NS	Part 91
Flight hours, total	317,999,117	24,446,927	61,751,000	507,516,000
Incidents, total	7647	1921	2189	27,919
Incidents per million flight hours	24.047	78.578	35.449	55.011
Incidents caused by engine icing	7	3	1	2
Incidents caused by engine icing per million flight hours	0.022	0.123	0.016	0.004
Incidents caused by engine icing, percent	0% (7/7647)	0% (8/21921)	1% (28/2189)	0% (2/27919)

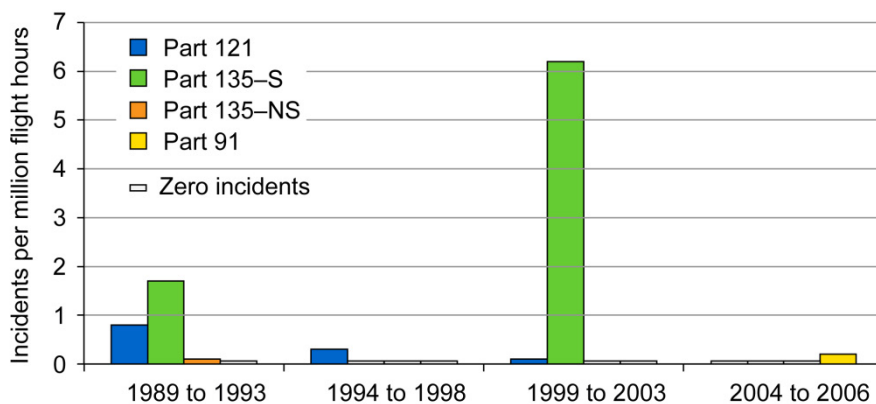


Figure 9.—Engine icing–related incident rate by operational category across four time periods.

TABLE 10.—ICING-RELATED INCIDENT DATA BY OPERATIONAL CATEGORY, 1989 TO 2006

Data category	Flight operation category			
	Part 121	Part 135-S	Part 135-NS	Part 91
Flight hours, total	317,999,117	24,446,927	61,751,000	507,516,000
Incidents, total	7647	1921	2189	27,919
Incidents per million flight hours	24.047	78.578	35.449	55.011
Incidents caused by icing conditions	32	8	28	95
Incidents caused by icing conditions per million flight hours	0.101	0.327	0.453	0.187
Incidents caused by icing conditions, percent	0% (32/7647)	0% (8/21921)	1% (28/2189)	0% (95/27919)

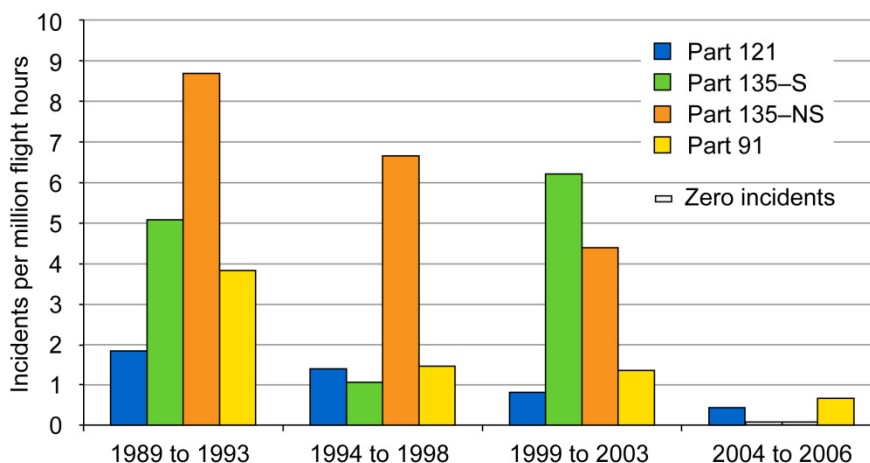


Figure 10.—Icing-related incident rates by operational category across four time periods.

Figure 10.—Icing-related incident rate by operational category across four time periods.

5.3 TC3: Atmospheric Hazard Sensing and Mitigation Technology Capability

This section examines incidents that were related to turbulence, wake vortex, lightning, low lighting and low visibility conditions. Information on icing conditions is found in Section 5.2.

5.3.1 Turbulence

A summary of the incidents that were affected by in-flight turbulence is found in Table 11. Terrain-induced and wake vortex turbulence are not included here, but turbulence related to thunderstorms is included. Less than 1 percent of all incidents in the FAA AIDS database were caused by turbulence. Figure 11 displays the incident rate related to turbulence across four time periods. The incidence rate has declined for all operation categories.

Of particular interest to the AEST Project is reducing the risk of encounters with CAT. Table 12 summarizes CAT-related incidents, which accounted for 3 percent of all turbulence-related incidents (10 of 295). Figure 12 displays the change in the incident rate related to CAT across four time periods. The rate has declined over time for Part 121 operations.

A summary of the incidents that were related to wake vortex are found in Table 13. These numbers include only aircraft that were affected by the wake vortex encounter, not the aircraft responsible for the wake vortex. Jet blast or propeller wash from engine run-up or movement from a standing position was not included either. Less than 1 percent of all incidents were influenced by wake vortex. Figure 13 displays the change in the incident rate related to wake vortex across four time periods. These rates increased during 1994 to 1998 and then decreased in the last two time periods. Although the incident rate related to wake vortex has been low and decreasing in the time period of this study, expected growth in the demand for air transportation will require denser en route and terminal area operations resulting in the need for wake vortex mitigation.

TABLE 11.—TURBULENCE-RELATED INCIDENT DATA BY OPERATIONAL CATEGORY, 1989 TO 2006

Data category	Flight operation category			
	Part 121	Part 135-S	Part 135-NS	Part 91
Flight hours, total	317,999,117	24,446,927	61,751,000	507,516,000
Incidents, total	7647	1921	2189	27,919
Incidents per million flight hours	24.047	78.578	35.449	55.011
Incidents in turbulence	190	8	17	80
Incidents caused by turbulence per million flight hours	00.597	0.327	0.275	0.158
Incidents caused by turbulence, percent	2% (190/7647)	0% (8/21921)	1% (17/2189)	0% (80/27919)

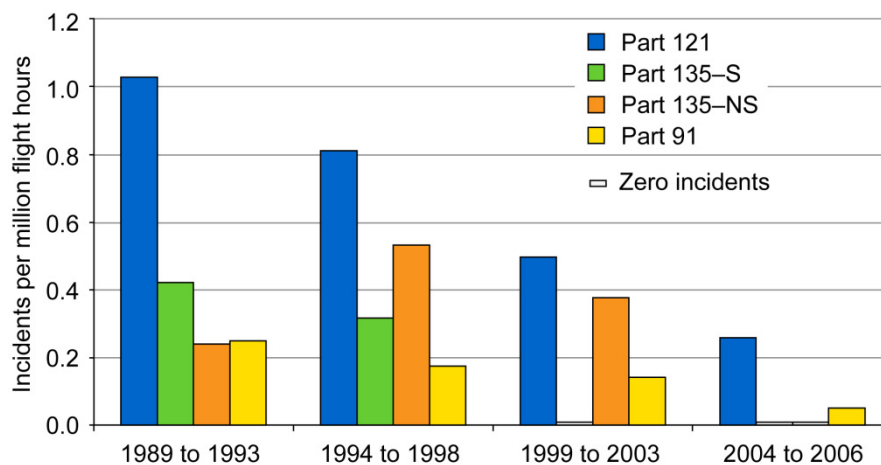


Figure 11.—Turbulence-related incident rate by operational category across four time periods.

TABLE 12.—CLEAR-AIR-TURBULENCE-RELATED INCIDENT DATA BY OPERATIONAL CATEGORY, 1989 TO 2006

Data category	Flight operation category			
	Part 121	Part 135-S	Part 135-NS	Part 91
Flight hours, total	317,999,117	24,446,927	61,751,000	507,516,000
Incidents, total	7647	1921	2189	27,919
Incidents per million flight hours	24.047	78.578	35.449	55.011
Incidents caused by CAT ^a	8	1	0	1
Incidents caused by CAT per million flight hours	0.025	0.041	0.000	0.002
Incidents caused by CAT, percent	0% (8/7647)	0% (1/21921)	0% (0/2189)	0% (1/27919)

^aClear air turbulence.

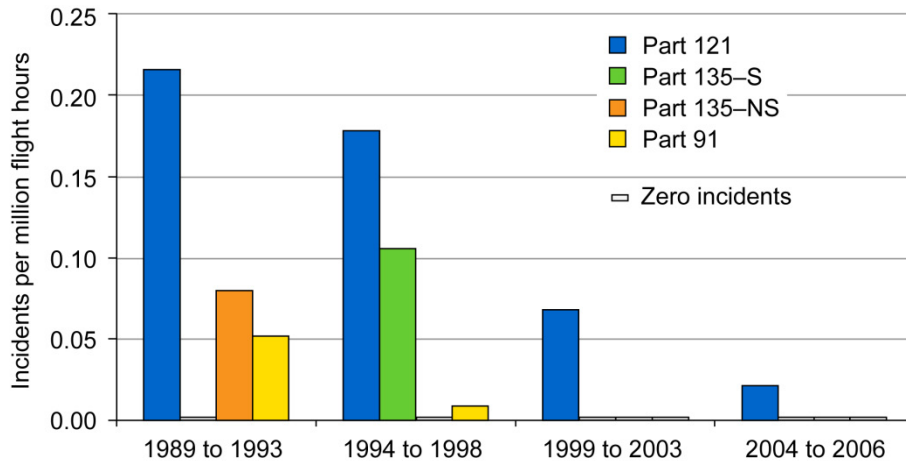


Figure 12.—Clear-air-turbulence-related incident rate by operational category across four time periods.

TABLE 13.—WAKE-VORTEX-RELATED INCIDENT DATA BY OPERATIONAL CATEGORY, 1989 TO 2006

Incident data	Flight operation category			
	Part 121	Part 135-S	Part 135-NS	Part 91
Flight hours, total	317,999,117	24,446,927	61,751,000	507,516,000
Incidents, total	7647	1921	2189	27,919
Incidents per million flight hours	24.047	78.578	35.449	55.011
Incidents caused by wake vortex	18	2	3	38
Incidents caused by wake vortex per million flight hours	0.057	0.082	0.049	0.075
Incidents caused by wake vortex, percent	0% (18/7647)	0% (2/21921)	0% (3/2189)	0% (38/27919)

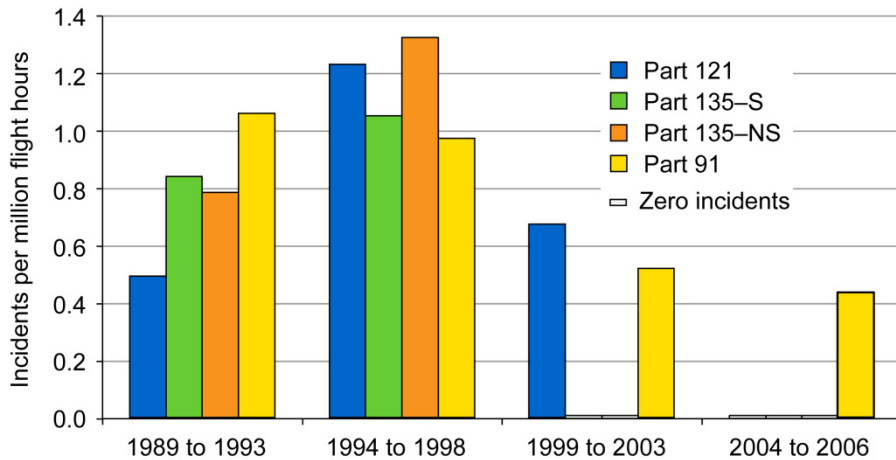


Figure 13.—Wake-vortex-related incident rate by operational category across four time periods.

5.3.2 Lightning

A summary of the incidents that were related to lightning are found in Table 14. Less than 1 percent of all FAA database incidents cited lightning as a cause or factor. Figure 14 displays the change in the incident rate related to lightning across four time periods. Generally, the incident rate has decreased for all operational categories over time.

TABLE 14.—LIGHTNING-RELATED INCIDENT DATA BY OPERATIONAL CATEGORY, 1989 TO 2006

Incident data	Flight operation category			
	Part 121	Part 135–S	Part 135–NS	Part 91
Flight hours, total	317,999,117	24,446,927	61,751,000	507,516,000
Incidents, total	7647	1921	2189	27,919
Incidents per million flight hours	24.047	78.578	35.449	55.011
Incidents caused by lightning	38	5	2	16
Incidents caused by lightning per million flight hours	0.199	0.205	0.032	0.032
Incidents caused by lightning, percent	1% (38/7647)	0% (5/21921)	0% (2/2189)	0% (16/27919)

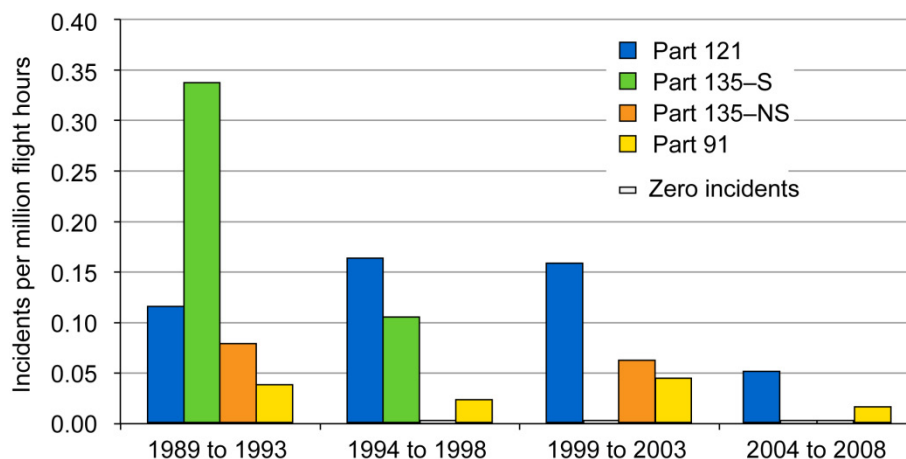


Figure 14.—Lightning-related incident rate by operational category across four time periods.

5.3.3 Low Visibility

A summary of the incidents that were related to low visibility are found in Table 15. Low visibility conditions affected the flight operations categories differently. In Part 121, low visibility affected 27 percent of all incidents, while in Part 135, low visibility impacted between 31 and 34 percent of incidents. Figure 15 displays the change in the incident rate related to low visibility across four time periods. The incident rate related to low visibility declined for all operational categories over time.

Incidents with low visibility as a cause or factor were further sorted by the type of low visibility to include

- Fog
- Low ceiling or clouds
- Precipitation
- Low lighting (dusk, dawn, or nighttime)
- Nonspecific

These low visibility conditions are summarized in Table 16. More than one condition might affect a particular incident. In all operational categories the most frequent condition was low lighting ranging from 13 to 30 percent.

TABLE 15.—LOW-VISIBILITY-RELATED INCIDENT DATA BY OPERATIONAL CATEGORY, 1989 TO 2006

Incident data	Flight operation category			
	Part 121	Part 135-S	Part 135-NS	Part 91
Flight hours, total	317,999,117	24,446,927	61,751,000	507,516,000
Incidents, total	7647	1921	2189	27,919
Incidents per million flight hours	24.047	78.578	35.449	55.011
Incidents caused by low visibility	2056	592	733	4329
Incidents caused by low visibility per million flight hours	6.465	24.216	11.870	8.530
Incidents caused by low visibility, percent	27% (2056/7647)	31% (592/21921)	34% (733/2189)	16% (4329/27919)

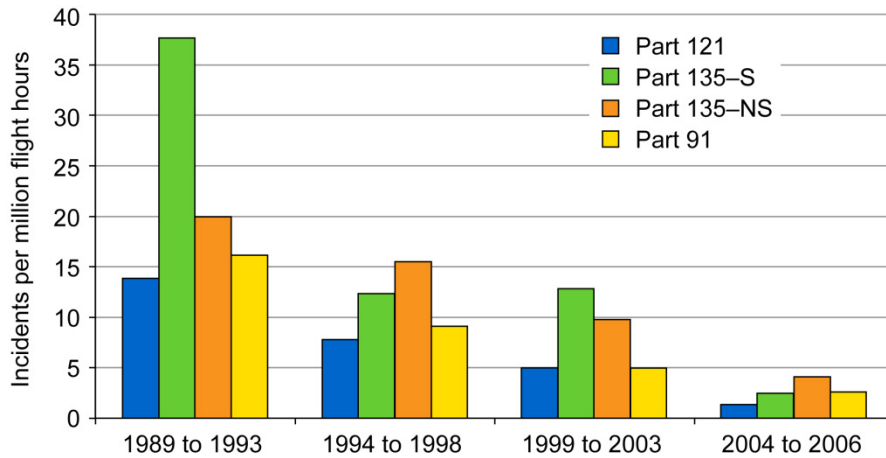


Figure 15.—Low-visibility-related incident rate by operational category across four time periods.

TABLE 16.—LOW VISIBILITY-RELATED INCIDENT FREQUENCY BY TYPE AND OPERATIONAL CATEGORY, 1989 TO 2008

Low visibility type	Flight operation category			
	Part 121	Part 135-S	Part 135-NS	Part 91
Low visibility, total	7647	1921	2189	27919
Fog	167 (2%)	80 (4%)	69 (3%)	407 (2%)
Low ceiling or clouds	194 (1%)	20 (1%)	46 (2%)	231 (1%)
Precipitation	133 (2%)	59 (3%)	69 (3%)	251 (1%)
Low lighting	1879 (25%)	512 (27%)	663 (30%)	3743 (13%)
Unspecified visibility	64 (5%)	38(2%)	26 (1%)	270 (1%)

5.3.4 Atmospheric Conditions Summary

A summary of the incidents affected by any of the six atmospheric conditions (icing, turbulence, CAT, wake vortex, lightning, and low visibility) are found in Table 17. Close to one-third of all incidents involved icing, turbulence, wake vortex, lightning, or low lighting/visibility for all operational categories except Part 91. Figure 16 displays the change in the incident rate (per million flight hours) for incidents affected by any of the six atmospheric conditions across four time periods showing a decline across all operational categories over time.

TABLE 17.—ATMOSPHERIC^a CONDITION-RELATED INCIDENT DATA BY OPERATIONAL CATEGORY, 1989 TO 2008

Incident Data Category	Flight operation category			
	Part 121	Part 135-S	Part 135-NS	Part 91
Flight hours, total	317,999,117	24,446,927	61,751,000	507,516,000
Incidents, total	7647	1921	2189	27,919
Incidents per million flight hours	24.047	78.578	35.449	55.011
Incidents caused by atmospheric conditions	2260	606	758	4508
Incidents caused by atmospheric conditions per million flight hours	7.107	24.788	12.275	8.882
Percentage of incidents caused by atmospheric condition, percent	30% (2260/7647)	32% (606/1921)	35% (758/2189)	16% (4508/27919)

^aIcing, turbulence, CAT, wake vortex, lightning, and low visibility combined.

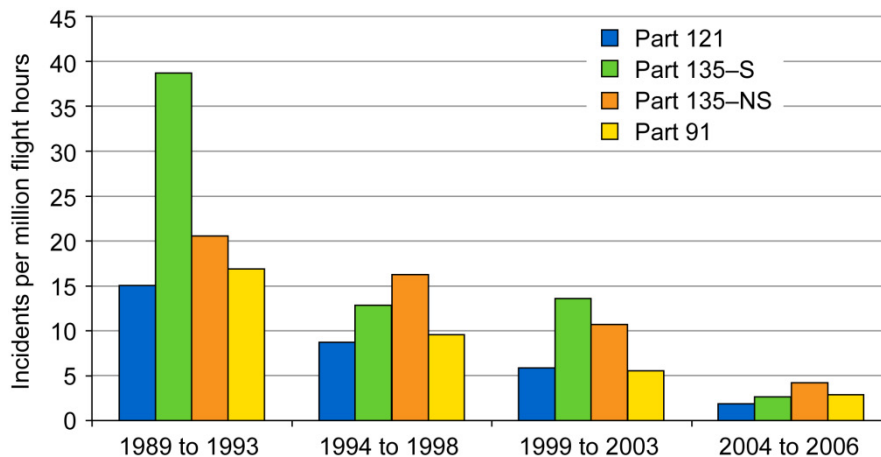


Figure 16.—Atmospheric-condition-related incidents rate (icing, turbulence, CAT, wake vortex, lightning, and low visibility combined) by operational category across four time periods.

6.0 Future Safety Risk Analysis

This section assesses the projected impact of the AEST TCs on the future aviation safety risks listed below. These future aviation safety risks were previously identified by the Aviation Safety Program's Systems Analysis Team after an exhaustive survey of a variety of sources (Ref. 7). Ten critical future safety risk areas were identified and include (in alphabetical order, not priority):

- (1) Aircraft mixed fleet equipage
- (2) Approach and landing accident reduction
- (3) Enhanced survivability in the event of an accident
- (4) Human fatigue
- (5) Icing and ice detection
- (6) Inadequate protection, analysis, and dissemination of safety data
- (7) Increasing complexity and reliance on automation
- (8) LOC—in flight
- (9) Runway safety
- (10) Super density operations

The AEST Project could have potential impact on 5 of the 10 critical future safety risk areas. A description of each of those five areas and applicable AEST TC research is provided in Section 6.1.

6.1 Approach and Landing Accident Reduction

Approach and landing is the most demanding phase of flight and carries the highest safety risk. This risk area includes unstabilized approaches, that is, approaches where airspeed, rate of descent, aircraft attitude, configuration, or power settings do not meet stabilized approach criteria at the prescribed approach point. These types of accidents often are manifestations of deficiencies that begin in or prior to the approach phase.

Approach and landing accidents often involve high-energy approaches. The most significant threats during approach are fast airspeeds, high groundspeeds (not appreciating wind effects), and high and/or steep approach above the desired flight path. Early control of high energy, the combination of these conditions, can reduce these threats. Situations should be assessed based on the following parameters: airspeed, altitude, runway length, runway surface conditions, wind, and visibility. Stabilized approaches provide bases for good landings. Monitoring these flight parameters to detect anomalies is crucial to understanding causes of unstabilized approaches and, therefore, to discovering precursors to potential approach and landing accidents. Adverse environmental conditions in the terminal area that cause external hazards and disturbances, such as icing, freezing rain, and strong wake turbulence, are also precursors to approach and landing accidents.

The AEST Project is conducting research in airframe icing to simulate and model airframe and swept-wing ice accretion and related aerodynamic performance degradation for current and future aircraft configurations in an expanded icing environment that includes freezing drizzle and rain. A significant outcome of this research will be the ability to accurately predict the ice-shape profile that could result from an icing encounter in supercooled large droplet (SLD) conditions. This capability will allow analysis of the SLD ice accretion impact on aircraft performance, ice protection systems, and ice detection systems. With the limited SLD-experimental simulation capabilities that are currently available it is critical that computational-SLD ice-accretion simulation tools be developed, especially for freezing rain conditions. Airframe icing research will develop the experimental and computational simulation

capability to prevent and mitigate adverse events during the approach phase of flight using reliable icing assessments and effective design approaches.

The National Research Council (NRC) recognizes the need to develop techniques, including lidar and laser-acoustic systems, and to predict and measure the formation, trajectory, and decay of upstream wake vortices. In addition, affordable new sensors, system technologies, and procedures must be developed to improve prediction and measurement of wake strength, location, motion, and aircraft upset risk in terminal and en route airspace to enable safe flight with reduced in-trail wake separation (Ref. 8). AHSM research is focused on developing mature technologies to sense and measure icing, turbulence, and wake vortex hazards to provide aircraft with a greater ability to avoid external hazards including icing conditions, kinetic air hazards, and convective weather.

The goal of AEST icing weather systems research is to enable safe flight through hazardous environmental conditions during the critical approach and landing phase of flight. Milestone AEST3.3.27 will allow development and assessment of icing hazard detection algorithms for terminal area coverage. Milestones AEST4.3.05 and AEST4.3.09 in the lidar electro-optical research element are aimed at conducting field tests to determine the imaging capability of real-time observation of wake vortices and to characterize wake vortex hazards in the terminal area.

6.2 Icing and Ice Detection

Adverse weather conditions, including storms and icing conditions, significantly reduce the capacity and reliability of the air transportation system. Adverse weather also degrades system safety. In-flight or ground (i.e., deicing-related) accumulation of snow, ice, freezing rain, or frost on aircraft surfaces and sensors adversely affects aircraft control and performance. This issue is important to both civil and military aviation, and is critical for all types of aircraft, particularly for turboprop aircraft. Research is needed to improve the ability to predict and monitor environmental conditions and to develop robust aerodynamic designs and techniques for adverse conditions. Currently, icing hazards are handled by regulatory constraints on flight operations, and prediction techniques are largely empirical. Low-cost techniques to measure upstream environmental conditions should be developed. Techniques to predict and mitigate the impact of adverse environmental conditions on the aircraft operation, including validation of icing prediction capabilities, should be improved (Ref. 8).

AEST research conducted under the TC2, airframe icing simulation and engineering tool capability, will produce ice accretion models that will be validated over the freezing drizzle and freezing rain SLD icing regime. This capability will allow regulators and aircraft manufacturers to use computational codes for more effective designs and as a basis for certification. Research will be conducted to develop and demonstrate a validated computational-simulation capability for ice buildup on three-dimensional aircraft surfaces that are subjected to SLD icing conditions. A significant outcome of this research will be the ability to accurately predict the ice-shape profile resulting from an icing encounter in SLD conditions. This capability will allow analysis of the impact of SLD ice accretions on aircraft performance, ice protection systems, and ice detection systems. With the limited experimental SLD simulation capabilities that are currently available, it is critical that computational SLD ice-accretion simulation tools be developed, especially for freezing rain conditions.

The consequences of operating an airplane in icing conditions without first having thoroughly demonstrated adequate handling and controllability characteristics in those conditions are sufficiently severe that they warrant a thorough certification test program, including application of revised standards to airplanes that are currently certified for flight in icing conditions. The airframe icing safety issue is well known and has been confirmed by several studies and by the international icing community. The aviation community, including airframe manufacturers, airlines, pilots, and the flying public, is aware of the

problem and is calling for it to be addressed. Their concerns have been well documented in expert venues including the FAA Ice Protection Harmonization Working Group (Refs. 9 and 10) and the NASA 2009 Airframe Icing Workshop. In addition, the joint government/industry Commercial Aviation Safety Team has developed a safety enhancement plan to encourage manufacturers of new turboprop-type designs to adapt and implement systems that automatically detect the presence of icing conditions that exceed those for which the aircraft has been certified including an estimate of accretion rate for advisory purposes and to provide annunciation to the flight crew if feasible (Ref. 11).

Finally, the NTSB's "Most Wanted List" includes "Reduce Dangers to Aircraft Flying in Icing Conditions" as one of their top 10 transportation improvements. The NTSB's specific recommendations for reducing these dangers are to use current research on freezing rain and large water droplets to revise the way aircraft are designed and approved for flight in icing conditions; to apply revised icing requirements to currently certificated aircraft; and to require that airplanes with pneumatic deice boots activate the boots as soon as the airplane enters icing conditions (Ref. 12). Research to address TC2 is focused on assessing current ice protection system simulation methods and on developing strategies for improving the experimental capability for ice protection systems in ground-based icing facilities. Strategies will also be recommended for improving experimental ice-accretion simulation capabilities for ice buildup on aircraft surfaces that are subjected to SLD icing conditions.

There is a significant need for increased detection, information collection, and mitigation capabilities for atmospheric hazards, including icing conditions. Terminal area ground remote sensing to monitor and enforce pending regulations for SLD icing certification is not currently available. Operations will require real-time atmospheric diagnostic capabilities beyond those being used today. Research conducted under the icing weather systems development element of TC3, AHSM technology capability, will address this need by improving the detection and measurement capabilities for in-flight icing hazards and also by further developing NASA AvSP remote sensing technologies research. An important Level 1 milestone (AEST3.1.06) will focus on conducting a terminal area icing algorithm and remote sensing system assessment to meet joint FAA and NASA standards. The resulting operational capabilities and constraints of the terminal area icing remote sensing systems will either define additional development work required or enable installation of these systems into the NextGen airspace system.

The icing and ice detection critical future safety risk area encompasses engine icing as well as the icing hazards encountered on the airframe and aircraft surfaces. The term "engine icing" has been used historically to describe ice accreting on exposed engine surfaces as an aircraft flies through a cloud of SLDs. Liquid droplets freeze on impact, or shortly thereafter, and form obstructions and distortions to air flowing into engines. Engine icing caused by ice accretion inside the normally hot core of jet-based engines that fly in clouds containing highly concentrated ice crystals is a recently identified problem and occurs with alarmingly high frequency worldwide. This counterintuitive and complex phenomenon has produced numerous calls for research to better understand and effectively address engine icing. The complex aerothermodynamic processes that permit ice to accrete inside the core of an engine in flight are not understood to a level that allows for effective analysis and prevention or mitigation techniques to be employed with confidence. Therefore, the AEST Project is planning to invest its engine-icing resources in HIWC icing research.

Evidence indicates that engine icing incidents caused by ice accreting inside the core of turbojet engines have been occurring for more than two decades. Since the early 1980s, studies of worldwide aircraft engine incidents have identified over 140 engine power loss events caused by engine core icing (Ref. 13). These events include compressor surge and stall, combustor flameout, engine rollback, and engine damage during and after flight in high ice water content (HIWC) conditions. Both commuter and large transport airplanes were involved. Project level milestone AEST3.1.01 is aimed at developing a

suite of enhanced icing instruments to withstand the particularly harsh HIWC environments to characterize the atmospheric environment associated with engine icing power loss events.

Research will attempt to determine which environmental conditions can lead to engine core icing; the location inside the engine where it will occur; and how much ice will accrete. Additionally, NASA intends to conduct a flight campaign using a specially instrumented research aircraft to characterize natural HIWC environments. Advanced radar enhancement research efforts and post-flight analyses will focus on discovering a signature for HIWC conditions; providing data for icing researchers that characterizes HIWC conditions; and evaluating designs and making performance estimates for future commercial detection systems.

The NRC (Ref. 8) has indicated the need for better analytical models to predict adverse weather (e.g., rain, ice, hail, and crosswinds) impact on fans, compressors, and combustor stability. These models should be physics-based and validated with experimental data. Detailed weather data, as a function of altitude, are needed for altitudes up to 20,000 ft. Data on water concentration and droplet size are especially important. Analyses of the impact of ingested freezing rain and ice as they traverse the propulsion system need to be improved. Better models will lead to more robust engine designs and improved operational procedures.

A significant segment of TC1, engine icing characterization and simulation capability, is focused on development and application of advanced numerical simulation codes to address the engine core icing hazard. Three key AEST Level 2 milestones are planned to target engine icing simulation capability. Milestone AEST3.2.02 will develop a tool to generate compression system performance maps with assumed simulated and computed blockage effects caused by ice crystal engine icing for use in an engine system modeling code. Milestone AEST3.2.04 will develop a tool to calculate mixed-phase ice accretion on engine components and assess the sensitivity of an engine to mixed-phase icing. The tool will predict ice accretion rates and locations by comparing the calculated results with results from engine icing laboratory tests. Finally, milestone AEST3.2.05 will produce an engine icing validation test to assess the Propulsion Systems Laboratory (PSL) icing test cell capability at the NASA Glenn Research Center and to simulate an engine icing event.

6.3 Loss of Control in Flight

LOC in flight involves accidents that occur during airborne phases of flight where aircraft control is lost. LOC can occur during either IMC or visual meteorological conditions. LOC in flight may be caused by a stall, an icing-related event, a severe atmospheric turbulence or wake vortex encounter, or a flight-critical system or component malfunction or failure. Aircraft energy management systems (excessive airspeed, altitude, and rate of descent) and aircraft configuration (flaps, slats, speed brakes, and onboard systems) can also result in LOC accidents or incidents. Analyses of NTSB accident and FAA incident data established that both powerplant and nonpowerplant system or component failures and malfunctions are significant contributing factors to aviation safety risk (Ref. 14).

The National Aeronautics Research and Development Plan states that research is needed to facilitate implementation of advanced systems logic and architectures to avoid, detect, and resolve upset conditions that can lead to loss of stability and maneuverability caused by hazardous convective environments or icing (Ref. 15). HIWC atmospheric conditions capable of causing ice accretion on vital aircraft sensors and inside jet engines are representative of the types of hazardous weather environments that are potential contributors to upset conditions that can lead to LOC accidents or incidents.

Portions of the AEST project are addressing icing-related events and powerplant system failures and malfunctions as causal factors in LOC accidents through current work on airframe and engine icing. Research conducted under TC2 will increase flight safety in icing conditions by introducing validated and

accepted icing simulation tools earlier in the design cycle. Reliable assessments and effective mitigation design approaches will be provided, and technology to enable safe flight operations in SLD environments will be developed.

TC1 focuses on developing engine core icing simulation tools and techniques to predict ice accretion inside engines. Research will determine the environmental conditions in which icing can occur, the location inside the engine where it will occur, and how much ice will accrete. Another key component or research element of TC1 is the development of automatic engine control methods to mitigate the effects of, or prevent engine core icing altogether. The ultimate goal—reducing engine core icing events—depends on discovering how it occurs and affects engine operation, as well as finding effective means to prevent it. A sophisticated engine simulation and control methodology was developed, validated, and verified under the NASA AvSP’s Integrated Resilient Aircraft Control project called Vehicle Systems Safety Technology (VSST). The AEST and VSST projects are working to capitalize on this technology by applying it to this TC.

Finally, one of the objectives of TC3 is to develop mature technologies to remotely sense and measure icing conditions, and to provide real-time information to the pilot and operators in the NAS. This will provide aircraft with a greater ability to avoid the hazards of icing, convective weather, and wake vortices that are precursors to LOC accidents and incidents. The icing weather systems development element of TC3 includes research activities that will expand detection and measurement capabilities for in-flight icing hazards for long-term adoption in the NextGen airspace system. Research will focus on mapping ground-based and airborne remote sensing of meteorological conditions that are conducive to in-flight icing hazards. In addition, the advanced radar enhancements element will support development of hazard characterization studies for aircraft engine and airframe icing conditions and aircraft wake vortex investigation and modeling. The need for icing remote sensing technologies has long been recognized within NASA, and an FAA-sponsored international review of in-flight icing issues concluded that remote sensing could be useful in avoiding severe icing conditions by all aircraft (Refs. 16 and 17).

6.4 Runway Safety

Runway safety encompasses runway incursions, excursions, and confusion (takeoffs and landings on wrong runways or taxiways). The number of runway and taxiway incursions remains unacceptably high despite recent efforts to minimize their occurrence. Runway incursions are expected to remain as a critical safety risk in the future. Flight deck workload and distractions preflight are contributing factors. The NTSB considers runway incursions one of its top three aviation safety issues, noting that “these incidents continue to occur with alarming, and increased, frequency” (Ref. 12). Implementing the NTSB’s recommended safety system for ground movement will ensure the safe movement of airplanes on the ground and provide immediate warnings of probable collisions and incursions directly to flight crews in the cockpit.

The Flight Safety Foundation conducted the Runway Safety Initiative (RSI) to address safety concerns and events involving runway incursions, excursions, and confusion. The RSI project team consisted of about 20 representatives from worldwide organizations, including operators, manufacturers, air navigation service providers, pilot groups, and other industry associations. After reviewing all these areas, the RSI team focused primarily on reducing runway excursion risks since 97 percent of runway accidents were found to have been caused by excursions (Ref. 18). The team also pointed out that runway incursion and confusion interventions would be useful to improve runway safety, including moving map displays and vision enhancement technologies. In the NextGen Integrated Work Plan (IWP), the Joint Planning and Development Office outlined a set of research and development activities that are required to support the proposed NextGen operational concepts (Ref. 19). Key activities identified in the IWP were

applied research and development of low visibility and surface operations technologies to increase operator situational awareness in poor visibility terminal and airport surface conditions.

Higher numbers of aircraft in the system increases air and ground aircraft density. To address this increased demand, research needs to develop systems that improve pilot and controller awareness of airport surface conditions (aircraft and ground vehicle locations, runway occupancy, and pavement conditions), particularly in low visibility situations. Improving flight crew and ground controller situational awareness is critical to reducing incidents and accidents on the ground (Ref. 15).

Poor visibility conditions are also a significant contributing factor to runway and taxiway surface incidents. AEST research is addressing runway safety through the smart visual awareness element of TC3. Level 2 milestones AEST4.2.14 and AEST4.2.15 plan to complete both a laboratory and flight demonstration of a real-time testbed of a basic pattern recognition engine for enhanced vision. These demonstrations are the culmination of the development of the pattern-recognition engine known as the streamlined spatial vision tree. The resulting smart avionics imaging sensor is a compact flight test unit that uses both image enhancement and pattern recognition. The research focuses on the low-visibility hazard and on terrain detection, as well as takeoff, landing, and taxiing hazards in poor visibility conditions. Moreover, Laser Imaging Through Obscurants, an active imaging system, and Forward-Looking Interferometry, a hyperspectral passive imaging system, are both being pursued under the AEST Project to enable equivalent VFR operations under low visibility conditions.

6.5 Super Density Operations

Expected growth in the demand for air transportation will require more efficient and dense en route and terminal area operations. New procedures will be needed to reduce minimum spacing requirements during all phases of flight and in all weather conditions, through an integrated approach that leverages a suite of emerging technologies such as performance-based navigation and automatic dependent surveillance broadcast. Performance-based navigation procedures such as required navigation performance, area navigation, optimized profile descents, and tailored arrivals for oceanic flights, are being developed to increase the capacity and efficiency of the NAS, as well as provide environmental benefits such as reductions in fuel emissions and aircraft noise.

Higher levels of air traffic will require simultaneous arrival procedures at airports with closely spaced parallel runways to achieve the capacity and efficiency gains needed in the NextGen environment. NextGen Operational Improvements 0400 and 0401 specify wake turbulence mitigation procedures for departures and arrivals to allow more closely spaced arrival and departure operations to maintain airport and runway capacity (Ref. 19). The National Aeronautics Research and Development Plan states that “reduced aircraft separation will require a move to trajectory-based operations, performance-based navigation, and a new allocation of responsibilities between air and ground and between humans and automation. In addition, planned advanced airspace design concepts that can be dynamically adjusted to meet demand requirements and avoid hazardous weather conditions must be developed with safety in mind.” (Ref. 15).

The introduction of increased operational complexity and new technologies in the NextGen will likely give rise to unanticipated consequences that could reduce the safety profile of aircraft and the NAS. Atmospheric hazard information presented to flight deck crews is currently limited and must be improved to provide greater safety, especially as NextGen operations evolve. Thus, there is a significant need for increased atmospheric hazard detection, information collection, and mitigation capabilities. A remote sensing capability does not currently exist on aircraft to detect CAT, wake vortex, icing conditions, and ice-crystals, or to see through low-visibility aircraft environments. Current atmospheric hazard sensing, lightning sensing, and mitigation deficiencies have been confirmed by several independent studies and

aviation community feedback. The FAA's NextGen Reduce Weather Impact solution set supports integration of a broad range of weather information into air traffic decisionmaking and the implementation of remote atmospheric hazard sensor technologies to mitigate the effects of weather resulting in safer operations in the NAS (Ref. 20). Also, several published reports including the "Decadal Survey of Civil Aeronautics," confirm the need for continued remote sensing research and development. In this report the NRC calls for improved onboard weather systems and tools to minimize the impact of weather on the control of flight in heavy traffic. The report identifies affordable new sensors, system technologies, and procedures to improve wake turbulence prediction and measurement as an important research technology and challenge. It states, "Existing wake vortex separation standards reduce system capacity during takeoff and landing operations and instrument approaches. Research by the FAA and NASA has been focused on procedural enhancements that take advantage of wake transport by winds. However, the relaxation of in-trail wake separation standards awaits improved measurement and prediction of wake behavior. Existing sensors and models do not adequately characterize wake decay phenomena, especially at typical final approach altitudes. Improved sensors, including coherent pulsed lidars, capable of directly measuring wake rotational momentum, are needed to support phenomenological studies and enable more accurate predictions of wake magnitude and decay in various atmospheric conditions. Those predictions, combined with models of aircraft upset risk, should allow reduced wake separation standards without degrading safety" (Ref. 8).

AEST research activity that addresses TC3 will enable pilots and controllers to obtain real-time accurate information on a broad range of atmospheric hazards, including CAT, wake vortex, icing, ice crystals, and low visibility aircraft environments. Research will be conducted to develop advanced airborne radar technology for safety applications such as windshear detection and enhanced turbulence detection. Milestone AEST 4.2.12 will result in ground-based testing and verification of a new fiber optics-based lidar system that will be used to detect kinetic air hazards (e.g., turbulence, wake vortices, and windshear) on commercial transport and business jet aircraft. In addition, two key TC3 Level 3 milestones are focused on: (1) a forward-looking interferometer field test for wake vortex hazard observation (AEST 4.3.05) and (2) characterization of wake vortex hazards in terminal area and en route airspace to provide models and hazard signatures for sensor algorithm development and validation (AEST 4.3.09).

7.0 Discussion and Conclusion

7.1 National Transportation Safety Board Accident Data

The NTSB accident data was analyzed to identify trends related to the AEST Project TCs. Four types of NTSB operational accident data were examined across four time periods (1989 to 2008): Parts 121, 135-S, 135-NS, and 91. The specific accidents types were engine icing related to ice crystals (TC1), icing/freezing rain/drizzle (TC2), and turbulence, wake vortex, lightning, low visibility, and low lighting (TC3).

TC1's focus is the characterization and simulation capability related to ice-crystal icing. A search of the NTSB accident data set did not yield accidents related to propulsion systems that were impacted by ice crystals and less than 5 percent of all accidents were affected by icing conditions (TC2). When icing was involved in Part 91 and 135-S operations, however, between 25 and 54 percent involved fatalities.

Turbulence (excluding terrain-induced and wake vortex) was a cause or factor in 24 percent of Part 121 accidents compared with less than 1 percent of accidents in other flight operations. Less than 3 percent of fatal accidents and fatalities, regardless of flight operation, were affected by turbulence. Turbulence accidents usually did not involve any fatalities. Turbulence-related accident rates have

declined over time for Parts 91 and 135–NS, while the accident rate for Part 121 has fluctuated over time. CAT was involved in 19 percent of all turbulence accidents. In general, less than 1 percent of all accidents involved wake vortex and have decreased over time, except for Part 91 operations. Although the accident rate related to wake vortex has been low and decreasing during this study, expected growth in the demand for air transportation will require more dense en route and terminal area operations resulting in the need for wake vortex mitigation.

Lightning was a cause or factor in less than 1 percent of all accidents. With the exception of Part 135–NS, the rate of lightning incidents has remained fairly constant over time. Even though the rate is low, there is concern that future aircraft, with more composite structures, will be more impacted by lightning.

Low visibility/lighting was involved in 6 to 23 percent of all accidents depending on operational category. While only 10 percent of Part 91 operations involved low visibility/lighting, 60 percent of these involved fatalities. Generally, the rates of low visibility/lighting accidents have been declining over time, except for Part 121 operations where the rate has remained steady. Most low visibility/lighting accidents involved low lighting.

All icing, turbulence, wake vortex, lightning, low visibility, and low lighting accidents combined (account for nearly one-third of all accidents. The lowest percentage of accidents affected by any of these atmospheric conditions was in Part 91, yet 58 percent involved fatalities. The combined rate of accidents for all atmospheric conditions declined for Parts 91 and 135–NS, increased for Part 135–S, and remained steady for Part 121 operations.

7.2 Federal Aviation Administration Incident Data

The FAA’s Accident/Incident database was analyzed to identify trends related to the AEST Project TCs. Four types of FAA operational incident data were examined across four time periods (1989 to 2006): Parts 121, 135–S, 135–NS, and Part 91. The specific incident types were engine icing related to ice crystals (TC1), icing/freezing rain/drizzle (TC2), and turbulence, wake vortex, lightning, low visibility, and low lighting (TC3).

TC1’s focus is the characterization and simulation capability related to ice crystal icing. A search of the FAA database set yielded 38 incidents related to propulsion system failures. Of those, 14 were caused by engine icing; two specifically cited ice crystals in the propulsion system as a cause for engine flameout. Most of the engine icing incidents occurred during Part 121 operations. The incidents were often not thoroughly investigated; the report giving little information as to the cause of the engine issues.

Less than 2 percent of incidents were affected by airframe icing. Reported icing-related incidents declined during this study, except for Part 135–S operations.

Turbulence caused less than 3 percent of incidents in the FAA incident database, and the rates declined during this study. CAT was found in only 3 percent of the turbulence-related accidents. Wake vortex and lightning were each involved in less than 1 percent of the reported incidents and the rate of these types of incidents has declined over time as well. Low visibility/lighting was a factor in 27 percent of the incidents and declined during the study. Part 135 operations were most affected by low visibility/lighting conditions.

Close to one-third of all incidents in Part 121s and 135 operations were affected by one or more of the six atmospheric conditions reviewed in this study (icing, turbulence, wake vortex, lightning, low lighting, and low visibility).

7.3 Future Safety Risk

A summary of the evaluation of research in the three TC areas’ projected impacts on critical future safety risk areas is provided in Table 18 showing how each research area maps to the critical future safety risk areas.

An evaluation of the AEST Project research and technology development activities against several critical areas of future safety risk in the air transportation system was completed. These high-level qualitative future safety challenges were identified from multiple literature sources and are documented in the Systems Analysis of NASA AvSP—Final Report (Ref. 7). As stated in the AEST Project Plan (Ref. 1), the AvSP, including the AEST project, will “identify and develop tools, methods, and technologies for improving overall aircraft safety of new and legacy vehicles operating in the Next Generation Air Transportation System.” More specifically, the AEST Project will investigate sources of risk and provide needed technology to ensure safe flight in, and around atmospheric hazards.

The focus of AEST research is on in-flight icing, both engine and airframe, as well as investigating other high-priority atmospheric hazards and sensor technologies required for their detection. These include wake vortex encounters, convective weather, turbulence, reduced visibility conditions, and lightning. The research is relevant to the safety needs of the aviation community and is crucial to the mitigation of future aviation safety risks associated with icing and atmospheric hazards for several reasons. First, icing is still a safety concern across all categories of subsonic aircraft and engine icing incidents are occurring on a frequent basis with the aviation community calling for action. Secondly, new aviation regulatory requirements necessitate development of new and enhanced icing simulation tools. Finally, operations in the NextGen environment will demand precise information about the atmosphere and awareness of weather hazards.

The engine icing characterization and simulation capability (TC1) will explicitly address the future safety risk area of icing/ice detection through its emphasis on developing analytical methods and both computational and experimental simulation tools to prevent ice crystal icing that can cause turbofan engine interruptions and failures. It will also target engine icing-related events as causal factors that can lead to in-flight LOC accidents and incidents.

TABLE 18.—PROJECTED IMPACT OF AEST TECHNICAL CHALLENGE (TC) RESEARCH ON CRITICAL FUTURE SAFETY RISK AREAS

Critical future safety risk areas	TC areas		
	TC1 engine icing	TC2 airframe icing	TC3 AHSM ^a
Aircraft mixed fleet equipage			
Approach and landing accident reduction		✓	✓
Enhanced survivability in the event of an accident			
Human fatigue			
Icing/ice detection	✓	✓	✓
Inadequate protection, analysis, and dissemination of safety data			
Increasing complexity and reliance on automation			
Loss of control—in flight	✓	✓	✓
Runway safety			✓
Super density operations			✓

^aAtmospheric hazard sensing and mitigation

The airframe icing simulation and engineering tool capability (TC2) will develop and demonstrate the capability to simulate and model airframe ice accretion and related aerodynamic performance degradation for current and future aircraft configurations over an expanded range of icing conditions. In addition, this research will have a positive impact on solving the problem of icing effects that can lead to LOC and approach and landing accidents by disrupting the aircraft's aerodynamic lift characteristics.

Research carried out under the AHSM technology capability (TC3) will address several areas of future aviation safety risk. The major focus of this TC is to develop advanced technologies for sensing and measurement of icing, turbulence, and wake vortex hazards for real-time information in the cockpit and throughout the NAS. As a result, risks associated with icing and ice detection, LOC in flight, and approach and landing accidents will be reduced. In addition, research to develop new technologies for enhanced vision systems and advanced imaging sensors will enable automatic detection of aviation safety hazards, in particular runway, terrain, and midair collisions during poor visibility flight conditions. This smart visual awareness research will bring about safer runway operations and improvements in safety as capacity increases in the NextGen environment. Finally, Super Density Operations, a foundational NextGen capability, will significantly increase the capacity in the NAS in response to the projected growth in demand. Enabling technologies required to achieve this NextGen operational concept are defined in the NextGen IWP (Ref. 20), and include wake vortex advisory systems to mitigate inadvertent wake turbulence encounters; enhanced onboard vision systems to allow VFR operations in low visibility conditions; and onboard turbulence mitigation systems to allow aircraft to safely travel through greater intensities of adverse weather. Research in this TC will produce technological advances in all of these areas, and allow for a safe reduction in the longitudinal and lateral spacing requirements needed in the super density environment.

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