NASA/TM–2015–218928

Real-Time Monitoring and Prediction of Airspace Safety

Indranil Roychoudhury
SGT, Inc., NASA Ames Research Center, Moffett Field, CA

Lilly Spirkovska
NASA Ames Research Center, Moffett Field, CA

Matthew Daigle
NASA Ames Research Center, Moffett Field, CA

Edward Balaban
NASA Ames Research Center, Moffett Field, CA

Shankar Sankararaman
SGT, Inc., NASA Ames Research Center, Moffett Field, CA

Chetan Kulkarni
SGT, Inc., NASA Ames Research Center, Moffett Field, CA

Scott Poll
NASA Ames Research Center, Moffett Field, CA

Kai Goebel
NASA Ames Research Center, Moffett Field, CA

December 2015

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Kai Goebel
NASA Ames Research Center, Moffett Field, CA

National Aeronautics and
Space Administration

Ames Research Center
Moffett Field, California 94035

December 2015

Acknowledgments

This work was supported by the SMART-NAS project under the Airspace Operations and Safety (AOSP) program within the NASA Aeronautics Research Mission Directorate (ARMD).

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Abstract

The U.S. National Airspace System (NAS) has reached an extremely high level of safety in recent years. However, it will become more difficult to maintain the current level of safety with the forecasted increase in operations. Consequently, the Federal Aviation Administration (FAA) has been making revolutionary changes to the NAS to both expand capacity and ensure safety. Our work complements these efforts by developing a novel model-based framework for real-time monitoring and prediction of the safety of the NAS. Our framework is divided into two parts: (offline) safety analysis and modeling, and real-time (online) monitoring and prediction of safety. The goal of the safety analysis task is to identify hazards to flight (distilled from several national databases) and to codify these hazards within our framework such that we can monitor and predict them. From these we define safety metrics that can be monitored and predicted using dynamic models of airspace operations, aircraft, and weather, along with a rigorous, mathematical treatment of uncertainty. We demonstrate our overall approach and highlight the advantages of this approach over the current state-of-the-art through simulated scenarios.

Executive Summary

The U.S. National Airspace System (NAS) has reached an unprecedented, extremely high level of safety due to the efforts of a plethora of national and international organizations conducting regular risk assessments, establishing standards, enacting rules and regulations, auditing for compliance, providing education, and improving technology for aircraft, avionics, and air traffic control. However, NAS operations are forecast to increase, due both to increases in commercial flying and the integration of Unmanned Aerial Systems (UAS) into the NAS. Because the same accident *rate* will result in an increased *number* of accidents and incidents – an unacceptable eventuality – the Federal Aviation Administration (FAA) has been making revolutionary changes to the NAS to both expand capacity and ensure safety. Our work complements these efforts. We utilize the improved technologies of the FAA's Next Generation Air Transportation System (NextGen); however, we do not depend on them. We can use even current NAS technology to potentially improve safety through increased shared situational awareness, leading to more informed flight planning and preemptive diversions.

NAS safety is the goal of every stakeholder involved in the aviation domain. The state-of-the-practice for assessing the safety of the airspace relies on anticipating hazards prior to flight using an acceptable-minimums checklist such as those advocated by the FAA's Flight Risk Assessment Tool (FRAT) or the hazard analysis promoted by the FAA's Safety Management System (SMS). If the risk is acceptable, the pilot then updates the assessment during flight using available information. Unfortunately, very little information is available in flight. This is projected to change with NextGen. Even then, the pilot would need to divide attention away from the flying tasks to retrieve and decipher the data, evaluate it in the context of her flight, and decide whether to alter the current plan. The decision must consider multiple factors simultaneously. For example, if the pilot decides to deviate to avoid weather, she must consider the restrictions due to fuel reserves, required arrival times, and restricted airspaces, among others. Moreover, the lack of information is also prevalent in Air Traffic Control (ATC) facilities. Each ATC controller has a limited set of data available and little time to devote to planning very far ahead.

To address the challenges of assessing safety with the current state-of-the-practice, in this report, we present a novel framework for real-time monitoring and prediction of the safety of the NAS. Our framework is general enough to include any hazard that can be modeled quantitatively. Another contribution of our work to improving NAS safety is our approach to handling uncertainty. Rather than ignoring uncertainty (of the weather forecast or expected traffic, for example) or just adding a "fudge factor" to account for uncertainty (separating aircraft by a little extra, for example, to account for uncertainty in when a pilot will slow on final approach to landing), we present a systematic, integrated framework for the rigorous, mathematical treatment of uncertainty. Based on principles of probability and Bayesian analysis, the proposed methodology can compute the entire probability distribution of NAS-related quantities of interest without making significant assumptions regarding their distribution type and/or parameters.

Our framework is divided into two parts, an (offline) safety analysis and modeling part, followed by an (online) real-time monitoring and prediction of safety part. The goal of the safety analysis task is to identify hazards to flight – conditions that can contribute to incidents or accidents, and to codify these hazards within our framework such that we can monitor and predict them. We distilled the hazards from several national databases, such as the NASA Aviation Safety Reporting System (ASRS), the National Transportation Safety Board (NTSB), and the FAA, into three categories: airspace hazards (e.g., diversity of traffic mix, radar coverage, inoperative equipment, etc.), environmental hazards (e.g., convective weather, bird activity, low sun angle, etc.), and human workload hazards (e.g., complexity of required tasks, communication issues, flow control restrictions, etc.). These hazards were then transformed into a set of *safety metrics* – quantities of interest that could be evaluated based on available data and are predictive of an unsafe event. For example, *aircraft separation* is a safety metric that constantly needs to be monitored and predicted in order to predict a *loss of separation* unsafe event. Lastly, we associate each safety metric with a threshold that specifies when the state of the NAS, as evidenced by the available data, transitions from *safe* to *unsafe*. These thresholds can be determined through analysis, consultation with subject matter experts (SMEs), learned from historical NAS data through data mining, or other techniques. Continuing with the loss of separation safety metric example, the threshold could be set to 1000 feet vertically and five nautical miles laterally, to mimic en-route ATC separation standards.

The offline safety analysis and modeling is then used for the online real-time monitoring and prediction. To enable monitoring and prediction, models of airspace operations and aircraft dynamics are developed. Models can be detailed and complex, taking into account numerous factors to compute precise values, or they can be considerably simplified as required by the application. In order to estimate the current level of safety, the state of the NAS must first be estimated using the dynamic models of the NAS. Given the state estimate and a probability distribution of future inputs to the NAS, we can then predict the evolution of the NAS – the future state – and the occurence of hazards or *unsafe* events. For robustness to actual operations, which are highly stochastic, the monitoring and prediction algorithms rigorously account for uncertainty.

To demonstrate our overall approach, we construct several simulated scenarios in which we compute the current level of safety and show how it evolves in time as operations progress. We construct scenarios that highlight the advantages of our approach over the current state-of-the-art. Predictions accounting for common sources of uncertainty are included and we show how the predictions improve in time, become more confident, and change dynamically as new information is made available to the prediction algorithm.

In future work, this framework can be used for several applications, such as improving shared situational awareness through automated assessment of multiple factors for potential flight routes, minimizing the necessity of in-flight route modification through more informed route selection, and supporting strategic planning between users and the ATC system. Through predictive safety computation that includes rigorous handling of uncertainty, pilots and ATC controllers can receive advance warning of precursors to unsafe events. This enables preemptive actions that have a higher chance of avoiding unsafe events rather than having to mitigate them. Additionally, the computed time-to-unsafe-event can be used to improve current operations to accommodate more demand without compromising overall system safety. Further, predicted safety can be incorporated into automated decision-making tools, perhaps providing pilot-in-command capability to UAS. Finally, global/local sensitivity analysis techniques can be used to identify quantities that pertain to safety, risk analysis methods can be used to incorporate criticality of multiple events, and the likelihood of unsafe events can be calculated in specific contexts.

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Chapter 1

Introduction

The U.S. National Airspace System (NAS) consists of people, facilities, and technology, along with the rules and regulations that are needed to protect persons and property on the ground, and to provide a safe and efficient airspace environment for civil, commercial, and military aviation. The NAS is among the safest in the world, and flying is safer now than it has ever been. In fact, there has not been an airliner fatality on scheduled US-flag carriers since 2009. Considering how many millions of flight hours are flown each year and how many passengers are transported, the likelihood of dying in an aviation accident is minuscule. According to the National Safety Council, the odds of dying in an air and space transport accident are 1 in 8015. One has higher odds of dying in a pedestrian incident (1 in 704) [1].

This improvement of NAS safety to historically unprecedented levels has been achieved mainly through a combination of risk assessment, regulation, education, and auditing for compliance. Some of the rules and regulations enabling safety cover diverse topics, such as airport layout, runway overshoot or undershoot mitigation, pilot work hours, building aircraft for accident survivability, maximum airport occupancy limits for emergency egress, dangerous goods transport regulations, and so on. Through the years, the Federal Aviation Administration (FAA) has established many rules and regulations regarding who can operate aircraft; and when, where, what, and how aircraft can operate. Regulations have been enacted to ensure operators (whether pilots, controllers, mechanics, etc.) are well rested, not under the influence of performance-degrading substances, are adequately trained, and have well-honed procedures to follow. Through the efforts of the FAA and various other organizations, aircraft have improved safety features, and technology has improved both in the air traffic control facilities as well as the aircraft and their avionics. As a result of these and many other efforts, accident rates have significantly declined.

However, although the statistics stated above are impressive, they do not tell the whole story with regards to the safety of the NAS. The first drawback in the above-stated statistics is how *safety* is defined. The statistics quoted above consider only fatal accidents. But, accidents that result in non-fatal injuries should also be considered, as should accidents that result in significant damage to an aircraft or to property on the ground. Further, there are actions that do not necessarily result in an accident, not because the action is safe per se, but more often because of the many checks and balances in the NAS, and sometimes only due to sheer luck. Loss of standard separation between aircraft (generally, within 5 nautical miles laterally en-route) falls in this category. In a few cases, the loss of separation results in an accident, oftentimes fatal for the occupants of both aircraft. More typically, one of the pilots spots the other aircraft in time, an air traffic controller detects and resolves the conflict, or on-board automation detects and resolves the conflict. Just in December 2014, there were 638 FAA-recorded loss of separation events [2]. Any of them could have resulted in fatalities.

Another drawback in compiling aviation safety statistics is not taking into account the diversity of the NAS operators. For example, in addition to scheduled commercial airline flights, there are on-demand charter flights, company business jet flights, twin and single piston-engine planes used by owners for business or family travel and others primarily for local recreation, unpowered gliders, hot-air balloons, unmanned aircraft systems (UAS), and even parachute jumpers that are not always included in such statistics. This results in skewed numbers since each of these groups uses some portion of the NAS and there are significant differences in their safety statistics.

Moreover, even if the accident rates remain the same, the popularity of commercial flying is forecast to increase over the coming decades, and thus, the number of accidents, incidents, and unsafe events will only increase. For example, the increase in NAS operations is considerable, with total operations at large airports expected to rise from 12.3 million operations in 2013 to 17.8 million operations in 2034, at an average annual increase of 1.7% a year [3]. Furthermore, with the integration of UAS in the NAS, the NAS operations will increase even more. UAS spending is forecast to increase from 5.2 billion dollars annually in 2014 to 11.6 billion dollars by 2023 [4]. This increase in UAS operations will be because of UAS that will be returning from defense-missions abroad as well as an unprecedented increase in commercial UAS development for business, security, reconnaisance, fire safety, and other applications. The FAA is currently working on an integration plan that supports safe operations of UAS in the NAS.

Hence, to maintain current rates, or, optimally, to decrease the rates further will require new approaches. Toward this end, the FAA has been upgrading the NAS to the Next Generation Air Transportation System (NextGen) that aims to transform the NAS by making revolutionary, and not just evolutionary, changes to “ensure safety” and “expand capacity” [5]. The NextGen vision specifies eight key capabilities to achieve these goals, such as Aircraft Trajectory-Based Operations, Super-Density Arrival/Departure Operations, and others. We believe that the ability to accurately assess expected conditions along candidate flight routes and to check evolving conditions along the selected route will aid in the further improvement of safety and efficiency of NAS as part of NextGen upgrades. Even in today’s NAS, an FAA federal aviation regulation (FAR 91.103) specifies that pilots must “become familiar with all available information concerning that flight.” [6] Airline dispatchers do a thorough review of all known information. Unfortunately, the current NAS does not allow for all NAS stakeholders to have direct access to all relevant information.

Other operators, such as charter operators or general aviation, also typically follow the best practice of identifying potential hazards to a flight and basing “go/no-go” decisions on that information. Once in flight, access to relevant information can be more difficult or impossible to obtain in a timely manner. NextGen addresses both of these issues with the System Wide Information Management (SWIM) system and with traffic and flight information services provided via ADS-B “In”. There are also efforts on creating bidirectional data links to airlines [7–9]. However, only available information can be disseminated. It is an open question as to what information needs to be disseminated to improve safety.

We believe that an effective approach to determining what information to share is to first understand the hazards that lead to unsafe situations, and whether the result is a fatal accident, an injury, property damage, or an event with potential negative consequences. We then need to provide information to operators that can be used to make "go/no-go" or "continue/divert" decisions. Human cognitive biases, external pressures, and inertia often seep into decision-making. Our goal is to provide techniques and tools to assess and predict the safety of an airspace, transforming subjective, potentially-stale decisions to objective, regularly updated, informed decisions, thereby improving safety for all NAS users. Providing access to known hazards, forecasting their evolution, and very importantly, providing information about the airspace safety will allow users to take preemptive actions that avoid safety-averse situations rather than having to take reactive actions that attempt to mitigate them.

In this report, we present a framework for real-time monitoring and prediction of safety of the NAS. We feel that being able to accurately monitor and predict the safety of the airspace in real-time complements existing safety efforts and can improve planning of trajectories, preemptive actions, and shared situational awareness of factors affecting flight safety. Further, this work serves as the foundation of advanced safety-integrated decision-support tools and automation technologies for the NAS.

1.1 Research Goals

Unsafe events occur when safety is compromised; these are events that are undesirable, such as loss of separation, tailwind landings, unstable approach, and so on. Unsafe events can lead to incidents or accidents. *Hazards* are conditions that contribute to unsafe events. Hazards can be categorized into broad themes; we focus on three themes, namely airspace and surface-related hazards (e.g., inoperative runway lights, inoperative navigational aids, etc.), cognitive or human workload-related hazards (e.g., excessive communication for air traffic controllers, large number of avoidance areas that the controller needs to account for, congested areas that controller needs to avoid, etc.), and environmental hazards (e.g., low visibility, turbulence, thunderstorms, icing, terrain obstructions, etc.). Once these hazards can be assessed quantitatively through a set of *safety metrics*, one can determine thresholds that define the regions of reduced safety in the operational space of aircraft. Unsafe events may occur when aircraft operations enter any such region of reduced safety. By monitoring and predicting NAS aircraft operations in real-time, one can determine the safety of the NAS and also determine the *safety margin*, i.e., how far these operations are from the boundary of the regions of reduced safety, so that we can avoid unsafe events. Given the terminology described above, the main goals of this research are as follows:

- Identify hazards that compromise safety,
- Define safety metrics to quantitatively assess these hazards,
- Determine thresholds defining regions of reduced safety, and
- Monitor and predict airspace safety in real-time to assess safety margins.

1.2 Approach

To accomplish the above research goals, we first have to perform an (offline) safety modeling and analysis that is followed by an (online) real-time monitoring and prediction approach.

Safety Modeling and Analysis: As part of the offline safety analysis, we review several national databases, such as the NASA Aviation Safety Reporting System (ASRS) database [10], the National Transportation Safety Board (NTSB) database [11], and FAA reports [12], in order to identify the causes and conditions leading to unsafe events. Then, we analyze these scenarios and identify cognitive or human workload-related, airspace and surface-related, and environmental hazards that could have caused these unsafe events. After identifying the hazards, we develop a set of safety metrics to assess these hazards quantitatively. Then, thresholds are determined to define the regions of reduced safety that should be avoided. The thresholds can be determined through analysis, consultation with subject matter experts (SMEs), learned from historical NAS data through data mining, or other methods. Once these regions of decreased safety are determined, real-time safety of the NAS can be evaluated and predicted.

Real-Time Monitoring and Prediction of Safety: The real-time online monitoring and prediction framework takes as inputs weather forecasts, expected traffic, system parameters, and so on. Monitoring and prediction algorithms use models of aircraft dynamics and airspace operations. Predicted airspace states are compared to thresholds to determine when unsafe events may occur or how far away the airspace state is from the boundaries of regions of reduced safety. All monitoring and prediction algorithms take into account uncertainty.

To demonstrate our overall approach, we construct several simulated scenarios in which we compute the current level of safety and show how it evolves in time as operations progress. We construct scenarios that highlight the advantages of our approach over the current state-of-the-art and have high potential of complementing the current state-of-the-practice. Predictions accounting for common sources of uncertainty are included and we show how the predictions improve in time, become more confident, and change dynamically as new information is made available to the prediction algorithm.

In this report, we do not focus on mechanical failures of individual aircraft. Analysis of unsafe events resulting from criminal activity are also out of the scope of this report as that will entail prediction of criminal activity. Moreover, we only provide some illustrative examples of the hazards, thresholds, and so on. An exhaustive list of hazards applicable to a particular operation is dependent on numerous factors, such as pilot, controller, and aircraft capabilities, or an operator's business model regarding acceptable risk. The framework we present is applicable to any hazards that can be measured and predicted. The hazards included in any particular instantiation of the framework depends on the operator's needs.

Safety of the airspace is the goal of every stakeholder involved in the domain of aviation. Current state-of-the-art approaches for assessing the safety of the airspace include the FAA's Flight Risk Analysis Tool (FRAT) and FAA's Safety Management System (SMS), among others. However, none of these tools have addressed the problem of real-time monitoring and prediction of safety of the airspace. Moreover, many of the tools mentioned above focus on a subset of all possible hazards that can affect airspace safety. On the other hand, our framework is general enough to include any hazard that can be modeled quantitatively. Another contribution of our work to improving NAS safety is our approach to handling uncertainty. Rather than ignoring uncertainty (of weather forecast or expected traffic, for example) or just adding a “fudge factor”to account for uncertainty (separating aircraft by a little extra, for example, to account for uncertainty in when a pilot will slow on final approach to landing), we present a systematic, integrated framework for the rigorous, mathematical treatment of uncertainty. Based on principles of probability and Bayesian analysis, the proposed methodology can compute the entire probability distribution of NAS-related quantities of interest without making significant assumptions regarding their distribution type and/or parameters.

1.3 Report Organization

This report is organized as follows. Chapter 2 presents some background of the NAS and current state of safety assessment and risk assurance in the NAS. We formulate our problem and present our approach for implementing the real-time NAS safety monitoring and prediction framework in Chapter 3. Chapters 4 and 5 present the offline safety analysis and the online real-time monitoring and prediction of NAS safety modules of our framework. Chapter 6 presents some illustrative scenarios demonstrating our implementation of this framework in simulation. Finally, Chapter 7 concludes this report and presents future work.

Chapter 2

Safety of the National Airspace System: A Brief Background

The NAS has significantly evolved over the decades to suit user needs [13]. In the mid 1930s, Bureau of Air Commerce controllers separated en-route aircraft using maps, blackboards, and mental calculations. In the 1940s, the Civil Aeronautics Administration expanded the control role to include takeoff and landing operations at airports. A midair collision between two airliners in the mid 1950s led to the establishment of the Federal Aviation Administration (FAA) and significant expansion of facilities, rules, and regulations to support the increased traffic from the growing aviation industry. Traffic separation became more efficient with the introduction of radar and computers in the 1970s. Additional computational support in the 1980s and 1990s fulfilled the greater need for efficiency required by the more competitive environment created by airline deregulation.

The current NAS is structured to ensure *safe* and *efficient* flow of air traffic. To this end, air traffic controllers coordinate aircraft positions and prevent collisions between aircraft operating in the system, while organizing and expediting the flow of traffic. Rules and regulations, airspace type and extent, and procedures help protect aircraft operating under air traffic control (ATC). Airspaces are designated to protect arrival, departure and en-route corridors, and congruently, arrival, departure, and en-route procedures are designed to fit within the protected airspace. The rules and regulations associated with the various airspaces vary to accommodate the density of traffic, the performance of aircraft, the performance of the surveillance technology (e.g., radar or satellite), and the surrounding environment.

In this chapter, we present the state of the art that helps maintain safety in the NAS. Section 2.1 presents a brief background of the structure and operations of the NAS to ensure safety. In Section 2.2, we describe the current state of safety assurance in the NAS and the various roles different stakeholders have in this regard. Finally, we present the planned NextGen initiatives that will further improve NAS safety in the future in Section 2.3.

2.1 Structure and Operations of the NAS for Safety

The NAS is structured to facilitate safety. It is segregated into a variety of airspace types, each with different entry requirements and provided services. In general, flights operating within controlled airspace are protected from each other and are provided additional surveillance to protect them from terrain, obstacles, or other adversities. Traffic is both controlled at the tactical level and strategically managed to reduce the possibility of collision.

In this section, we describe how the various types of airspace segregate air traffic by flight mission and performance capabilities, decreasing the likelihood of loss of separation. We also describe the types of air traffic control facilities that have been created to deal with air traffic and their roles in controlling traffic flow.

2.1.1 Airspace Classes

As established in 14 CFR Part 73, the NAS can be divided into Class *A*, *B*, *C*, *D*, *E*, and *G*; *Special Use Airspace* (SUA), such as *Restricted*; *Prohibited* airspace; *Military Operations Areas* (MOA); *Warning areas*; *Alert areas*; and *Controlled Firing Areas* (CFA). Figure 2.1 shows the airspace classes at a glance, reproduced from the FAA's Aeronautical Information Manual (AIM) [14]. Since weather is critical to operations and is considered in many of the regulations, the definition of some of the airspaces is based on weather conditions. Weather conditions are described as either *Visual Meteorological Conditions* (VMC), i.e., conditions under which pilots can see and avoid each other, or *Instrument Meteorological Conditions* (IMC), i.e., conditions in which pilots need external assistance, e.g., air traffic controllers, to strategically avoid other aircraft. The operational flight rules define weather conditions under which visual-only flight is permitted using Visual Flight Rules (VFR) and weather requiring the use of Instrument Flight Rules (IFR). An aircraft can operate IFR in VMC or IMC, but can operate VFR only in VMC.[1] Permissible weather conditions - defined by visibility and height above ground of the lowest layer of clouds (or other obscuring phenomena) that covers more than half the sky (the "ceiling") – and the required distance from clouds are specific to each type of airspace, as defined below:

- Class A: The airspace above 18,000 ft mean sea level (MSL) up to flight level (FL) 600 (approximately 60,000 ft MSL). It is used for en-route, high-altitude transit. Unless otherwise authorized, all aircraft must be IFR.

- Class B: The airspace from the surface to 10,000 feet MSL surrounding the nation's 29 busiest airports in terms of IFR operations or passenger enplanements. Everyone is under ATC control in class B; however, operations can be either IFR or VFR.

- Class C: The airspace from the surface to 4,000 feet above the airport elevation (charted in MSL) surrounding 122 airports that have an operational control tower, are serviced by a radar approach control, and that have a certain number of IFR operations or passenger enplanements. Operations can be either VFR or IFR and two-way radio communication must be established prior to entering.

- Class D: The airspace from the surface to 2,500 feet above the airport elevation (charted in MSL) surrounding those airports with an operational control tower. Operations can be either VFR or IFR and two-way radio communication must be established prior to entering.

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[1] There are exceptions to this rule, codified in the Special VFR rules.

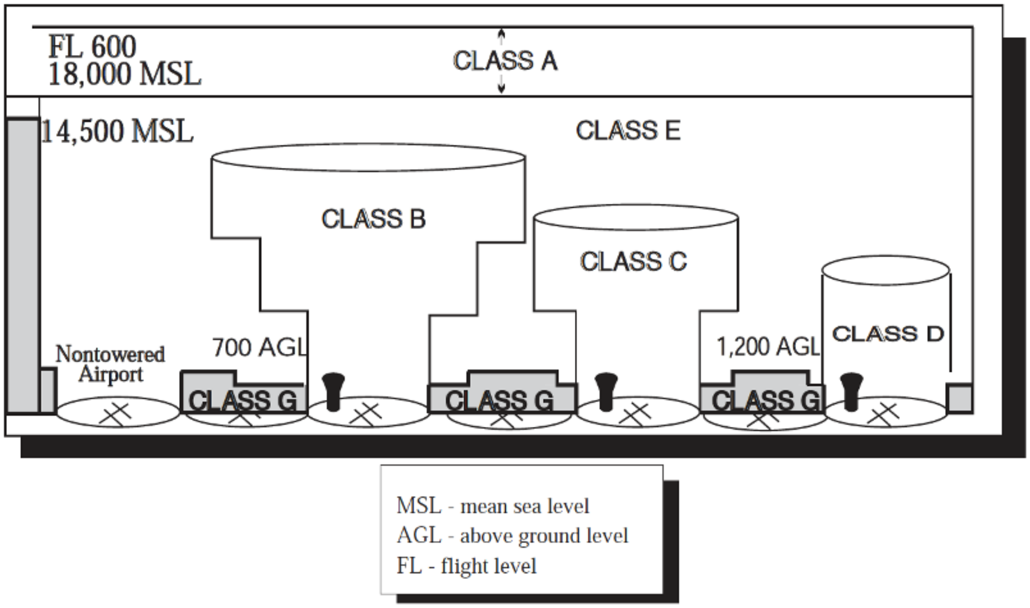


Figure 2.1: NAS Airspace Classes, reproduced from [14].

- Class E: If the airspace is not Class A, Class B, Class C, or Class D, and it is controlled airspace, it is Class E airspace. Examples of Class E airspace include surface area for airport to include instrument procedures, extensions to a surface area to protect instrument approach procedures but not require communication from all, federal airways from 1200 ft to 18,000 ft MSL, transition from/to terminal/en-route, en-route domestic areas and offshore airspace areas, etc.
- Class G: This airspace falls in the uncontrolled airspace category. Separation services are not provided by ATC to any aircraft, VFR or IFR. It is generally uncongested airspace far from major airports.
- Special Use Airspace: Special Use Airspaces are those that are considered hazardous to civil aircraft and includes Prohibited, Restricted, Warning, Alert, MOA, and CFA.

2.1.2 Air Traffic Control System

As mentioned above, the primary purpose of the ATC system is two-fold: it must provide *safety* by preventing collisions among aircraft and between aircraft and terrain/obstructions, and provide *efficiency* by organizing and expediting the flow of traffic. An air traffic controller's first priority is to separate aircraft and issue safety alerts if aircraft are in unsafe proximity to terrain, obstructions, or other aircraft. All other services are on a workload-permitting basis. Aircraft are serviced in a first-come, first-served basis with some priorities placing air carriers toward the top of the priority list, other IFR flights lower, and VFR flights at the bottom. The ATC system is composed of five types of facilities:

- Tower: This facility sequences aircraft for departure and arrival, in conjunction with TRACON, and controls airport surface operations.

- Terminal Radar Approach Control (TRACON): This facility services arriving or departing controlled flights in busy airspace around large airports.

- Air Route Traffic Control Center (ARTCC) or "Center": This facility services aircraft operating on IFR flight plans within controlled airspace and principally during the enroute phase of flight. When equipment capabilities and controller workload permit, certain advisory/assistance services may be provided to VFR aircraft.

- Air Traffic Control System Command Center (ATCSCC) or "Command Center": This facility anticipates and issues traffic management initiatives (TMI) to minimize delay and congestion while maximizing operations. The TMIs are communicated to the NAS operators and implemented by the Centers, TRACONs, and towers.

- Flight Service Station (FSS): This facility provides weather and flight plan information to general aviation pilots. Assists pilots in emergencies and coordinates search and rescue (SAR) operations for missing and overdue aircraft.

The NAS is split into 22 Centers, as shown in Figure 2.2 [15]. Each Center is divided into Sectors, each with a horizontal and vertical extent, only some of which start at the surface. Each Sector also has a unique radio frequency. As flights progress through airspace, pilots switch frequencies to talk to the appropriate sector controller (as advised by the previous controller). Centers service arrivals, departures, and over-flights (i.e., those aircraft flying through a Center's airspace that did not depart or will not land at any airports within the Center's surface-projected boundary.). Traffic is coordinated with TRACON over arrival/departure gates and metering fixes – agreed-upon geographical areas through which aircraft are funneled to facilitate organization from or toward a major airport. Traffic Management Coordinators (TMC) and Center controllers sequence the aircraft, safely separated, and hand off to the TRACON at a rate that fully complies with, but does not exceed, the capacity of the TRACON and destination airports. Determining that rate is key and changes with demand and with weather.

Like Centers, TRACONs are also divided into Sectors, each with its own frequency. TRACON jurisdiction is not the same as Class B or Class C. Rather, typically, they control traffic about 30 to 50 nm from busy airports; where there are many busy airports in near proximity, a consolidated facility may service them. An example of this is the NorCal TRACON that services airports covering a large part of Northern California from San Francisco, CA to Reno, NV.

Airports can be either towered ("controlled") or non-towered ("uncontrolled"). The tower controllers are responsible for aircraft movement on the airport surface, for runway separation, and separation between IFR aircraft in Class D. At airports with dedicated airliner ramps, responsibility for the airport surface is shared with the (airline-employed) ramp controllers.

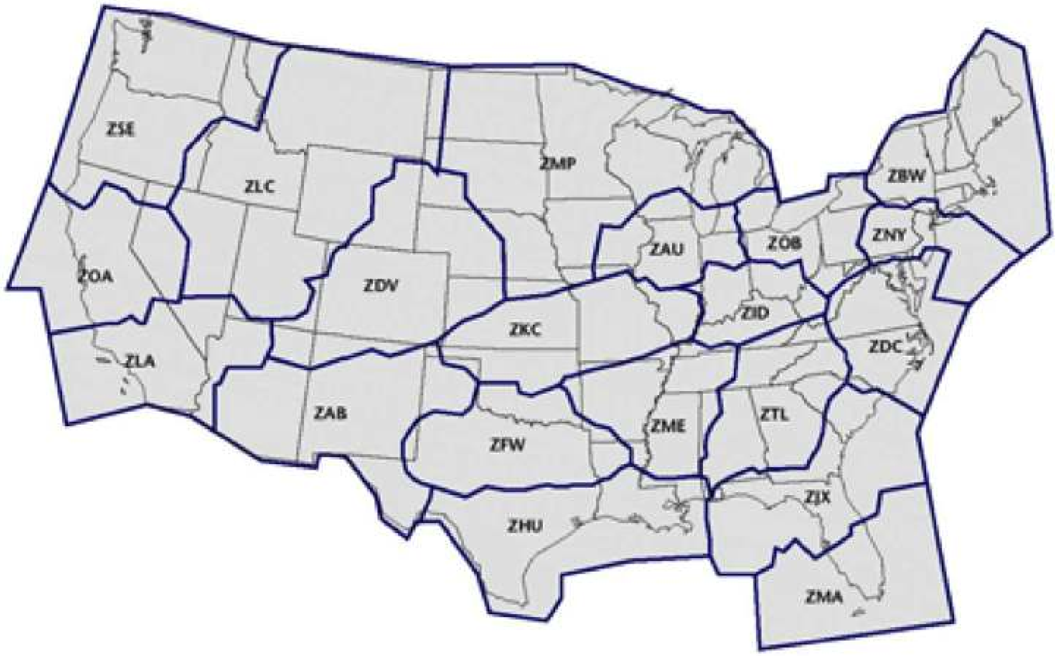


Figure 2.2: NAS is divided into 22 Air Route Traffic Control Centers (ARTCC), or "Centers". Archorage Center and Honolulu Center are not shown. Reproduced from [16].

2.1.3 Traffic Flow Control

Approximately 30,000 flights are serviced by ATC each day [17]. These flights are not evenly spaced through the 24 hours. Instead, with the hub-and-spoke system favored by the airlines and daytime flights favored by passengers, flights arrive in batches, mostly during the day. With limited available runways, some flights in these clumps get delayed awaiting their turn to depart or land.

Airport capacity is determined by required separation between aircraft, runway layout, runway availability, and weather conditions. For example, wind velocity dictates runways in use, wet or icy runways increase runway occupancy time (i.e., the time a flight spends on the runway decelerating to a safe turn-off speed), visibility conditions affect whether parallel runways can be used simultaneously, and thunderstorms in the vicinity of the airport can cause the controllers to shutdown all arrivals and departures. Center, TRACON, and tower controllers coordinate to fit the flights within available capacity defined by the Airport Arrival Rate (AAR) [18] set for a particular airport condition.

A number of methods are available to ATC to control the flow of traffic and remain within the AAR as well as balance saturated and low-use sectors. At the controller level, speed adjustments, route adjustments, and airborne holding can be used to slow or redistribute traffic. At the Command Center level, various traffic management initiatives

(TMI) [18] can be issued to delay inbound aircraft prior to departure. One of the issues with TMIs is that the delayis enforced only at the departure point, and pilots speed up to make up the delay, defeating the Command Center's computations. Controllers also are often not privy to the Command Center plan and approve pilot requests for shortening the route.

As mentioned earlier, weather near an airport can have upstream effects on traffic. Enroute convective weather and non-convective turbulence can also wreak havoc on the system as flights deviate around thunderstorms or request altitude changes. Each operator has a different perspective on the weather and different standards for intent, amount, and direction for circumnavigating the weather, and ATC must share decision-making with each pilot-in-command (PIC) of a flight. The uncertainties of weather movement, of how each PIC will deviate, and of how each controller will handle a situation lead to unpredictable system-wide operations – a deficiency that adversely affects the ability of commercial airlines to plan and execute an efficient flight schedule.

2.2 Current State of Safety Assurance in NAS

Regardless of disruptions to the system or clumps of traffic, ATC must assure *safety*. The Code of Federal Regulations (49 CFR) part 830, section 830.2, and the FAA define safety as follows [19–21]:

Definition 1 (Safety)**.** Freedom from those conditions that can cause death, injury, occupational illness, or damage to or loss of equipment or property, or damage to the environment. Absolute safety implies freedom from all harm or danger – an impossible circumstance. Therefore, safety is a relative term that implies a level of accepted risk.

At present, several entities work together to ensure safety of the NAS. Some of these players and their roles in assuring safety are presented below.

2.2.1 Role of Pilots in Assuring Safety

The pilot-in-command is the final authority on the operation of a flight and can take any necessary action to ensure its safety. That said, unless required for safety, the pilot must comply with rules, regulations, and procedures imposed on the operation by the FAA, the airline or company (as applicable). Before even contemplating flight, pilots must meet a number of requirements that support safety, such as appropriate training; flight and medical certification; abstinence from drugs, alcohol, or medications that may diminish performance; and sufficient rest, to name a few. Prior to a particular flight, pilots must comply with a catch-all regulation FAR 91.103 to become familiar with all available information concerning that flight. The regulation goes on to detail a number of specific items that must be considered, such as fuel requirements, aircraft performance requirements, and any flight impacts due to weather, expected traffic delays, possible alternates, etc. Airline pilots typically receive flight preparation assistance from airline operations center (AOC) dispatchers. Nevertheless, the pilot must review the provided information and accept responsibility for the flight. Once aloft, other regulations specify requirements for assuring separation from other traffic, terrain, special use airspace, or other hazards.

Pilots continually evaluate the current flight situation and anticipate the remaining route, considering such hazards as the health of the aircraft, performance of on-board automation, weather, fuel use, need to divert to an alternate airport, need to request a re-route that better satisfies business goals, and the safety and comfort of the passengers. If any constraints are violated or may be violated without timely action, pilots coordinate with company dispatch or maintenance, or with controllers to ensure their aircraft's safety without causing undue hazard to other flights. Because they have a localized view of the airspace, they depend on information from their company, other pilots, and controllers to maintain adequate situational awareness and assure safety of flight. With the strong interdependence of all airspace operators, pilots also assure future safety by reporting anomalies they observe, whether due to their own or another pilot's action, a controller's action, a procedure, or the environment.

2.2.2 Role of Controllers in Assuring Safety

Controllers accept a great deal of responsibility to assure the safety of NAS operations. To qualify for (non-trainee) assignment to a console position, controllers must meet training and certification requirements and abide by numerous regulations regarding operations, performance-degrading substance use, rest periods, etc. Controllers must meet stringent certification requirements and demonstrate that they can instantly recall necessary frequencies and other information about adjoining sectors, effectively manage the amount of traffic expected in their area, properly coordinate with other facilities, work as a team with fellow controllers and pilots, understand aircraft performance limitations, anticipate problems, and numerous other skills. To keep workload within manageable limits, letters of agreement (LOA) are established with neighboring facilities explicitly coordinating operations.

Releasing and receiving controllers must mutually acknowledge a handoff of a flight prior to a pilot being directed to contact the receiving controller. On first contact with a controller (that is, not a handoff situation), pilots must receive appropriate acknowledgement prior to entering controlled airspace. To ensure orderly traffic, handoffs typically occur on agreed-on routes, spaced adequately for the receiving controller. A controller receiving flights from many directions must organize the flow, deciding how to sequence them toward the airport or the next controller, and how to keep them separated while in his airspace, whether by heading, altitude, or speed assignments. To decrease pilot workload and reduce frequency congestion, controllers must plan ahead so the same flight does not need to, for example, speed up and then slow down. Also to decrease pilot and controller workload while assuring safety, standard flow organizing routes have been established, namely Standard Terminal Approach Routes (STAR) and Standard Instrument Departure routes (SID). A complex series of heading and altitude changes are coded into a single named procedure, greatly decreasing frequency congestion that would otherwise be required to issue each instruction separately. Flight management systems (FMS) can be directed to fly the complex procedure by entering only its name, further decreasing pilot workload. Controllers must release (or clear) flights onto those routes, ensuring adequate spacing between flights. When a flight is not on a SID or STAR, the controller must anticipate the aircraft performance and the speed of pilot compliance to issue orders that maintain separation of that flight from other aircraft, obstacles, and special use airspace, and smoothly get it to its destination. A controller's primary responsibility does not include separating aircraft from weather. Pilots often have much better insight into the local weather. Hence, the controller's responsibility is to best accommodate pilot requests for avoiding weather, offering suggestions only upon pilot request and only when the controller knows more about the weather than the pilot does (often the case with general aviation pilots due to their limited on-board weather detection systems).

In addition to tactical control of flights, controllers observe pilot compliance with directives and procedures, and their own and other controllers' management of flights. If unsafe situations are detected, controllers inform appropriate authorities with the goals of improving future safety through pilot or fellow controller re-training or more drastic measures as needed, and of improving overall operations by documenting situations with adverse effects or unanticipated consequences.

2.2.3 Role of Command Center in Assuring Safety

Up the hierarchy, the Command Center assures safety by regulating the controller's workload, which is affected by both volume of traffic as well as diversity of type, equipage, and performance. Many factors determine the volume of traffic an airspace and controller can safely manage, including separation standards, weather, terrain, SUA, training operations in effect, and runway availability. Separation standards vary per situation and are determined by aircraft type and performance; surveillance type (e.g., radar or visual) and location; ATC display limitations; weather conditions and flight rules; operational needs; etc. As technology changes, separation standards are reevaluated and modified as required. Weather, terrain, and SUA all contribute to decreasing the permeability of an airspace, i.e., blocking to some degree areas of airspace that are not available for normal operations. The Command Center must anticipate these restrictions well in advance, given weather forecasts and SUA stated requirements. Based on forecast restrictions and knowledge of scheduled flights through those areas, it then issues TMIs that endeavor to sufficiently thin the traffic.

The Command Center is also involved in assuring safety by balancing the demand profile at popular major airports like those in the NY metroplex, Chicago, or Washington DC, and when unusual traffic volume is expected at an airport, for example, for a major sporting event. Requiring landing reservations benefits safety by reducing congestion and restricting access to the most qualified operators.

2.2.4 Role of FAA in Assuring Safety

Up the hierarchy one more level, the FAA establishes rules and regulations that promote safety, and ensures that operators are appropriately qualified and facilities are operating as required. As alluded to above, the FAA also takes enforcement action against pilots and controllers suspected of lacking required skills. In addition to supporting current NAS operations, the FAA conducts research and development to satisfy the expected requirements of future operators. The current NAS serves primarily traditional aircraft. That is changing, however, with the introduction of unmanned aircraft systems (UAS) and commercial space vehicles, expanding the challenges of safely and efficiently managing the NAS.

The FAA is concerned with quantifying the risk of operating in the NAS. Risk assessment considers factors such as the level of compliance with agreed-upon policies, procedures, certifications, infrastructure; frequency and severity of incidents and accidents;

environmental hazards, such as elevation around airport, frequency of low ceilings or low visibility; and quality of operating assets, such as fleet modernization. A numeric score can reflect a baseline risk for operations at each airport and/or for each operator.

Despite the best efforts to ensure safety prior to flight, some level of risk persists due to human performance variability, environment variability, and interactions complexity. Much like building a bridge to handle 50% or 100% more than the expected maximum load, aviation best practice prescribes adding a buffer to the minimum as-regulated conditions, that is, a safety margin.

Operations in the NAS vary vastly. Not every operation in the NAS carries with it the same hazards or the same level of risk. For example, a local area flight from an airport surrounded by flat fields, in clear and calm weather conditions, in a well-maintained simple aircraft, flown by an experienced pilot puts very little stress on the safety envelope designed into the NAS. The risk to that flight is minimal. As each of those characteristics is varied, the level of risk rises.

To manage these flight-specific (dynamic) hazards, operators are strongly encouraged to establish a Safety Management System (SMS) [22] or, for smaller operators, utilize the concepts of the FAA's Flight Risk Assessment Tool (FRAT) to set up evaluation criteria for assessing potential hazards.

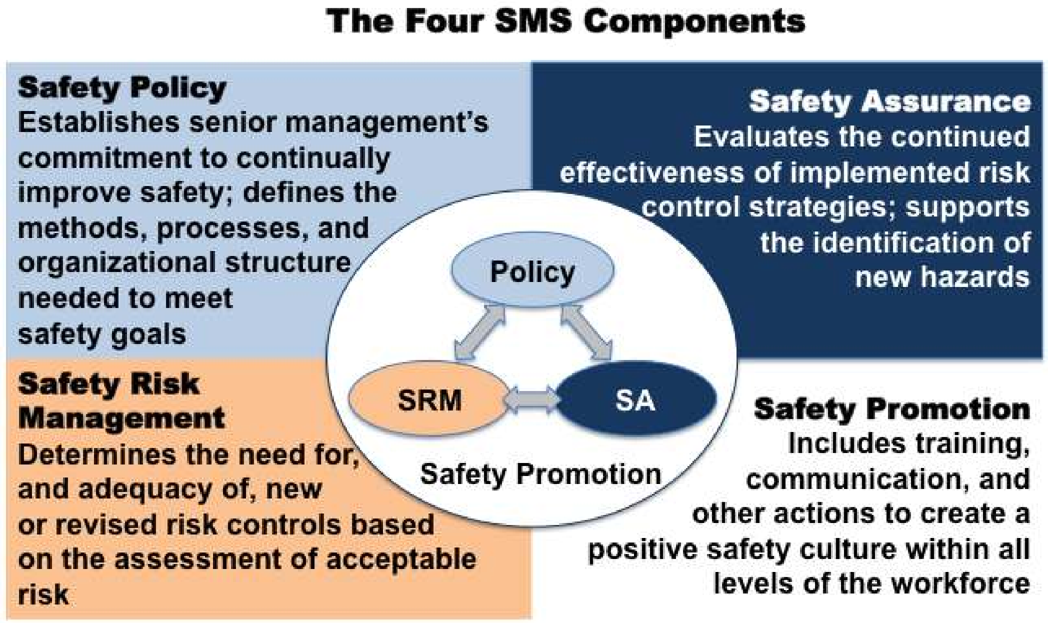
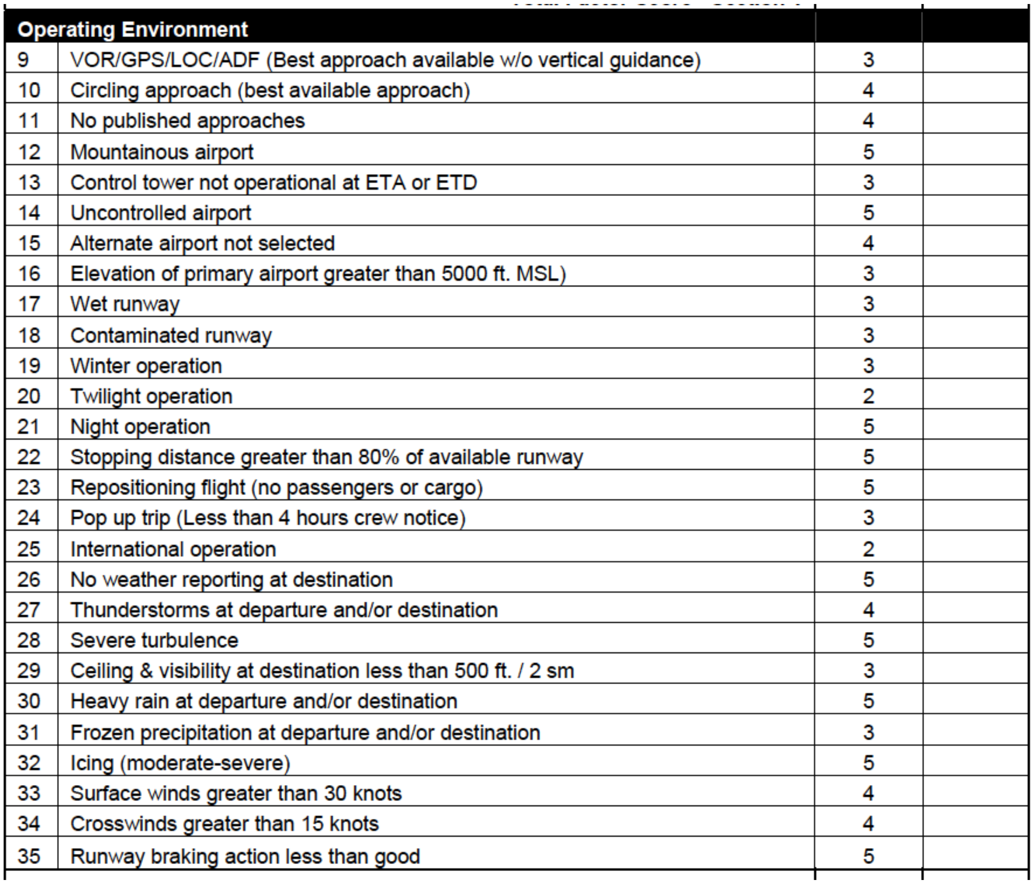


Figure 2.3: FAA Safety Management System (SMS) components.

A Safety Management System (SMS) has four components, as shown in Figure 2.3, that help an organization manage risk, promote a safety-conscious culture, document the organization's commitment to safety, and evaluate the effectiveness of the safety plans in practice. Much like our work, one of the critical aspects of an SMS is performing a hazard analysis, assessing the risk (severity and likelihood) of each hazard, and determining how safety will be assured.

For GA pilots and smaller operators, the FAA Information for Operators (InFO) document 07015 entitled Flight Risk Assessment Tool describes a tool for quantifying risk by analyzing the potential risks and setting up minimum criteria for flight operations. The document advises pilots to consider the risk from all hazards, defined as *”A condition that could foreseeably cause or contribute to an aircraft accident as defined in Title 49 of the Code of Federal Regulations (49 CFR) part 830, section 830.2.* The risk assessment tool described in the FAA notice categorizes risk into three sections: (1) Pilot Qualifications and Experience, (2) Operating Environment, and (3) [Aircraft] Equipment. The Operating Environment section of the FRAT is shown in Figure 2.4 as an example of the hazards to be considered. Hazards are identified independent of flight (that is, completed separately from a particular flight), before operational pressures influence the decision making process. Risk is then assessed for each flight before departure and re-assessed during flight. Because the conditions under which flight is acceptable are considered separately from a flight, risk assessment may be more objective and flight may potentially be safer.



Operating Environment			
9	VOR/GPS/LOC/ADF (Best approach available w/o vertical guidance)	3	
10	Circling approach (best available approach)	4	
11	No published approaches	4	
12	Mountainous airport	5	
13	Control tower not operational at ETA or ETD	3	
14	Uncontrolled airport	5	
15	Alternate airport not selected	4	
16	Elevation of primary airport greater than 5000 ft. MSL)	3	
17	Wet runway	3	
18	Contaminated runway	3	
19	Winter operation	3	
20	Twilight operation	2	
21	Night operation	5	
22	Stopping distance greater than 80% of available runway	5	
23	Repositioning flight (no passengers or cargo)	5	
24	Pop up trip (Less than 4 hours crew notice)	3	
25	International operation	2	
26	No weather reporting at destination	5	
27	Thunderstorms at departure and/or destination	4	
28	Severe turbulence	5	
29	Ceiling & visibility at destination less than 500 ft. / 2 sm	3	
30	Heavy rain at departure and/or destination	5	
31	Frozen precipitation at departure and/or destination	3	
32	Icing (moderate-severe)	5	
33	Surface winds greater than 30 knots	4	
34	Crosswinds greater than 15 knots	4	
35	Runway braking action less than good	5	

Figure 2.4: Operating Environment section of the FAA’s Flight Risk Assessment Tool (FRAT).

2.2.5 Other Stakeholders in Assuring Safety

Various other organizations are concerned with assuring aviation safety, such as:

- International Civil Aviation Organization (ICAO) [23];
- *Accident investigation agencies*, such as U.S. National Transportation Safety Board [24], and International Transportation Safety Association (ITSA) [25];
- *Operator (air traffic controller, pilot or airline) organizations*, such as International Air Transport Association (IATA) [26], U.S. National Air Transport Association (NATA) [27], U.S. Regional Airline Association (RAA) [28], National Business Aviation Association (NBAA) [29], Aircraft Owners and Pilots Association (AOPA) [30], Experimental Aircraft Association (EAA) [31]; U.S. National Air Traffic Controllers Association (NATCA) [32], International Federation Air Traffic Controllers' Association (IFATCA) [33], and Air Line Pilots Association, International (ALPA) [34]; and
- *Research organizations*, such as NASA [35], the MITRE Corporation [36], as well as various other industry and universities.

Many of these organizations have a counterpart in other countries. Because aviation is a global enterprise, domestic and international organizations cooperate to ensure worldwide aviation safety. Generally, these organizations seek to understand circumstances that could lead to or contribute to undesired events (accidents or incidents) and to influence aviation safety through recommended practices, standards, procedures, or regulations for aircraft and aircraft equipment, airspace and airspace equipment, and personnel (pilot, controller, etc.) training. With this approach, safety is achieved through a combination of risk assessment, regulation, education, and auditing for compliance. Rules have been enacted for such diverse topics as airport layout, runway overshoot/undershoot areas, pilot work hours, building aircraft for accident survivability, maximum aircraft occupancy limits for emergency egress, dangerous goods transport, etc.

One organization with particular benefit to our work is NASA's Aviation Safety Reporting System (ASRS) group. ASRS was created with full agreement from the FAA as a non-enforcement entity. Pilots, controllers, mechanics, flight crew, and others are encouraged to submit reports whenever they are part of or observe an unsafe situation or incident. The reporters are given immunity from enforcement of any rules and regulations they may have unintentionally broken, encouraging them to share the information for the benefit of others rather than hiding it for their own protection. The ASRS de-personalizes these reports, compiles them in a database, and extracts and shares with appropriate policy-makers the deficiencies or discrepancies and hazards in the system that adversely affect safety. Pilots, controllers, and others are also able to search the database and learn from others' mistakes or infractions. The ASRS immunity does not apply if an aviation accident, crime, or intentional violation of regulations is reported. Aviation accidents are reportable to the NTSB. They too maintain a publicly-searchable database of unsafe situations that cause or contribute to accidents. As we discuss in Chapter 4, we extensively referenced both the ASRS and NTSB repositories.

2.2.6 Impact of Uncertainty on NAS Safety

As explained earlier in Chapter 1, the treatment of uncertainty is central to the approach developed in this report. There are several sources of uncertainty that affect the operations and the overall safety of the NAS. It is important to understand and analyze these sources of uncertainty, systematically quantify their impact on the operations of the NAS, estimate the effect of uncertainty on safety, and aid risk-informed decision-making activities to ensure smooth operation of the overall system.

There are a few researchers who have studied the impact of uncertainty on NAS operations and overall safety. For example, Landry and Archer [37] have focused on enumerating the different sources of uncertainty in the NAS. In this work, several sources of uncertainty were identified; however, the relationships between them and their overall effects on NAS-level safety were not addressed. The researchers classified sources of uncertainty into three types: (1) sources that affect conflict detection and resolution (for example, likelihood of conflict affected because of impending collision, loss of separation, and other proximity-related events, detection of likelihood of conflict affected by software and hardware failures, and response time to conflict); (2) sources that affect control aircraft states (for example, uncertainty in aircraft trajectory prediction that may be caused due to uncertainty in initial conditions, modeling uncertainty, environmental uncertainty, etc.); (3) sources that affect management of air traffic resources (for example, demand and capacities at airport level and sector level).

In several research manuscripts, e.g., [38–40], flow models for air traffic management have been discussed and these models are able to account for some types of uncertainty. These uncertainties are mostly modeled using simplistic Gaussian variables that may rely on unrealistic assumptions; the true underlying distribution may not be Gaussian and need to be estimated, and such cases have not been addressed. Further, this analysis has been started only for a few uncertain variables (say, for instance, departure delays), and several other sources of uncertainty have not been studied, modeled, or accounted for.

Weather has been accounted for in a few publications (such as [41]) and the methods discussed are mostly based on collecting existing data and using simplistic linear regression-based models. The effects of weather delays in the overall NAS (system-wide, not localized to a specific area) and delay propagation have not been studied in detail. More importantly, mitigation strategies in the presence of weather-related uncertainties have not been fully developed (in part, for example, by rigorously estimating and accounting for the uncertainties involved). Many papers merely acknowledge the presence of uncertainty, without developing mathematical frameworks for dealing with them. It is necessary to develop improved models, verify and validate them, systematically account for uncertainty in prediction, and efficiently manage this uncertainty.

Only a few sources of uncertainty have been researched in some detail. For example, Wanke et al. [42] discuss quantifying uncertainty in airspace demand predictions, Kim et al. [43] and Garcio-Chico et al. [44] discuss trajectory uncertainty modeling, Tu et al. [45] study estimating flight departure delays. As acknowledged by these authors, such analysis appears to be at a very early stage in general and more work is still needed to improve the state-of-the-art, so that uncertainty analysis can be put into practice. Some effects of various uncertainties have been mentioned but not fully addressed. Further research is necessary to determine efficient ways of managing these sources of uncertainty. There are also sources of uncertainty for which even the initial analysis has not yet been done.

As a result, we have identified several gaps in the state-of-the-art with respect to uncertainty management for the national airspace system. Some important (and necessary) research activities and questions that need to be addressed are summarized below:

1. In the context of traffic flow management, there has been a considerable amount of work in modeling and including some sources of uncertainty (for example, traffic counts, airspace-region demand/capacity, air traffic flow, etc.). Further research is necessary to quantify some other sources of uncertainty (for example, weather uncertainty and its impact on traffic flow and associated safety, uncertainty in airspace trajectories, etc.) and estimate the effect of these sources of uncertainty on NAS-level operations (for example, what is the impact of terminal-level uncertainty in departure pushback on airspace-level weather avoidance or collision avoidance). It is also necessary to adapt existing models and/or build new models if necessary. Methods for traffic flow optimization need to be re-thought after many more sources of uncertainty are considered.

2. There has been very little work in studying uncertainty in delays, and understanding how these uncertainties propagate throughout the NAS. Prioritizing activities needs to be based on risks and costs associated with delays, and this needs to be addressed using a theoretical framework that can effectively manage the aforementioned uncertainty. For instance, weather-related uncertainty is very significant and how delays caused by weather affect the whole NAS is very important.

3. In trajectory-based operations, previous work at NASA Ames suggests that we are only at the beginning of accounting for uncertainty in trajectories. There is a clear need to improve the state-of-the-art by analyzing, in detail, what causes uncertainty in trajectories, what is the overall uncertainty in trajectories, and how we choose trajectories by managing this uncertainty.

4. An important goal is to predict the demands and capacity at multiple levels of the NAS (at sector-level, terminal-level or airport-level), and the uncertainty associated with these quantities. Some past work on this topic seem to suggest that this analysis is significant, but not all challenges have been addressed.

5. There are several other sources of uncertainties that have not at all been studied or some others that have just been barely understood (for example, trajectory uncertainty, departure pushback uncertainty, environmental uncertainty including weather-related uncertainty, etc.). While it is not feasible to look at all of them, it is possible to select one subset. For example, one idea is to collect the uncertainty sources in the airport terminal operations and study their effect on the overall NAS.

The methodology discussed in this report is a first step towards addressing some of the important goals above. While addressing all of them will take considerable time and effort, we believe that the proposed methods will pave the way for improving the overall state-of-the-art in the context of uncertainty management.

2.3 NextGen Initiatives for Safety Assurance in NAS

Having discussed the current state of safety assurance in NAS in the previous section, we now briefly discuss some NextGen initiatives for assurance of safety in NAS.

The challenges of safely and efficiently managing aircraft with diverse equipage and performance, together with the inability of the current system to handle the forecast demand, led to the Vision 100 – Century of Aviation Reauthorization Act (Public Law 108-176) and the creation of the *NextGen* solution. NextGen aims to transform the NAS by making revolutionary, not just evolutionary, changes. The goal is to revamp the system and ensure that aviation remains an economically viable industry. The 2007 NextGen concept of operations document [5] addresses six major goals to *"... significantly increase the safety, security, capacity, efficiency, and environmental compatibility of air transportation operations, and by doing so, to improve the overall economic well-being of the country."* Although our work supports most of these goals, we emphasize the goals to "ensure safety" and "expand capacity."

The NextGen vision also specifies eight key capabilities necessary to achieve the above-stated goals: Network-Enabled Information Access; Performance-Based Operations and Services; Weather Assimilated into Decision Making; Layered, Adaptive Security; Positioning, Navigation, and Timing (PNT) Services; Aircraft Trajectory-Based Operations (TBO); Equivalent Visual Operations (EVO); and Super-Density Arrival/Departure Operations.

One of the main thrusts of NextGen is shared situational awareness. Information is shared with all relevant communities of interest (COI) and decision making is coordinated to maximize safety, predictability and throughput. Our work on real-time monitoring and prediction of NAS safety directly benefits NextGen by improving operator awareness of hazards, enhancing the understanding of off-nominal airspace conditions, and consolidating information required for optimal decision making.

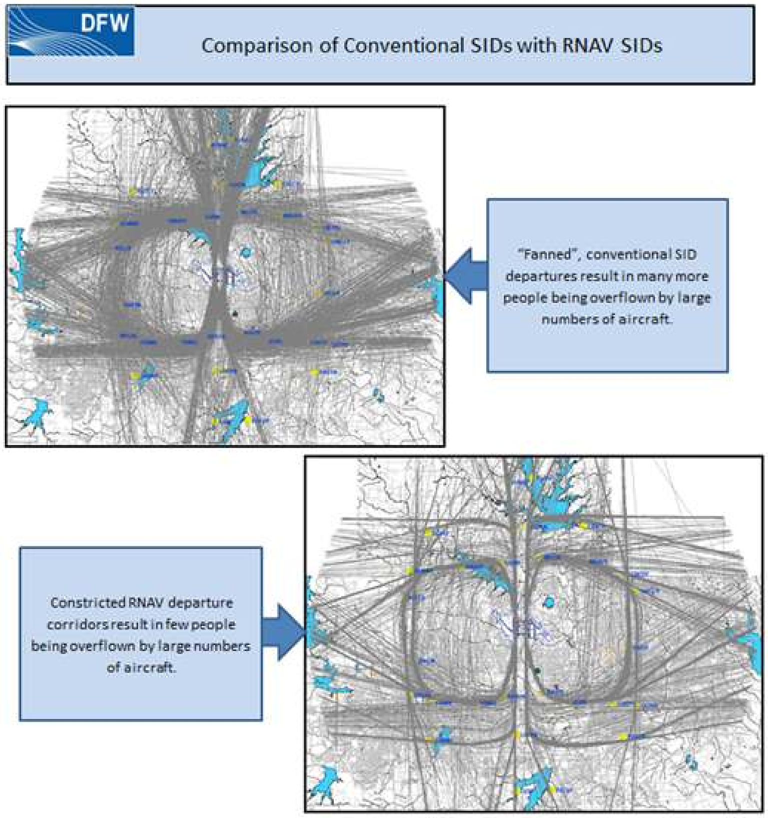
A number of NextGen technologies are currently in use or imminent, including Automatic Dependent Surveillance - Broadcast, Performance Based Navigation, and Collaborative Trajectory Options Program, as explained below. These technologies have the potential to greatly improve efficiency and safety of operations.

2.3.1 Automatic Dependent Surveillance - Broadcast

Automatic Dependent Surveillance - Broadcast (ADS-B) is a cooperative surveillance technology in which an aircraft determines its position via satellite navigation and periodically (1 Hz) broadcasts it, enabling it to be tracked. Via ADS-B "Out", the information can be received by ATC ground stations as a replacement for radar and by other aircraft for self (non-ATC) separation. It is automatic, meaning no pilot action is required, and dependent on data from the aircraft's navigation system. A complementary system ADS-B "In" receives flight and traffic information via datalink. Flight Information Services - Broadcast (FIS-B) receives weather and terrain information; Traffic Information Services - Broadcast (TIS-B) receives traffic within a specified nearby volume, as well as information about current temporary flight restrictions (TFR) and notices to airmen (NOTAM). All aircraft flying in "busy" airspace must equip with ADS-B "Out" by January 1, 2020. Unlike radar which updates position and velocity of aircraft every 4-15 seconds (depending on type of radar), ADS-B updates every second, resulting in more accurate positions than radar. Furthermore, because ADS-B depends on satellites, it does not have radar's limitations and can be used in remote or inhospitable areas.

2.3.2 Performance Based Navigation

Performance Based Navigation (PBN) describes an aircraft's ability to navigate using performance standards rather than predefined routes because it fulfills the traditional requirements for sensors and avionics. Unlike traditional navigation in which navigation beacons (e.g., VOR, NDB) are used to specify intersections and routes, PBN specifies only the navigation performance required to utilize a route. Available avionics can then be selected based on their ability to comply with those standards. Old avionics can be upgraded as long as the performance standards are met. PBN provides numerous advantages over the sensor-based approach, including reducing the costs of maintaining ground-based sensors and updating navigation procedures, and facilitating avionics upgrades as technology improves.



DFW Comparison of Conventional SIDs with RNAV SIDs

"Fanned", conventional SID departures result in many more people being overflown by large numbers of aircraft.

Constricted RNAV departure corridors result in few people being overflown by large numbers of aircraft.

Figure 2.5: Many overlaid arrival and departure paths to Dallas-Ft. Worth (DFW) airport showing the increased path precision of RNAV (Area Navigation) approaches. [46]

PBN is currently comprised of two systems: Area Navigation (RNAV) and Required

Navigation Performance (RNP). With RNAV, aircraft are able to fly on any desired flight path within the coverage of ground- or space-based navigation aids, providing flexibility in route design with the potential to save time and fuel, and to utilize more of the airspace. Additionally, RNAV routes based on satellite navigation can be much more precise, as shown in Figure 2.5.

RNP adds to RNAV by requiring monitoring and alerting functions. The avionics and pilots must monitor the achieved navigation performance and the avionics must alert the pilot if it detects that operational requirements are not being met. The avionics are required to keep the aircraft within a tightly specified corridor of width w with a guarantee that accuracy of w is achieved 95% of the time and a nearly 100% probability that the aircraft remains within a corridor of width $2w$. RNAV enables flexibility and efficiency of the airspace. RNP's precision allows further optimization of flight paths, reduced separation with other aircraft or terrain, utilization of simultaneous approaches on parallel runways in bad weather conditions, and deconfliction of approaches to close proximity airports, as is the case in the New York metroplex.

2.3.3 Collaborative Trajectory Options Program

The Collaborative Trajectory Options Program (CTOP) is an ATC and airline collaborative airspace flow program (AFP) that manages traffic to a point or an arc of airspace, or more generally, a flow constrained area (FCA). When traffic through an FCA is expected to exceed capacity, ATC sets an acceptance rate. Aircraft with flight plans through the FCA may then provide multiple trajectory options (routes), some of which avoid the FCA, and rank them as to their desirability to the airline's business needs. An FAA system selects the option that gives the best overall system performance, taking the airline preferences into account. CTOP has been tested at the Dallas-Ft. Worth (DFW) airport. It worked well to distribute traffic to different arrival fixes and reduce delays. It has also been tested under various scenarios in simulation. However, it is not yet fully operational. Although geared to address delay issues, it also helps improve airspace safety by dispersing congestion.

2.3.4 System Wide Information Management

System Wide Information Management (SWIM) is a program conducted by the FAA aimed at standardizing and simplifying access to various sources of air traffic management information. This information includes flight data, status of special use airspaces, restrictions in effect in NAS, airport operational status, and weather information (see Figure 2.6). SWIM will implement Service Oriented Architecture (SOA), allowing various types of information providers and consumers to connect to the system in a secure manner using uniform software interfaces, data structures, and protocols. SWIM is being built using commercial off-the-shelf hardware and software. SWIM is expected to contribute to safer NAS operations in the following ways:

- Provide consistent and up-to-date information to all key participants of NAS, i.e. controllers, pilots, and dispatchers;
- Help to efficiently manage traffic around weather and restricted areas;

- Enable subscriptions to various data sources, on-demand access, and push notifications.

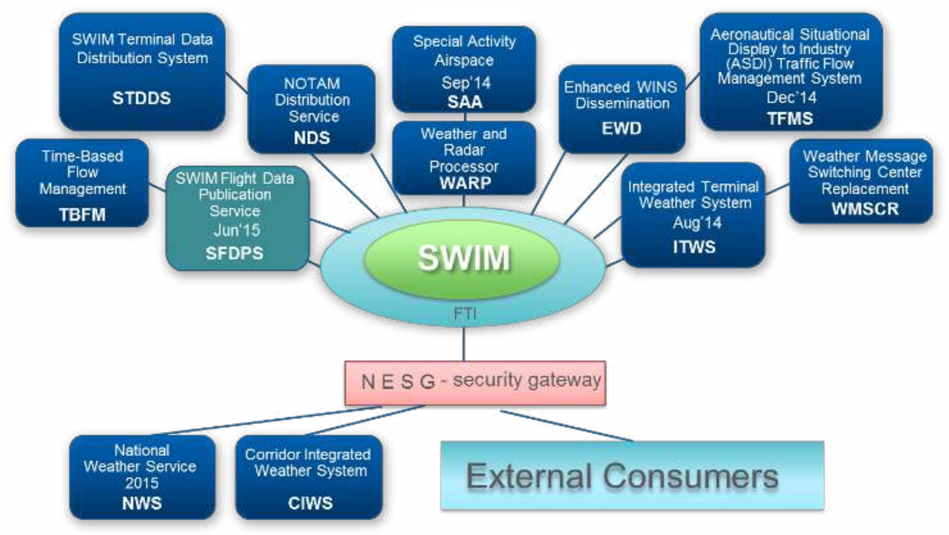


Figure 2.6: SWIM

Having provided a brief background on the safety of the NAS, in the remainder of this report we present our framework for real-time monitoring and prediction of the safety of the NAS. We will show how we utilize current as well as NextGen technologies (e.g., SWIM, ADS-B, etc.) to both expand capacity and ensure safety by providing an enhanced situational awareness to different NAS stakeholders.

Chapter 3

Problem Formulation

As previously discussed, NAS safety is currently assured through a variety of processes executed by diverse stakeholders. The system works well, but can benefit from additional techniques to further lower the accident rate to accommodate forecast growth. Two of the major deficiencies in the current system are (*i*) the restrictions to effective flight planning and en-route replanning due to limited access to relevant information, and (*ii*) the increased workload placed on pilots and controllers to forecast the evolution of flights. To this end, the goal of this work is to develop methods to evaluate the current safety level of the NAS through a set of *safety metrics*, and to predict how these safety metrics evolve in time. This up-to-date, customized information can then be continuously shared with all relevant stakeholders through advanced decision-support tools that facilitate informed decisions. The information can also be provided to automated decision-making tools to further reduce the workload imposed on pilots and controllers.

In this chapter, we develop a mathematical formulation of the problem, and propose an algorithmic approach to solving it. We also describe how uncertainty is rigorously and formally incorporated in our monitoring and prediction methodology. The chapter is organized as follows. The problem is first formally defined in Section 3.1, and the proposed solution methodology is overviewed in Section 3.2.

3.1 Problem Definition

At any discrete time point k, the NAS, or a subset of interest, is in some state:

$$\mathbf{x}(k) = \begin{bmatrix} x_1(k) \\ x_2(k) \\ \vdots \\ x_n(k) \end{bmatrix}, \tag{3.1}$$

including, for example, aircraft positions and speeds, weather system positions, etc. From these states, at time k, we can compute a set of safety metrics, $\boldsymbol{\phi}$, using an algebraic function

$\mathbf{F}$ of the states:

$$\boldsymbol{\phi}(k) = \begin{bmatrix} \phi_1(k) \\ \phi_2(k) \\ \vdots \\ \phi_m(k) \end{bmatrix} = \begin{bmatrix} F_1(\mathbf{x}(k)) \\ F_2(\mathbf{x}(k)) \\ \vdots \\ F_m(\mathbf{x}(k)) \end{bmatrix} = \mathbf{F}(\mathbf{x}(k)) \tag{3.2}$$

So, if we know the state of the NAS at some point in time, using $\mathbf{F}$ we can compute the corresponding safety metric vector.

There are points in the space of $\boldsymbol{\phi}$ (or, equivalently, $\mathbf{x}$) that are unacceptable to NAS operations, corresponding to unsafe events $e \in E$ such as loss of separation, an aircraft being within a convective weather region, high congestion, low fuel, etc:

$$E = \{e_1, e_2, \ldots, e_p\}. \tag{3.3}$$

The boundary between the acceptable and unacceptable space of $\boldsymbol{\phi}$, is defined through a threshold function on that space:

$$\mathbf{o}_E(k) = \begin{bmatrix} o_{e_1}(k) \\ o_{e_2}(k) \\ \vdots \\ o_{e_p}(k) \end{bmatrix} = \begin{bmatrix} T_{e_1}(\boldsymbol{\phi}(k)) \\ T_{e_2}(\boldsymbol{\phi}(k)) \\ \vdots \\ T_{e_p}(\boldsymbol{\phi}(k)) \end{bmatrix} = \mathbf{T}_E(\boldsymbol{\phi}(k)), \tag{3.4}$$

where $\mathbf{o}_{e_i}(k)$ is a Boolean variable that indicates whether event e_i has occurred ($\mathbf{o}_{e_i}(k) = true$) or not ($\mathbf{o}_{e_i}(k) = false$). The NAS is in an acceptable state if all elements of $\mathbf{o}_E(k)$ are false, and in an unacceptable state otherwise. The time of occurrence for some event e, k_e, is then defined as the first time at which its threshold function evaluates to true, i.e.,

$$k_e(k) \triangleq \inf\{k_i \in \mathbb{N} \colon k_i \geq k \wedge T_e(\boldsymbol{\phi}(k_i)) = true\}, \tag{3.5}$$

where k is the current time. The time remaining until that event, Δk_e, is defined as:

$$\Delta k_e(k_P) \triangleq k_e(k_P) - k_P. \tag{3.6}$$

We define the vector of event times as

$$\mathbf{k}_E = \begin{bmatrix} k_{e_1} \\ k_{e_2} \\ \vdots \\ k_{e_p} \end{bmatrix}. \tag{3.7}$$

Since the state of the NAS is not known exactly, and there is much uncertainty in future conditions and operations, all of these quantities are uncertain and must be described by probability distributions. Thus, the goal is to compute the probability distributions of these quantities, not point estimates. We can then define the *monitoring problem* as follows.

Problem 1 (Monitoring)**.** The *monitoring* problem is, for the current time k, to compute the probability distribution $p(\boldsymbol{\phi}(k))$.

Given $p(\boldsymbol{\phi}(k))$, we can also compute $p(\mathbf{o}_E(k))$ using $\mathbf{T}_E$ to determine the probability of any of the safety-related events occurring at time k.

For prediction, without loss of generality, we introduce a prediction horizon, $k_H > k$. We are interested only in predicting what happens up to time k_H. We denote the future values of a variable $\mathbf{a}$ from time k to k_H using $\mathbf{A}_k^{k_H}$.

Problem 2 (Prediction)**.** The *prediction* problem is, for the current time k, to compute the probability distribution $p(\boldsymbol{\Phi}_k^{k_H})$.

Given $p(\boldsymbol{\Phi}_k^{k_H})$, we can also compute $p(\mathbf{O}_{E,k}^{k_H})$ using $\mathbf{T}_E$, compute the probability of some event e_i or any event in E occurring within $[k, k_H]$, and the probability distribution $p(\mathbf{k}_E)$, among other quantities of interest.

3.2 Proposed Solution

This section describes the overall solution proposed in this report; first, our integrated monitoring and prediction approach is discussed, and then, aspects of incorporating uncertainty into this approach are discussed.

3.2.1 Integrated Monitoring and Prediction

Our approach to this problem is model-based, that is, we develop models of the NAS and its various components and how they interact, in order to predict its behavior over time, i.e., we define the state vector $\mathbf{x}$, the safety metric vector $\boldsymbol{\phi}$, the safety metric equation $\mathbf{F}$, the set of undesirable events E, and the threshold function $\mathbf{T}_E$ (Chapter 4).

In order to predict the value of $\boldsymbol{\phi}(k)$ in the future, and to predict when undesirable events will occur, we require a model describing how the state $\mathbf{x}$ evolves in time:

$$\mathbf{x}(k+1) = \mathbf{f}(k, \mathbf{x}(k), \mathbf{u}(k), \mathbf{v}(k)), \tag{3.8}$$

where $\mathbf{f}$ is the state function, $\mathbf{u}$ is the input vector, and $\mathbf{v}$ is the process noise vector. The state equation allows us to compute future values of the state given the inputs, and to compute future values of $\boldsymbol{\phi}$ and evaluate the threshold function, $\mathbf{T}_E$.

In order to make a prediction at time k using $\mathbf{f}$, we require $\mathbf{x}(k)$, which, in general, is not known. Instead, we have available an output vector $\mathbf{y}$, defined through an output equation:

$$\mathbf{y}(k) = \mathbf{h}(\mathbf{x}(k), \mathbf{u}(k), \mathbf{n}(k)), \tag{3.9}$$

where $\mathbf{h}$ is the output function, and $\mathbf{n}$ is the sensor noise vector. We need to infer $\mathbf{x}(k)$ from $\mathbf{y}(k)$ using $\mathbf{f}$ and $\mathbf{h}$, and for this we use state estimation algorithms.

In the monitoring step, given the inputs $\mathbf{u}$, the outputs $\mathbf{y}(k)$, the state equation $\mathbf{f}$, and the output equation $\mathbf{h}$, we must estimate the current state $p(\mathbf{x})$, and, given $p(\mathbf{x})$ and the safety metric equation $\mathbf{F}$, compute $p(\boldsymbol{\phi}(k))$. In the prediction step, at time k, given the output of the monitoring step, $p(\mathbf{x}(k))$, the state function $\mathbf{f}$, the safety metrics $\boldsymbol{\phi}$, the safety metric function $\mathbf{F}$, the set of events E and threshold function $\mathbf{T}_E$, the future input trajectory probability distribution $p(\mathbf{U}_k^{k_H})$, and the future process noise probability distribution $p(\mathbf{V}_k^{k_H})$, we must compute probability distributions for $\mathbf{X}_k^{k_H}$, $\boldsymbol{\Phi}_k^{k_H}$, $\mathbf{O}_{E,k}^{k_H}$, $\mathbf{k}_E$ and $p(e)$ for each $e \in E$.

3.2.2 Incorporating Uncertainty

In order to systematically and accurately account for the presence of uncertainty in the NAS, a series of uncertainty-related activities needs to be performed. Fig. 3.1 qualitatively explains these activities using a few examples, and also briefly states the ongoing work in the context of each of these activities.

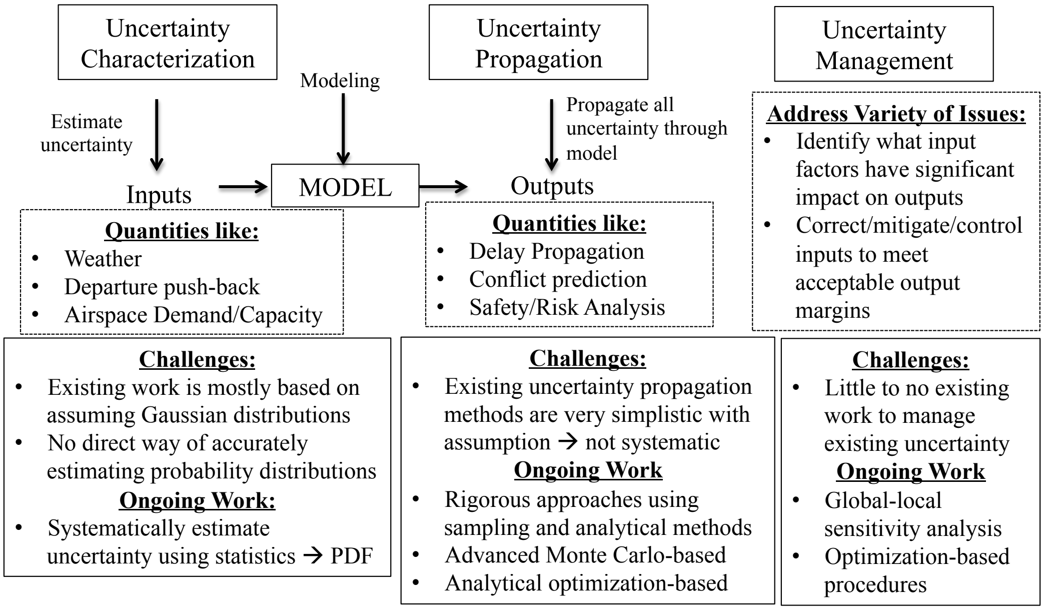


Figure 3.1: Summary of Uncertainty-related Activities

Uncertainty Characterization

Uncertainty characterization deals with estimating the uncertainty in quantities that affect the overall operations of the NAS. These quantities may include NAS-level, terminal-level, sector-level, and airport-level quantities. It is essential to consider the set of desired hazards and safety metrics, and isolate all quantities that impact such safety and hazard analysis. Then, it is necessary to characterize the uncertainty in these quantities using historical data. For example, Tu et al. [45] discuss estimating flight departure delays by looking at year-long data at a desired airport.

While uncertainty characterization is traditionally performed using methods of probability and statistics, alternative approaches have also been investigated by researchers. Such approaches are based on fuzzy methods [47], Dempster-Shafer theory [48], etc. However, there is a general consensus that probabilistic methods are the most widely applied for applications of the prognostics-kind [49], where the goal is to predict the occurrence of safety-related incidents in the future.

There are several sources of information that are useful for uncertainty characterization.

These sources include data collected from design of experiments, historical data, expert opinion, categorical information, etc. A major advantange of using a probabilistic approach for the treatment of uncertainty is that this framework can handle and account for all the aforementioned types of information.

Uncertainty Propagation

Once the uncertainty is characterized using various important quantities, the next step is to quantify the impact of these quantities on the safety metrics. This is typically formulated as an uncertainty propagation problem. For instance, if a safety metric Y depends on a list of uncertain quantities $\boldsymbol{X}$, then such dependence is first modeled as:

$$Y = G(\boldsymbol{X}) \tag{3.10}$$

The goal of uncertainty propagation is to compute the probability density function $f_Y(y)$ given the joint probability density function $f_{\boldsymbol{X}}(\boldsymbol{x})$. This calculation is trivial only when the underlying model G is linear, and the joint density $f_{\boldsymbol{X}}(\boldsymbol{x})$ is normal; in other cases, advanced statistical methods (e.g., sampling-based methods such as Monte Carlo sampling, and analytical methods based on first-order approximations) need to be used to compute $f_Y(y)$.

Uncertainty Management

The topic of uncertainty management deals with a variety of issues that broadly address the questions of the type: "Given that there is uncertainty, what can we do about it, and how can we deal with it?" This requires identifying what factors have significant impact on safety, and developing methods for mitigation and control in the presence of such uncertainty. An important challenge in this regard is that there has been no significant past work that directly focuses on uncertainty management. Hence, it will be necessary to start developing fundamental approaches to identify and address important uncertainty management issues in the context of the NAS.

3.2.3 Monitoring and Prediction under Uncertainty

As explained earlier, it is necessary to systematically include the various sources of uncertainty during both monitoring and prediction. A very generic computational model is used here to illustrate the underlying concepts. The implementation details of these concepts are later explained in Chapter 5.

For the purpose of general discussion, consider a generic computational model $Y = G(\boldsymbol{X}; \boldsymbol{\Theta})$ in Figure 3.2, which is used to represent the performance of an engineering system. The input is a vector and hence denoted in bold as $\boldsymbol{X}$, whereas the output Y is a scalar. The vector of model parameters is represented using $\boldsymbol{\Theta}$. The model G is deterministic, i.e. for a given realization of $\boldsymbol{X}$ and $\boldsymbol{\Theta}$, there is a corresponding output, which is a realization of Y. The inputs $\boldsymbol{X}$ are uncertain and represented by probability distributions, and this leads to uncertainty in the output Y. Generic realizations of $\boldsymbol{X}$, $\boldsymbol{\Theta}$, and Y are denoted as $\boldsymbol{x}$, $\boldsymbol{\theta}$, and y, respectively.

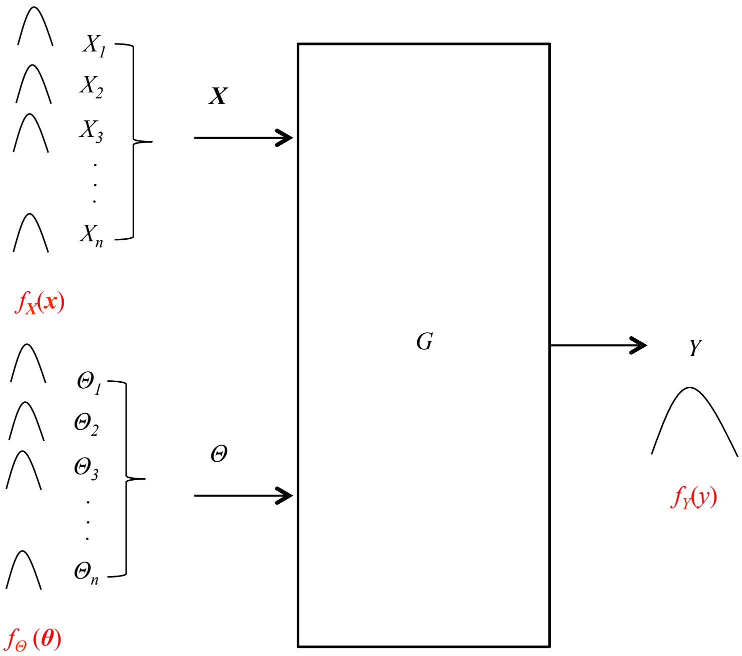


Figure 3.2: Generic Computational Model: $Y = G(\boldsymbol{X}, \boldsymbol{\Theta})$

The most significant difference between estimation and prediction is in what quantity needs to be calculated; in estimation, the goal is to compute parameters $\boldsymbol{\Theta}$ whereas in prediction, the goal is to compute the output Y.

Estimation using the Bayesian Method

The most generic problem of estimation involves the computation of state variables and/or model parameters by collecting input-output measurements. The simplistic version of estimating parameters in a time-invariant problem is first described in this section; later in Chapter 5, the estimation of states in a time-dependent context is explained in detail. The goal of such a presentation is to first explain the idea of Bayesian inference (using a simple model parameter estimation problem) and then use this idea in real-time monitoring context (using a time-dependent model and estimating states continuously).

Consider the estimation of parameters ($\boldsymbol{\Theta}$) by collecting input-output measurements ($\boldsymbol{x_i}$ vs. y_i; $i = 1$ to n). The experimental data are assumed to be unbiased; in other words, $\epsilon_i = y_i - G(\boldsymbol{x_i})$ follows a normal distribution with zero mean. The quantity $\epsilon \sim N(0, \sigma^2)$ is referred to as the fitting error. The goal in parameter estimation is to estimate $\boldsymbol{\Theta}$ using the above information. In general, the approaches for estimation can be classified into three types: least squares-based optimization, likelihood-based optimization, and Bayesian inference. In this report, we primarily use the Bayesian inference approach.

All the current knowledge regarding this parameter is represented in the form of a prior distribution denoted by $f'(\boldsymbol{\theta})$. The choice of the prior distribution reflects the subjective knowledge of uncertainty regarding the variable before any observation. It is assumed that the prior distribution is able to explain the data with some degree of uncertainty; in other words, there exists a non-empty set E such that $\forall\ \theta \in E$, the prior probability density function (PDF) and likelihood values evaluated $\forall\ \theta \in E$ are both non-zero.

Measurement data (D) are collected on a quantity which depends on the parameter ($\boldsymbol{\theta}$). This information is then used to update the distribution of θ to arrive at the posterior distribution ($f''(\boldsymbol{\theta})$), as:

$$f''(\boldsymbol{\theta}) = \frac{L(\boldsymbol{\theta})f'(\boldsymbol{\theta})}{\int L(\boldsymbol{\theta})f'(\boldsymbol{\theta})d\boldsymbol{\theta}} \tag{3.11}$$

In Eq. 3.11, $L(\boldsymbol{\theta})$ is the likelihood function of $\boldsymbol{\theta}$ and is proportional to $P(D|\boldsymbol{\theta})$, i.e. probability of observing the data D conditioned on the parameter $\boldsymbol{\theta}$, as explained earlier.

The denominator on the right-hand side of Eq. 3.11 is simply a normalizing constant, which ensures that $f''(\boldsymbol{\theta})$ is a valid PDF. So, Eq. 3.11 is sometimes written as:

$$f''(\boldsymbol{\theta}) \propto L(\boldsymbol{\theta})f'(\boldsymbol{\theta}) \tag{3.12}$$

The posterior in Bayesian inference is always known only up to a proportionality constant and it is necessary to generate samples from this posterior for uncertainty analysis. When there is only one parameter, the proportionality constant can be calculated through one-dimensional integration. Often, multiple parameters may be present, and hence, multi-dimensional integration may not be affordable to calculate the proportionality constant. Therefore, a class of methods popularly referred to as Markov Chain Monte Carlo (MCMC) sampling is used to generate samples from the Bayesian posterior. In general, these methods can be used when it is desired to generate samples from a PDF which is known only up to a proportionality constant. The Metropolis algorithm [50] and the slice sampling [51] algorithm are a few examples of MCMC sampling methods that are useful for Bayesian inference.

In time-dependent problems (as developed in this report for NAS safety analysis), there are states that need to be estimated in addition to the parameters; hence, Eq. 3.11 needs to be rewritten in terms of state variables instead of model parameters, as explained later in Eq. 5.1 in Chapter 5.

Prediction using Uncertainty Propagation Methods

For the purpose of prediction, the parameters and inputs are treated similarly; hence, the methods for uncertainty prediction can be explained using the model $Y = G(\boldsymbol{X})$, where $\boldsymbol{X}$ represents the concatenated vector containing both the inputs and the parameters.

In order to predict the response of the system, it is necessary to propagate all the uncertainty in $\boldsymbol{X}$ through G, and thereby compute the uncertainty in Y. This can be accomplished by estimating the probability distribution of Y, that may be expressed using the PDF of Y (denoted by $f_Y(y)$) or the CDF of Y (denoted by $F_Y(y)$). The entire CDF of Y can be calculated as:

$$F_Y(y) = \int_{g(\boldsymbol{X})<y} f_{\boldsymbol{X}}(\boldsymbol{x})d\boldsymbol{x} \tag{3.13}$$

It is harder to write a similar expression for PDF calculation, although the following equation attempts to.

$$f_Y(y) = \int f_Y(y|\boldsymbol{x}) f_{\boldsymbol{X}}(\boldsymbol{x}) d\boldsymbol{x} \tag{3.14}$$

In Eq. 3.14, the domain of integration is such that $f_{\boldsymbol{X}}(\boldsymbol{x}) \neq 0$. Note that Eq. 3.14 is not very meaningful because y is single-valued given $\boldsymbol{x}$, and hence $f_Y(y|\boldsymbol{x})$ is nothing but a Dirac delta function. Alternatively, the PDF can be calculated by differentiating the CDF, as:

$$f_Y(y) = \frac{dF_Y(y)}{dy} \tag{3.15}$$

The above calculation of PDF and CDF is popularly referred to as an uncertainty propagation problem, and can be accomplished using a variety of statistical methods. Such methods can be classified into two categories: sampling-based methods and analytical methods.

Most of the sampling-based methods are based on Monte Carlo simulation [52]. The basic underlying concept of Monte Carlo simulation is to generate a pseudo-random number which is uniformly distributed on the interval [0, 1]; then the CDF of $\boldsymbol{X}$ is inverted to generate the corresponding realization of $\boldsymbol{X}$. Following this procedure, several random realizations of $\boldsymbol{X}$ are generated, and the corresponding random realizations of Y are computed. Then the CDF $F_Y(y)$ is calculated as the proportion of the number of realizations where the output realization is less than a particular y_c. The generation of each realization requires one evaluation/simulation of G. Several thousands of realizations may often be needed to calculate the entire CDF, especially for very high/low values of y. Error estimates for the CDF, in terms of the number of simulations, are available in the literature [53]. Alternatively, the entire PDF $f_Y(y)$ can be computed by constructing a histogram based on the available samples of Y, using kernel density estimation [54]. There are several variations of the basic Monte Carlo algorithm that are used by several researchers [55].

1. **Importance Sampling**: This algorithm [56] does not generate random realizations of $\boldsymbol{X}$ from the original distribution. Instead, random realizations are generated from a proposal density function, statistics of Y are estimated and then corrected based on the original density values and proposal density values. Sometimes, the proposal density is iteratively adapted in order to obtain improved accuracy; this approach is known as adaptive sampling [57].

2. **Stratified Sampling**: In this sampling approach [58], the overall domain of $\boldsymbol{X}$ is divided into multiple sub-domains and samples are drawn from each sub-domain independently. The process of dividing the overall domain into multiple sub-domains is referred to as stratification. This method is applicable when subpopulations within the overall population are significantly different.

3. **Latin Hypercube Sampling**: This is a sampling method commonly used in design of computer experiments. When sampling a function of N variables, the range of each variable is divided into M equally probable intervals, thereby forming a rectangular grid. Then, sample positions are chosen such that there is exactly one sample in each row and exactly one sample in each column of this grid. Each resultant sample is then used to compute a corresponding realization of Y, and thereby the PDF $f_Y(y)$ can

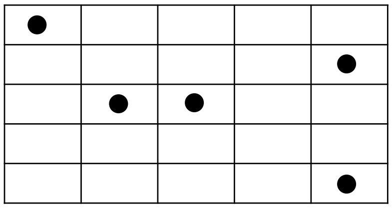


Figure 3.3: Illustrating Random 2-D Sampling

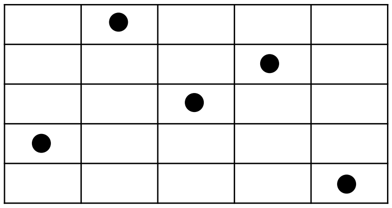


Figure 3.4: Illustrating 2-D Latin Hypercube Sampling

be calculated [59]. The difference between two-dimensional random Monte Carlo sampling and two-dimensional Latin hypercube sampling is illustrated in Fig. 3.3 (Monte Carlo samples) and Fig. 3.4 (Latin Hypercube samples).

4. **Unscented Transform Sampling**: Unscented transform sampling [60] is a sampling approach which focuses on estimating the mean and variance of Y accurately, instead of the entire probability distribution of Y. Certain pre-determined sigma points are selected in the $\boldsymbol{X}$-space and these sigma points are used to generate corresponding realizations of Y. Using weighted averaging principles, the mean and variance of Y are calculated. While this approach has been predominantly used in the context of state estimation, it can also be used for prediction [61].

Some of the commonly used analytical methods are:

1. **First Order Second Moment Method**: This method uses only the mean and variance of all the uncertain quantities and the first-order Taylor's series expansion of G, and estimates the mean and variance of the response quantity Y.
2. **First Order Reliability Method**: This method calculates the CDF function $F_Y(y)$ by linearizing G around the so-called most probable point [53]. While this approach is an approximation, it can estimate the CDF with reasonable accuracy in many practical applications.
3. **Inverse First Order Reliability Method**: This method is the inverse of the first-order reliability method, i.e., it calculates the value of y that corresponds to a given value of β such that $F_Y(y) = \beta$. By repeating this approach for several values of β, the entire cumulative distribution function can be easily calculated, thereby estimating the uncertainty in Y.

In addition to the aforementioned methods, there are several surrogate modeling approaches that have been used for the purpose of uncertainty quantification. Such surrogate modeling approaches include regression techniques [53], polynomial chaos expansion [62], kriging [63], etc. Each of these methods use different types of basis functions and one may approximate G better than the other.

In summary, while the above list of methods are available for computing the uncertainty in prediction, presently, only basic Monte Carlo sampling has been implemented for NAS-level safety analysis. It is still necessary to investigate other methods and explore their applicability for the intended application and safety analysis; this investigation will be considered in future work. The implementation aspects of the estimation (Bayesian estimation through filtering) and prediction (Monte Carlo sampling) algorithms are discussed in detail in Chapter 5.

Chapter 4

Safety Analysis and Modeling

As mentioned in Chapter 1, unsafe events occur when safety is compromised. Loss of separation, loss of control, or flight into icing conditions without the appropriate equipment are all examples of such unsafe events, and reports collected in ASRS and NTSB databases document a large number of them. As a first step towards safety analysis of the NAS, the ASRS and NTSB documents were researched to identify the common hazards to flight operations. This process of determining hazards is the same as the first step of using SMS or FRAT tools, as described in Chapter 2. Once the hazards are extracted, safety metrics ($\boldsymbol{\phi}$) are developed for the purpose of monitoring, assessing, and predicting safety of the airspace. Thresholds (T_e) are determined for these safety metrics in order to define regions of reduced safety in the safety metric space, and consequently, the safe operational space of the aircraft and airspace. Using the terminology of safety metrics and thresholds, unsafe events (E) occur when safety metric values enter the subspace of reduced safety. This chapter focuses on the offline process of determining hazards, developing safety metrics, and identifying thresholds for the different safety metrics, i.e., determining unsafe events $e \in E$, the safety metric vector $\boldsymbol{\phi}$, the safety metric equation $\mathbf{F}$, and the threshold function $\mathbf{T}_E$.

4.1 Flight Hazards

There can be numerous hazards to flight and it would be an intractable task to list all of these exhaustively. However, as a result of studying ASRS and NTSB reports [1, 64], we identified a subset of frequently-occurring or particularly important hazards to flight. In broad terms, these hazards can be categorized into four main categories: (*i*) airspace-related hazards, e.g., inoperative navigation aids or high congestion; (*ii*) environmental hazards, e.g., convective weather or animal activity; and (*iii*) human-performance hazards, e.g., pilot fatigue or pilot distraction, and (*iv*) aircraft malfunction hazards, e.g., engine failure, structural issues, sensor malfunctions. In this work, we focus on the first three: airspace-related hazards, environmental hazards, and human-performance hazards. A lot of prior research, e.g., [65–71], has focused on the aircraft malfunction hazards, and hence that topic will not be covered in this work, altough our approach can allow for these hazards to be included in the analysis. Moreover, we focus on hazards that can be measured, modeled, and predicted using real-time data. The prediction horizon may vary from a few minutes to many hours, depending on available data.

We scrutinized several ASRS reports to extract causes of unsafe events. Specifically, these reports covered a variety of topics, such as altitude deviation, bird or animal strike, controlled flight into terrain (CFIT), communication, fuel management, near miss, runway incursion, wake turbulence, weather, and so on. Some examples of the unsafe events reported in these databases are given below in Table 4.1:

Table 4.1: Example Incidents from ASRS and NTSB Databases

Incident Identifier	Description
ASRS 1201963	Unusually heavy CRJ-200 encounters wake turbulence shortly after takeoff at ATL. "The new separation minimums between takeoffs in Atlanta needs to be altered. The company needs to present these issues to local ATC to prevent a major accident in the future."
ASRS 1194076	Weather delayed arrivals into the short-staffed midnight shift; maintenance went ahead with planned work regardless of the traffic; bad comm with pilots (who were talking with dispatch) and tower (who switched airport configuration without adequate comm to everyone involved).
ASRS 1195051	Deviating for weather puts flight in conflict with SUA.
ASRS 1170587	VFR pilot climbed into IFR aircraft. The two aircraft were talking to two different controllers. The VFR aircraft was not cleared to climb; it was given an altitude 500 ft lower than the inbound IFR aircraft.
ASRS 1171767	Aircraft cleared to land did a touch-and-go instead. Controller was not protecting departures from potential (always possible) go-around of arrival.
NTSB 04/27/12 Incident	Loss of Separation due to simultaneous independent runway operations on runways that do not physically intersect but whose flight paths intersect (LAS, go-around on 25L, departure on 19L; two controllers).
NTSB 12/01/11 Incident	Runway incursion caused by Tower LC clearing aircraft to cross runway immediately after clearing another aircraft to depart.
NTSB 08/08/11 Incident	Controller error: NMAC in airport airspace; aircraft departing Runway 32L passed within close proximity to aircraft on approach to Runway 9R; controller distracted by coordination requirements affecting two other airplanes.
NTSB 06/19/11 Incident	Controller error: NMAC in airport airspace; Tower Local Controller cleared two aircraft for takeoff from runways with intersecting departure flight paths without ensuring the first aircraft had passed the flight path intersection prior to clearing the second aircraft for takeoff (aircraft departing Runway 18 passed with 0 ft vertically and 300 ft laterally from aircraft departing just 16 sec later from Runway 14).
NTSB 05/21/10 Incident	Controller error: NMAC in airport airspace. A319 executed a missed approach for Runway 14, converging with B747 departed from Runway 25R. Aircraft came within 100 ft vertically and 0.33 mi laterally. NTSB probable cause: The approach controller's delayed transfer of communications on the A319 to the tower controller and failure to account for the aircraft's speed when he directed the crew to turn north. Contributing to the incident was the 747 crew's transfer of radio communications to departure control prior to being directed to do so by the tower controller.
NTSB 08/14/13 Accident	UPS Flight 1354 crash during a night-time non-precision instrument approach to landing, Contributing factors: night, incomplete weather briefing, fatigue.

To summarize the information obtained from these reports, we report some of the flight hazards that contribute to one of the following five unsafe events, namely: (*i*) collision (both while airborne and on ground), (*ii*) loss of control (while airborne), (*iii*) controlled flight into terrain (CFIT) (that includes obstacles), (*iv*) other injury accident or incident, and (*v*) other property damage. Tables 4.2 - 4.4 list various possible hazards to flight and document the contribution of these hazards to each class of unsafe events. See Appendix B for a longer list of these hazards and some notes on how these hazards affect flight operations.

As explained in Chapter 2, airspace can be controlled or uncontrolled and includes airport surface and vicinity, arrival and departure airspace, and en-route airspace. Airspace hazards can result from the design of the airspace (including airport), design of procedures, operational status of facilities, and traffic diversity and congestion, among others.

Table 4.2: Airspace-related Hazards

Hazard	Collision	Loss of control	CFIT	Injury Accident or Incident	Property Damage
Flight path precision	x	x			
Aircraft separation - reduced in-trail	x	x			
Aircraft separation - climbing/descending nearby	x	x			
Aircraft separation - crossing at similar altitude nearby	x	x			
Active SUA (MOA, restricted, alert, aerobatics, parachute jumping)	x				
TFRs, especially near instrument approach	x		x		
Noise sensitive areas	x	x	x		
Obstacles or terrain (near airport)			x		
Airspace complexity - airport layout	x				x
Airspace complexity - misplaced or missing signs					x
Airspace complexity - airport hotspots	x				
Airspace complexity - controller blind spots	x				
Airspace complexity - diverse traffic mix (small/large/heavy, jets/prop/helicopters, IFR/VFR, etc.)	x				
Airspace complexity - merging traffic paths - into sector	x				
Airspace complexity - merging traffic paths - intersecting runways	x				
Airspace complexity - parallel runways	x	x			
Airspace complexity - proximity of arrival to departure routes	x				
Airspace complexity - frequency of handoffs	x				
Airspace complexity - active approach recently changed or imminent change	x				
Airspace complexity - complex approach procedure					
Congestion (traffic) - Known UAS areas	x				
Congestion (traffic) - Known VFR routes, practice approach or maneuver areas	x				
Congestion (traffic) - volume	x				
Congestion (traffic) - density	x				
Congestion (traffic) - distribution within sector	x		x		
Training areas - Controller	x		x		
Similar sounding intersections (e.g., BLUZZ and BLEWS)	x		x		
Two RNAV points that are in the same space but with different names	x		x		
Runway - closed			x	x	
Glideslope aids (e.g., VASI, PAPI, ILS glideslope) - inop		x			
Radar coverage - OTS or blind spots	x		x		
Communication - facility OTS or blind spots	x		x		
Communication - handoff automation OTS	x		x		
Lights - inop			x	x	x
Lights - misleading, nearby airport			x		
Lights - bright LED, runway or approach	x				x
Alternatives - few available (e.g., nearby emergency landing sites)				x	x

Weather is one of the major hazards to flight operations and has among the biggest dynamic effects on airspace safety. Weather, of course, is always present, but some weather conditions are more benign and conducive to safe flight. The actual effects of particular weather on a particular flight's safety depends on a number of factors, among them the capability of the aircraft, the capability of the pilot, the location and extent of the weather, the interaction between the weather and the airspace (e.g., strong winds aligned with the runway are less hazardous than strong crosswinds), and contributions of other concurrent hazards (e.g., few alternate landing sites available). Although weather predictions have improved significantly recently, additional precision is still required to maintain the required NAS efficiency in busy airspace.

Table 4.3: Environmental Hazards

Hazard	Collision	Loss of control	CFIT	Injury Accident or Incident	Property Damage
Weather - significantly worse than forecast	x	x	x	x	x
Convective weather		x	x	x	
Hail					x
Rain - moderate	x			x	x
Icing		x			
Turbulence - moderate to severe		x		x	x
Wind - strong		x		x	x
Visibility	x	x	x		
Temperature		x	x		
Volcanic ash	x	x	x	x	x
Night	x	x	x	x	x
Low sun angle	x	x	x	x	x
Animal activity - birds	x			x	x
Animal activity - other	x			x	x
FOD	x			x	x

Finally, we enumerate some human-workload-related hazards that affect airspace safety. Some of these hazards affect the flight path and can lead to fuel exhaustion. Other hazards can lead to increased pilot or air traffic controller workload and contribute to errors that combine with other hazards to cause accidents or incidents. Examples of this type of hazard include emergency or off-nominal operations that can cause excessive workload for a controller, diversions due to inaccessible airspace for non-emergency flights (potentially leading to fuel exhaustion), or increased potential for collisions due to an unexpected behavior of an aircraft experiencing an emergency. The predictability of these emergency or off-nominal operations can vary significantly. For instance, a closed runway could be the result of a known hydraulic leak in the gear extension system of an incoming aircraft that alerts operators of a potential for a gear-up landing minutes to hours in advance. Alternatively, a closed runway could be the result of a badly flown approach that results in a runway excursion and can only be predicted as the approach is observed. Although the hazard to following flights in each case is the closed runway, the initiating hazard is either an aircraft mechanical issue with a long prediction window or an incorrect procedure with a prediction window of only a few minutes at best.

Perhaps a hazard that needs additional explanation is lack of attention on the part of either a pilot or a controller, and specifically why it is on the list of hazards we can predict. Lack of attention due to complacency or multi-tasking is difficult to predict when not observing a controller or a pilot directly. If one observes a controller chatting with a colleague, one could surmise that the airspace the controller is responsible for is, perhaps, less safe. Even more obvious is if the controller is sleeping or a pilot is working on an involved spreadsheet. But we do not usually have access to this type of information. This item is on the predictable list partly because we can estimate that certain actions over-tax human capacity - such as programming a flight computer for an approach or working multiple positions as a tower controller, and partly because of human nature - such as pilots or controllers becoming complacent in certain settings.

Table 4.4: Human-Workload-Related Hazards

Hazard	Collision	Loss of control	CFIT	Injury Accident or Incident	Property Damage
Elongated flight path – due to re-route				x	x
Elongated flight path - due to excessive vectoring or maneuvering (e.g., for weather)	x	x	x		
Takeoff - significantly delayed				x	x
Multiple speed changes on approach	x	x			x
Required tasks (procedures) - number and complexity	x		x		
Incorrect operations/procedures	x	x	x	x	x
Emergency / off-nominal situation	x			x	x
Aborted / botched approach	x	x	x	x	x
Communication issues (e.g., difficult accents, inexperienced pilots, multiple frequencies for one controller, etc.)	x		x		x
Flow control restrictions - active (e.g., MIT)					x
Lack of attention - complacency, multi-tasking	x	x	x	x	x

As mentioned earlier, the above list of hazards is not exhaustive, but only a sampling of hazards that can be assessed and predicted based on available or expected data sources. Hazards that cannot be predicted are outside the scope of this work. A few such hazards are listed below:

- Mechanical hazards, e.g., unnoticed mechanical issues, incorrect autopilot setting, extent of aircraft damage, extent of damage to aircraft systems from rodents or similar animals, as well as bird strikes, etc.

- Operational hazards, e.g., pilots unhappy with company policies (involving scheduling rest times, operating flights, staffing, etc.); certain company policies not giving safety priority; confusion due to contradicting policies regarding operation; adequacy of corporate procedures; management pressure and coercion; company culture; instructional or procedural charts lacking clarity of explanation; etc.

- Human-related hazards, e.g., pilot confusion; lack of situational awareness; incorrect inspection and/or mistaking alarms to be false alarms; inadequate crew resource management; crew becoming unresponsive and missing radio calls; circadian rhythm disruptions; incapacitation due to alcohol or drugs, etc.

4.2 Safety Metrics and Thresholds

The next step after determination of hazards is to develop a framework for modeling, monitoring, and predicting unsafe events that can be caused by such hazards, based on available data. To this end, as shown in Chapter 3, we develop a set of safety metrics, $\boldsymbol{\phi}$, as an algebraic function $\mathbf{F}$ of the states, $\mathbf{x}$. These safety metrics are quantities of interest that should be monitored and predicted in order to predict unsafe events. Recall from Chapter 3 that an unsafe event is a transition event from an acceptable to unacceptable space of $\boldsymbol{\phi}$, and these boundaries between the acceptable and unacceptable spaces are defined through threshold equations, $\mathbf{T}_E(\boldsymbol{\phi}(k))$. Threshold equations can take any general form.

As an example, *aircraft separation* is a safety metric that constantly needs to be monitored and predicted in order to predict a *loss of separation* unsafe event. The safety metric function for this safety metric takes in as inputs two aircraft identifiers, the time at which we want to determine the aircraft separation and makes use of known variables, such as aircraft velocities, coordinates, etc. and outputs the distance between these two aircraft, their heading with respect to each other, and the altitude difference. For the threshold on this safety metric, general separation standards for en-route flight provide the value of 5 miles for lateral separation and 1000 feet for vertical separation.

Table 4.5 lists this and other example safety metrics, the arguments their corresponding safety metric functions can take, the outputs of these safety metric functions, example threshold equations, and the sources based on which these example thresholds were obtained. Note that this list is provided for illustrative purposes and is by no means exhaustive. A NAS participant, such as a control center or an airline, would generate their own safety metrics, safety metric functions, and threshold equations based on their requirements.

Setting these safety thresholds is challenging. As mentioned above, we turn to various sources for assistance, including FAA and ICAO regulations; airline safety management systems (SMS) that define and employ a risk management approach to deal with potential risks; FAA's Flight Risk Assessment Tool (FRAT); personal minimums lists; aviation best practices; limits used by TCAS and GPWS; and so on.

For some safety metrics, these sources provide a reasonable default that can be customized by the operators as desired. For example, convective weather, with the associated heavy rain, wind shear, wind gusts, and turbulence, is extremely hazardous to flight. The accepted wisdom (aviation best practice) is to remain at least 20 miles away from thunderstorms. Getting closer than 20 miles does not guarantee an accident and thus NAS failure; many flights have traversed closer to a thunderstorm cell with no ill effects. Nor does remaining more than 20 miles away guarantee a successful outcome; wind gusts can affect landing flights more than 50 miles away. Nonetheless, it is generally accepted that adequate safety margin exists if the *distance and heading to weather event* safety metric is assigned a safety margin threshold of 20 miles.

For other cases, determining a threshold is not quite so straightforward. For example, the threshold for a *congested airspace* safety metric is affected by composition of traffic (e.g., all heavy jets vs gliders, helicopters, small GA aircraft, and large and heavy jets), flight paths (single stream vs multi-stream merging), and even the controller on console (some controllers move traffic more efficiently than others). In these cases, we can use a hybrid method to determine appropriate thresholds, combining information from the avail-

Table 4.5: Some Example Safety Metrics

Safety metrics	Safety Metrics Function Arguments	Safety Metrics Function Outputs	Example of Threshold Equations	Source of Thresholds
distance and heading to weather event	point of interest, weather severity, weather type, time	distance and heading	distance.thunderstorm $>$ 20 mi and thunderstorm.intensity $<$ MEDIUM	Best practice as documented in the Aeronautical Information Manual (AIM)
weather at coordinate	point of interest, time	matrix of all weather categories (e.g., hail, rain, snow, mist, mixed, turbulence, thunderstorm, wind, microburst, windshear, etc.) and their relevant properties (e.g., severity, phase, type, persistence, direction of movement, etc., temperature, humidity)	A threshold is needed for each element of the matrix. Some examples: turbulence.intensity $<$ MODERATE, thunderstorm.intensity $\leq$ MODERATE, rain.intensity $<$ SEVERE	The operator would need to determine own minimums to account for specific context defined by aircraft type and equipment, pilot proficiency, risk tolerance, etc. Standard thresholds can be established based on best practice documented in Aeronautical Information Manual (AIM) or based on federal aviation regulations (FARs). How context determines the threshold is illustrated by the following example: many commercial airline safety management systems specify that an aircraft cannot fly in areas of predicted thunderstorms if onboard weather radar is OTS. The same aircraft, if all equipment was working, would be allowed to fly in light thunderstorms. Thus, the threshold could be either thunderstorm.intensity $\leq$ LIGHT or thunderstorm.predicted $= 0\%$.
probability of aircraft icing	point of interest, time, $\{$weather at coordinate$\}$	probability of different types of icing e.g., structural (rime or clear or mixed) icing, carb icing, engine core icing, etc. expressed as a percentage	icing.structural $< 5\%$	FARs specify that aircraft not certified for flight into known icing (FIKI) are not allowed to fly in areas of predicted structural icing.

Table 4.5: Some Example Safety Metrics

Safety metrics	Safety Metrics Function Arguments	Safety Metrics Function Outputs	Example of Threshold Equations	Source of Thresholds
probability of runway contamination	point of interest, time, {weather at coordinate}	probability of all contamination categories such as ice e.g., black ice, slush, etc.; water; (FOD) debris; dead animals; and so on, expressed as a percentage	rwyContamination.blackIce = 0	Best practice due to impeded braking action.
wind component	point of interest, time, reference track (of aircraft or runway), {weather at coordinate}	crosswind, tailwind, headwind, vertical components	tailwind > "calm" makes LAHSO unavailable	FAA JO 7110.65V
visibility	point of interest, time, {weather at coordinate}	distance in miles	visibility > 1/2 mi	Per approach plate, minimum visibility for (many) ILS approaches
density altitude	point of interest, time, {weather at coordinate}	altitude in feet	density_altitude $\leq$ 8000 ft OR runway.length > 10000	Example takeoff density altitude (DA) maximum based on aircraft performance charts (needs to be customized for specific aircraft)
operation type	point of interest, time	high temperature operations, low temperature operations, night operations, IFR, VFR	operation_type.night = TRUE	night ops in effect alter fuel reserves, visibility requirements, etc., per FARs and personal minimums
wildlife at coordinate	point of interest, time	wildlife categories and attributes (type of wildlife, population size, persistence, etc.)	wildlife.birds.present = FALSE OR wildlife.birds.number $\leq$ LOW, wildlife.birds.persistence $\leq$ OCNL OR wildlife.birds.size < 5 lbs	helper function that determines wildlife_risk; size and persistence are based on aircraft type
risk of damage by wildlife	point of interest, time, {wildlife at coordinate}	risk category, e.g., low, medium, high	wildlife_risk.birds < HIGH	Best practice is to avoid due to potential collision risk
risk of wake turbulence	point of interest, time, {weather at coordinate}, type of preceding aircraft	risk category, e.g., low, medium, high	wake_turbulence_risk $\leq$ MEDIUM	Best practice
distance to avoidance areas	point of interest, time, type of avoidance area of interest	distance and heading	avoidance_area_distance.tfr > 1/2 mi	operator customizable value based on available surveillance technology

Table 4.5: Some Example Safety Metrics

Safety metrics	Safety Metrics Function Arguments	Safety Metrics Function Outputs	Example of Threshold Equations	Source of Thresholds
avoidance areas at coordinate	point of interest, time	matrix of avoidance area categories (e.g., SUAs such as restricted, warning, alert, TFR, practice areas, controller training areas, special event areas, etc., obstacles, noise sensitive areas, airport hotspots) and status (e.g., active/inactive, restriction type, allowed noise level, etc.)	avoidance_area.tfr.active $=$ FALSE	FARs specify TFRs must be avoided
operations within noise limits	point of interest, time, aircraft type, percent of power used, {avoidance areas at coordinate}	true or false	operation_within_noise_limits $=$ TRUE	Noise abatement procedures in effect at many airports (e.g., curfew at SJC)
controller observability	point of interest, time, position of controller, {weather at coordinate, visibility}	observability category, e.g., low, medium, high	controller_observability $>$ LOW	higher separation standards or modified operations may be in effect if controller cannot see potential conflicts
traffic homogeneity	volume of interest, time	category of vehicles (e.g., small, large, heavy, helicopters, etc.) and their numbers	not applicable; this safety metric is called by other safety metrics)	
traffic complexity	volume of interest, time, {traffic homogeneity}	complexity category, e.g., low, medium, high	traffic_complexity $<$ HIGH	differences in performance increase controller workload
airspace complexity	volume of interest, time, {avoidance areas at coordinate, weather at coordinate, traffic complexity}, direction of approach	complexity category, e.g., low, medium, high	airspace_complexity $<$ HIGH	contributes to additional workload of pilots and controllers
aircraft separation	aircraft 1 of interest, aircraft 2 of interest, time	distance, heading (wrt aircraft 1 and 2), and altitude difference	aircraft_separation.distance $\geq$ 5 miles AND aircraft_separation.altitude_diff $\geq$ 1000 feet	en-route general separation standard

Table 4.5: Some Example Safety Metrics

Safety metrics	Safety Metrics Function Arguments	Safety Metrics Function Outputs	Example of Threshold Equations	Source of Thresholds
aircraft within radius	point of interest, time, radius of interest	coordinates of all aircraft within the radius of interest and their status of operation (e.g., level, climb or descend, on approach, holding short, line-up-and-wait, etc.)	count(aircraft_within_radius) < 5	example threshold value for number of aircraft in airport vicinity that contributes to additional workload of pilots and controllers.
services operating status	volume of interest, time	matrix of all service categories (e.g., lights, navaids, glidescopes, ADS-B coverage, radar coverage, GPS coverage, communication facilities, runway, etc.) and degree of operational status (e.g., percentage with 0% indicating inoperative equipment and 100% indicating equipment is performing nominally)	services_operating_status.ads_b_coverage > 50%	unreliable ADS-B coverage requires additional separation
airport configuration at a given time and location	airport of interest, time	airport configuration	airport_config(area_of_interest, now) = airport_config (area_of_interest, now - 15 min)	operator customizable value
risk of jetblast	point of interest, time	risk category, e.g., none, low, medium, high	jetblast_risk ≤ LOW	operator customizable value
approach complexity	approach of interest, time, approach configuration, pilot experience with the airport, multiple speed changes on approach, equipment on board, multiple runway changes on approach, complex descent via RNAV clearences, (e.g., access to an interactive map), {weather at coordinate, aircraft at coordinate, visiblity, avoidance areas at coordinates, operations within noise limits, risk of wake turbulence, wildlife at coordinate, services operation status, etc.}	complexity category, e.g., low, medium, high	approach_complexity ≤ MEDIUM	operator customizable value

Table 4.5: Some Example Safety Metrics

Safety metrics	Safety Metrics Function Arguments	Safety Metrics Function Outputs	Example of Threshold Equations	Source of Thresholds
departure complexity	departure of interest, time, departure configuration, pilot experience with the airport, multiple speed changes on approach, equipment on board (e.g., access to an interactive map), {weather at coordinate, aircraft at coordinate, visibility, avoidance areas at coordinates, operations within noise limits, wildlife at coordinate, services operation status, etc.}	complexity category, e.g., low, medium, high	departure_complexity < MEDIUM	operator customizable value
taxi complexity	taxi clearance of interest, time, pilot experience with the airport, equipment on board (e.g., access to an interactive map), {weather at coordinate, aircraft at coordinate, visiblity, avoidance areas at coordinates, wildlife at coordinate, services operation status, risk of jetblast etc.}	complexity category, e.g., low, medium, high	taxi_complexity < HIGH	operator customizable value
controller workload	controller id, time, {services available, aircraft at coordinates, weather at coordinates, airspace complexity, congestion and density, visibility, traffic homogeneity, degree of operational normalcy, approach complexity}, communication issues (multiple languages, lack of command in English, multiple frequencies, etc.)	workload category, e.g., low, medium, high	controller_workload < HIGH	operator customizable value
probability of collision	volume of interest, time, {aircraft at coordinates, weather at coordinates, visibility, wildlife at coordinates, avoidance areas at coordinates, probability of controller error, probability of pilot error}	probability	collision_probability < 25%	operator customizable value
congestion and density	volume of interest, time, {aircraft at coordinates, airspace complexity, avoidance areas at coordinates}	congestion and density category: e.g., low, medium, high; or the number of aircraft per unit volume, and number of aircraft	density(sector_SW_corner) < MEDIUM AND density (sector_NE_corner) < HIGH	operator customizable value

Table 4.5: Some Example Safety Metrics

Safety metrics	Safety Metrics Function Arguments	Safety Metrics Function Outputs	Example of Threshold Equations	Source of Thresholds
probability of controller error	controller id, time, {controller workload, controller fatigue, controller observability}	probability	controller_error_prob $< 10\%$	operator customizable value
time to nearest traffic	point of interest, time, {aircraft at coordinates}	time	time_to_nearest_traffic > 3 min	standard separation on final approach
pilot workload	pilot id, time, {services available, aircraft at coordinates, weather at coordinates, airspace complexity, congestion and density, approach complexity, departure complexity, taxi complexity, visibility, wake turbulence, wind component, risk of damage due to animal or bird strike, distance to avoidance areas, operation type, traffic homogeneity, degree of operational normalcy, etc.}, communication issues (multiple languages, lack of command in English, multiple frequencies, etc.)	workload category, e.g., low, medium, high	pilot_workload $<$ HIGH	operator customizable value
pilot fatigue	pilot id, time, pilot workload, number of hours on duty, number of hours of sleep, experience level, days on duty, etc.	fatigue level, e.g., low, medium, high	pilot_fatigue $<$ HIGH	operator customizable value
controller fatigue	controller id, time, {controller workload}, number of hours on duty, number of hours of sleep, experience level, days on duty, etc.	fatigue level, e.g., low, medium, high	controller_fatigue $<$ MEDIUM	operator customizable value
degree of operational normalcy	volume of interest, time, number of restrictions (like MIT to an adjoining center), cumulative scheduled delay, flow control programs in effect, emergency/non-emergency situations	Normalcy score, e.g., low, medium, high	ops_normalcy $>$ LOW	operator customizable value

Table 4.5: Some Example Safety Metrics

Safety metrics	Safety Metrics Function Arguments	Safety Metrics Function Outputs	Example of Threshold Equations	Source of Thresholds
probability of fuel exhaustion	aircraft of interest, time, {weather at coordinates, congestion and density, degree of operational normalcy, controller workload, services operation status, airport configuration, avoidance areas at coordinate, departure complexity, wind components, probability of airplane icing, probability of runway contamination, etc.}	probability in percentages	$\text{fuel\_exhaustion\_probability} = 0\%$	operator customizable value
probability of pilot error	pilot id, time, {pilot workload, pilot fatigue}, incorrect operations/procedures	probability in percentages	$\text{pilot\_error\_probability} < 10\%$	operator customizable value
probability of miscommunication	volume of interest, time, {airspace complexity, pilot fatigue, pilot workload, controller workload, controller fatigue, congestion and density, weather at coordinates, degree of operational normalcy, operation type}, communication issues (multiple languages, lack of command in English, multiple frequencie, etc.)	probability in percentages	$\text{miscommunication\_probability} < 33\%$	operator customizable value

able documentation with information gathered via data mining or consultation with subject matter experts. We can also leverage individual information, such as personal minimums, level of certification, years of experience, etc., to determine such thresholds. For the purpose of this report, if a threshold for a safety metric cannot be determined by any of these methods, default values are assigned that can later be changed by individual operators to suit their needs.

4.3 Safety Margin

The idea of *safety margin* is used in finance and in structural engineering. In finance, safety margin accounts for the difference between the market price of a stock and its intrinsic value. It can also refer to how much the amount of sales can fall before a business reaches its break-even point. In engineering, *safety factor* refers to how much stronger a system is than it needs to be for the intended load. Analogously, in Europe, the *reserve factor* represents how much of a structure's capacity is held in reserve during loading. The extra strength allows for emergencies, unexpected loads, misuse, or degradation.

For the NAS, we build on these ideas and define safety margin for a safety metric as the distance of the current value of a safety metric from its assigned threshold. Fig. 4.1 presents the safety margin in the simplest case of a single safety metric. In a multi-dimensional safety metric space, the safety margin is multi-dimensional as well.

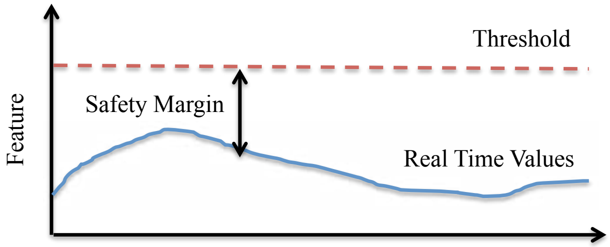


Figure 4.1: Safety Margin Example.

In the next chapter, we present how the analysis of hazards, development of safety metrics, and identification of thresholds can be used for real-time monitoring and prediction of NAS safety.

Chapter 5

Real-Time Monitoring and Prediction

As discussed in Chapter 3, the goal of this work is to, in real-time, monitor the safety metrics of the NAS, modeled as $\phi(k)$, and predict the occurrence of unsafe events, modeled as E. The previous chapter established how to model these quantities, based upon the current state of the NAS. Thus, in order to estimate the current value of $\phi(k)$, we must first estimate the state of the NAS, $\mathbf{x}$. Following a model-based approach, this requires dynamic models of the NAS. Given the state estimate and probability distributions of future inputs to the NAS, we can predict the future values of $\mathbf{x}$ and ϕ and the occurrence of events E.

First, in Section 5.1, we describe modeling approaches for the NAS. Section 5.2 discusses solutions to the monitoring problem, and Section 5.3 discusses solutions to the prediction problem, using these models.

5.1 Modeling

For the purposes of monitoring, estimation, and prediction, we require dynamic models of the NAS. This is so that we can (*i*) infer the state from the measured outputs, and (*ii*), predict the evolution of the state. Recall from Chapter 3 that, in order to do this, we must define the state $\mathbf{x}$, the inputs $\mathbf{u}$, the outputs $\mathbf{y}$, the state function $\mathbf{f}$, and the output function $\mathbf{h}$. In addition, we require models of the process noise $\mathbf{v}$ and sensor noise $\mathbf{n}$ and other sources of uncertainty.

To model the NAS at a system-level, we require models of aircraft, pilots, controllers, and weather systems. Each of these are described in the following subsections.

5.1.1 Aircraft Models

Aircraft models need to at least describe how their positions and velocities change in time. In addition, the amount of fuel and how it changes with aircraft usage should also be included. Each of these variables change in time based on the actions of a pilot or flight management system (FMS) and with environmental conditions (e.g., wind, temperature, pressure, etc.).

Since many automation tools within the NAS depend on knowledge of 4D trajectories, much work has been done in developing accurate and efficient models of aircraft navigation and dynamics. In [72,73] simple great-circle navigation models for level flight are used that take into account wind speed and direction, using a point mass approach. These models mainly describe how latitude, longitude, and altitude change with respect to intended velocities and flight path.

More detailed models that account for aerodynamics and consider climb and descent are available in several publications [74–79]. FACET, for example, combines great-circle navigation laws with first-order dynamic models and simple control laws simulation of aircraft in the NAS [80]. In FACET, simple control laws are used to determine aircraft control inputs to reach desired speed and position in 3D space.

5.1.2 Pilot Models

The inputs to an aircraft are determined by a pilot, and every pilot is different in how the aircraft is controlled, based on level of experience, personal preferences, etc. To be robust to these situations, some uncertainty must be considered here. In many cases, however, we can assume that the pilots follow intended flight paths fairly accurately, unless directed otherwise due to emergent conditions or controller instructions.

In some cases, we can also model how pilots will react to certain situations. For example, if approaching a landing too fast, one could reasonable assume with some probability that the pilot will infer a missed approach and perform a go-around.

5.1.3 Controller Models

In general, air traffic controllers must also be modeled, because they partially determine the aircraft inputs. Flights are often directed to modify their intended flight path, for purposes of safety or efficiency. It is difficult to model these actions because individual controllers all respond differently to situations, and there is an unpredictable delay between ATC directing a flight change and the pilot making it. If we want only to predict when ATC needs to take some action due to some predicted unsafe event, then we require only open-loop predictions and ATC does not need to be explicitly modeled.

5.1.4 Weather Models

Weather systems are very complex to model, and much work has been done in this area [81, 82]. This work can be taken advantage of by using exisiting systems for weather predictions. Weather models need to include how a hazardous weather region moves in time and changes shape, and is usually described by a dynamic area polygon specified by a set of weather parameters.

For example, in [81], three days worth of data generated by the Consolidated Storm Prediction for Aviation system was analyzed to verify how Consolidated Storm Prediction for Aviation (CoSPA) can be used to predict convective weather impacts on en-route airspace up to 8 hours in advance. The forecasts provide predictions of cloud water content, or VIL, and echo top heights, which were used to generate polygons that aircraft will likely avoid. The forecast sector impacts are modeled by a simplified weather coverage index using the

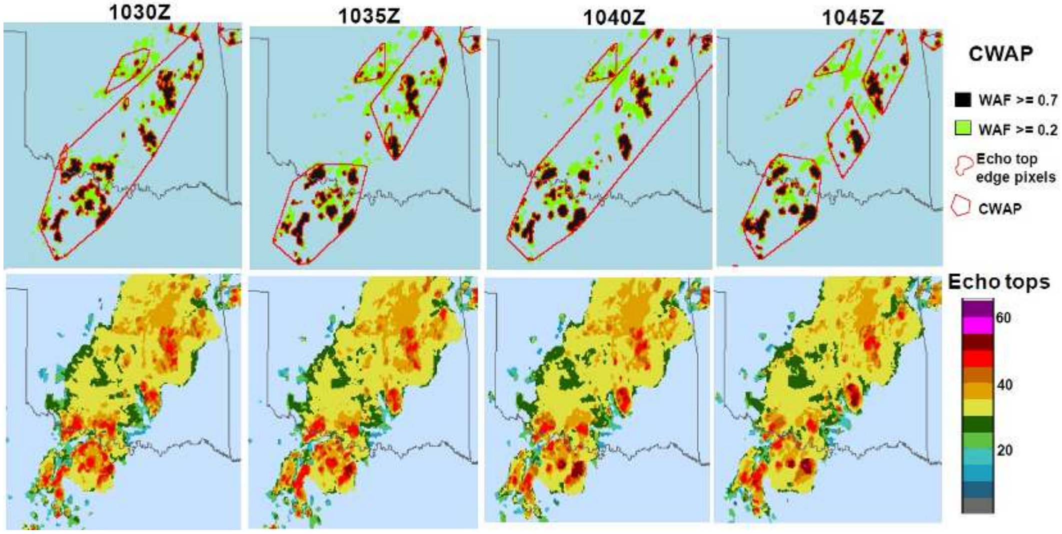


Figure 5.1: Inconsistencies in 10-minute forecast CWAP boundaries (May 14, 2010) with successive forecast updates

weather polygons to calculate the affected volume of each sector. The results show that the observed sector impacts are strongly correlated to the predictions up to 2 hours in advance, but the correlation decreases nearly monotonically as the look-ahead time increases. (This is one important safety metric we are looking into improving through our work.) The analysis is focused on sector-level impacts. Finally, a probabilistic model was developed to show how the predicted sector impacts can be used to estimate the likelihood and magnitude of convective weather impact on a sector.

In other work, the Convective Weather Avoidance Model (CWAM) assigns a probability of avoidance due to convective weather to each pixel on the image (1 km^2) in the region. The CWAM is a good predictor but cannot predict the boundaries of the trajectrories that the pilots tend to follow [82]. The Convective Weather Avoidance Polygon (CWAP) algorithm, along with the CWAM capability, is able to edge detect in the echo top field and winds at the flight altitude to indicate the storm boundaries that the pilots will tend to follow in case of avoiding convective weather. CWAPs are based on the assumption that storm boundaries may be identified by sharp edges in the echo tops field. The algorithm automatically identifies echo top edge pixels using the Canny edge detector, groups edge pixels into clusters that are presumed to represent individual storm boundaries, and then fits those clusters with a convex polygon. Polygons which do not enclose weather avoidance fields (WAF) contours of deviation probability ≥ 0.7 are filtered out, and the remaining polygons are the CWAP. The initial algorithm clustered edge points using the DBSCAN approach, which clusters edge points based on pixel density. The clustering step did not make use of the underlying echo top or WAF deviation probability contours, and on occasion, CWAP would chop up spatially coherent storms as relatively small clusters of echo top edge pixels appeared and disappeared from the weather scene as seen in Fig. 5.1.

In the revised CWAP algorithm, clusters are defined by the union of edge points and WAF ≥ 0.4 deviation probability contours that fall within the 30 kft echo top contour. The

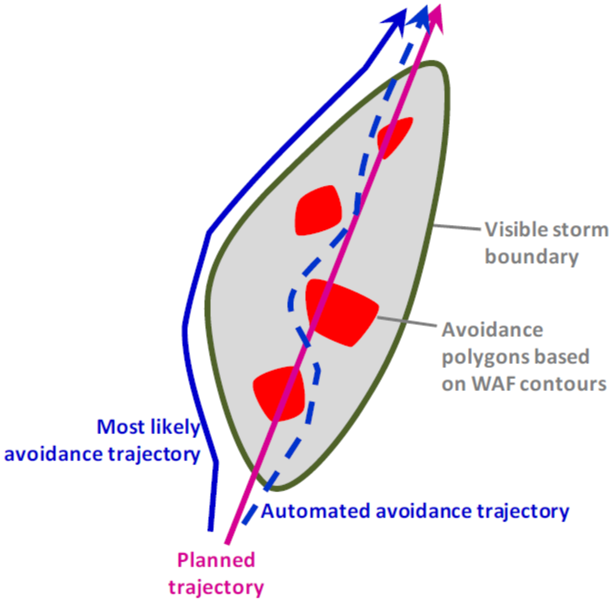


Figure 5.2: Notional illustration of a ‘noisy’ weather avoidance polygon field, based on simple WAF deviation probability contours that result in overly complex weather-avoiding trajectories.

choice of WAF deviation probability and echo top contour are both parameters of the new clustering algorithm. As a result, CWAP tend to be more consistent from one forecast to the next, as the dependence on potentially volatile detectable echo top edges is reduced.

The first step in developing convective weather-aware decision support is the translation of weather information into statements about aviation impact. An en-route convective weather avoidance model (CWAM) transforms gridded, deterministic forecasts of radar echo top height and vertically integrated liquid (VIL, a measure of precipitation intensity) into three-dimensional WAF, which give the probability at each grid point that a pilot will choose to deviate around the weather at that point (‘deviation probability’).

However, two significant problems reduce the effectiveness of CWAM in the prediction of weather-avoiding trajectories for time-based metering applications, where WAF contours must be converted to two- or threedimensional polygons that flight trajectories are likely to avoid (‘avoidance polygons’). Defining avoidance polygons as a particular deviation probability contour in the WAF sometimes results in noisy avoidance fields that, in turn, result in overly complex and unrealistic weather-avoiding trajectories (figure 5.2). Even though deviation can be predicted fairly well by identifying the maximum deviation probability that a flight will encounter along its planned trajectory, WAF contours do not always predict the boundaries of the avoidance polygons that deviating pilots follow.

This shortcoming arises from the fact that CWAM identifies regions of vigorous convection that pilots wish to avoid (high-topped thunderstorms), based only on local measurements of echo top height and VIL. CWAM does not attempt to identify boundaries of thunderstorms that pilots may be able to see outside the cockpit, and that may be used as a guide for safe and comfortable weather-avoiding trajectories. In some instances, pilots may still choose to fly gaps between thunderstorm 'turrets' that are part of a single storm complex, but more often, pilots will choose to avoid the storm altogether, if possible.

In order to increase the effectiveness of en-route CWAM in time-based metering applications, WAF must be enhanced to create more robust convective weather avoidance polygons (CWAP). Robustness implies that avoidance polygons contain convective weather that pilots wish to avoid, and that the preferred weather avoiding trajectory will follow the boundary of the polygon closely. Hence, automatically generated weather avoiding trajectories based on robust weather avoidance polygons will have a high likelihood of acceptance by pilots. As a result, pilot behavior may become more predictable, and the workload required to coordinate weather-avoiding deviations should be reduced.

5.1.5 Uncertainty

It is important to identify all quantities that can be potentially uncertain. It is essential that such analysis is performed right at the start of the modeling stage. A significant amount of effort in the topic of uncertainty management has wrapped uncertainty around the final results after complete analysis; such an approach would not be systematically correct. It is necessary to understand that uncertainty analysis needs to be a part of the fundamental framework for modeling, monitoring, and prediction. Consider any generic time-index k_P at which prediction is desired to be performed up to time k_H; the potential sources of uncertainty include:

1. The state at time-index k_P, given by $\mathbf{x}(k_P)$;
2. The measurement error at time-index k_P, given by $\mathbf{n}(k_P)$;
3. The input values for all future times in $[k_P, k_H]$, given by $\mathbf{U}_{k_P}^{k_H}$;
4. Process noise values for all future times in $[k_P, k_H]$, given by $\mathbf{V}_{k_P}^{k_H}$.

As a result of the above sources of uncertainty:

1. The safety metrics are uncertain at all future time-instants, i.e., $\mathbf{\Phi}(k)_{k_P}^{k_H}$ is uncertain. Hence, it would be necessary to compute the probability density function as $p(\mathbf{\Phi}(k)_{k_P}^{k_H})$.
2. There is a probability of occurrence of any safety-related event at each time point. This probability, denoted as $p(\mathbf{O}_{E,k_P}^{k_H})$ also needs to be computed.
3. The times until the occurrence of safety-related events is also uncertain and such time also needs to be represented using a probability density function, denoted as $p(\mathbf{k}_E)$.

5.2 Monitoring

Monitoring the NAS can be viewed as a Bayesian inference problem. We have various sensors measuring the current state of the NAS, such as GPS coordinates, radar, aircraft instrumentation, and weather observations. We have also a dynamic model of how the NAS evolves, $\mathbf{f}$, given its inputs $\mathbf{u}$, such as intended flight routes, scheduled departure times, etc.

The inputs to the monitoring problem are the known inputs to the NAS $\mathbf{u}$ and the available observations $\mathbf{y}$, and the goal is to use the model to infer or estimate the true state of the NAS $\mathbf{x}$. From the state, we can evaluate the safety metrics $\boldsymbol{\phi}$.

Fundamentally, the monitoring step involves the computation of state at any desired time-of-prediction. This step can be expressed using Bayes theorem, as:

$$p(\mathbf{x}(k_P)|\mathbf{y}(k_P)) = \frac{p(\mathbf{x}(k_P-1))p(\mathbf{y}(k_P)|\mathbf{x}(k_P))}{\int p(\mathbf{x}(k_P-1))p(\mathbf{y}(k_P)|\mathbf{x}(k_P))d\mathbf{x}(k_P)} \tag{5.1}$$

Note that the state-estimate from the previous time-step ($p(\mathbf{x}(k_P-1))$) is used as a prior for the current time-step. The likelihood term is denoted as $p(\mathbf{y}(k_P)|\mathbf{x}(k_P))$, and is computed based on the output model, explained earlier in Eq. 3.9. The challenging part in evaluating the state is the computation of the denominator in Eq. 5.1, and this denominator is analogous to the denominator in Eq. 3.11.

There are many algorithms that may be used to solve this general problem, such as Kalman filters, unscented Kalman filters, and particle filters [83–86]. These algorithms all have the same basic structure. For a new time step, we first predict the new state, based on the previous state and the inputs. Then, we correct the state based on the available observations based on the likelihood functions. Given some assumption of uncertainty in the model and some assumption of uncertainty in the observations, the algorithms find the most likely state. Different algorithms present different tradeoffs in space and time complexity, what kinds of models they are able to handle, and whether they are deterministic or stochastic. For example, the Kalman filter is an optimal estimator only for linear systems with additive Gaussian noise and is deterministic. In constrast, the particle filter makes no restrictions on the type of model or underlying noise, and stochastically computes many samples (i.e., "particles") in order to find an estimate of the state. As such, it has a very large computational requirement compared to the Kalman filter, which, in equivalent terms, works only with one sample. The state is represented by the mean and a covariance matrix, and in a particle filter, by a set of weighted samples.

Since the NAS is a large-scale system, it makes sense to employ distributed and decentralized versions of these algorithms. In such an implementation, aircraft and weather states could be independently estimated using approaches such as [87, 88].

Ultimately, the output of the monitoring algorithm is the probability distribution $p(\mathbf{x}(k))$, from which, using $\mathbf{F}$, we can compute $p(\boldsymbol{\phi}(k))$.

5.3 Prediction

The goal of the prediction problem is to compute the future evolution of the NAS state $\mathbf{x}$, the safety metrics $\boldsymbol{\phi}$, and the occurrence of safety events E, so that preemptive or corrective actions can be taken. To this end, we utilize a prediction interval k_I and predict up to time $k_H = k + k_I$. In conflict prediction, for example, a k_I of 20 minutes is used in practice. Ultimately, we want to find the probability distributions of the state trajectory, $p(\mathbf{X}_{k_P}^{k_H})$, the safety metric trajectory, $p(\boldsymbol{\Phi}_{k_P}^{k_H})$, and the event times $p(\mathbf{k}_E)$, as well as the probability of the different events occurring within the prediction horizon.

Ultimately, the prediction problem is an uncertainty propagation problem [89]. We have an uncertain estimate of the current system state, and uncertain future inputs to the

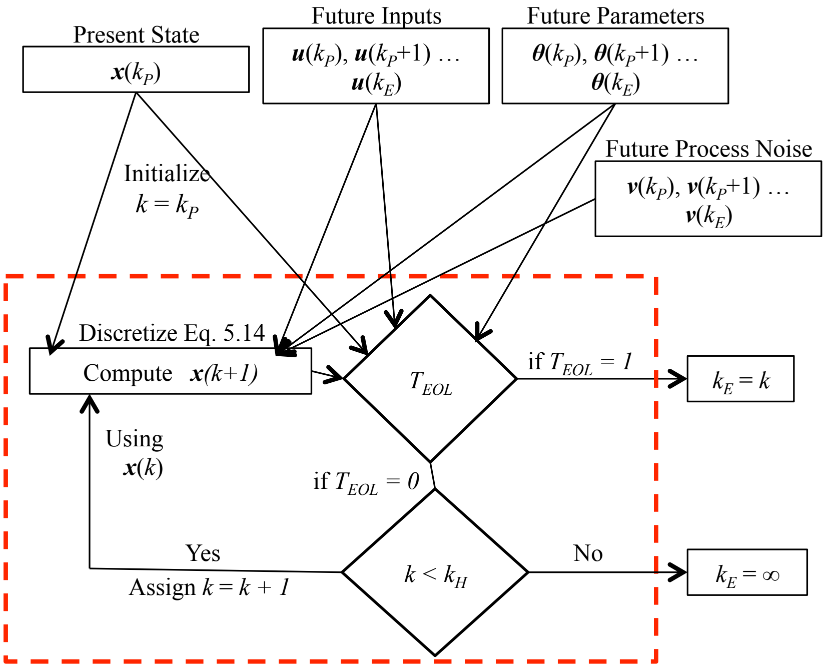


Figure 5.3: Prediction as Uncertainty Propagation

Algorithm 1 $\Phi_{k_P}^{k_H} \leftarrow \texttt{Predict}(\mathbf{x}(k_P), \mathbf{U}_{k_P}^{k_H}, \mathbf{V}_{k_P}^{k_H}, k_H)$

```
for $k = k_P$ to $k_H$ do
    $\mathbf{x}(k+1) \leftarrow \mathbf{f}(k, \mathbf{x}(k), \mathbf{U}_{k_P}^{k_H}(k), \mathbf{V}_{k_P}^{k_H}(k))$
    $\phi(k+1) \leftarrow \mathbf{F}(\mathbf{x}(k+1))$
end for
```

NAS. We need to propagate all these uncertainties through the model **f** to determine the probability distributions of future variables. This is the key difference with past approaches to prediction in the NAS, where instead deterministic models are used for prediction, and then prediction errors are accounted for after-the-fact, rather than bringing in all the sources of uncertainty from the beginning in a formal, principled way.

The underlying function to any prediction algorithm is given as Algorithm 1 (equivalently, in Fig. 5.3). At a given time of prediction k_P, with realizations of the state $\mathbf{x}(k_P)$, the future input trajectory $\mathbf{U}_{k_P}$, the future process noise trajectory $\mathbf{V}_{k_P}$, and a prediction horizon $k_H > k_P$, the algorithm simulates the NAS state forward up to k_H, and computes the corresponding safety metrics.

The most conceptually simple and easiest to apply prediction algorithm is Monte Carlo sampling, shown as Algorithm 2. A standard Monte Carlo approach generates many realizations of the prediction inputs, and calls Algorithm 1 for each realization.

We compute samples of future trajectories of the safety metrics, from which we can compute directly times of unsafe events, probabilities of events occurring at a certain time or within a certain interval, etc. This set of samples establishes a probability distribution for the safety metrics and the related variables. For example, we can compute the probability

```
Algorithm 2 $\{\boldsymbol{\Phi}_{k_P}^{k_H}\}_{i=1}^{N} = \texttt{MonteCarlo}(p(\mathbf{x}(k_P)), p(\mathbf{U}_{k_P}^{k_H}), p(\mathbf{V}_{k_P}^{k_H}), k_P, k_H, N)$
for $i = 1$ to $N$ do
    $\mathbf{x}(k_P)^i \sim p(\mathbf{x}(k_P))$ {Sample state}
    $\mathbf{U}_{k_P}^{k_H,i} \sim p(\mathbf{U}_{k_P}^{k_H})$ {Sample future inputs}
    $\mathbf{V}_{k_P}^{k_H,i} \sim p(\mathbf{V}_{k_P}^{k_H})$ {Sample future process noise}
    $\boldsymbol{\Phi}_{k_P}^{k_H,i} \leftarrow \texttt{Predict}(\mathbf{x}(k_P)^i, \mathbf{U}_{k_P}^{k_H,i}, \mathbf{V}_{k_P}^{k_H,i}, k_P, k_H)$
end for
```

of some e occurring by k_H simply as the number of samples with finite k_e divided by N. Algorithms 1 and 2 can also be easily extended to provide the probability of the event occurring at each time point within $[k_P, k_H]$. Over a set of events, we can also easily compute the probability of any safety event occurring within the prediciton horizon, and the probability of one occurring at each time point, and related probability distributions.

As with the monitoring approach, for prediction, a distributed implementation is also preferred due to the large-scale nature of the NAS. An approach for distributed prediction can be found in [90].

5.4 Effect of Uncertainty on Safety: Likelihood of Unsafe Events

Once the uncertainty in the prediction of safety-related quantities of interest is computed, the likelihood of unsafe events can be computed. Typically, safety can be defined in terms of pre-defined thresholds. Some thresholds can be easily defined based on one output quantity; for example, the minimum separatation distance between two aircraft needs to be at least 5 nautical miles. On the other hand, some complex thresholds may be defined in terms of more complex regions using a vector of output quantities. Recall that the probability distributions of these output quantities were computed in the previous subsection. Let the joint PDF be denoted as $f_{\boldsymbol{Y}}(\boldsymbol{y})$.

Consider a generic unsafe/undesirable event e and a set of output quantities $\boldsymbol{Y}$ that can be used to indicate whether e has occurred or not. Note that $\boldsymbol{Y}$ is uncertain; hence for certain (undesirable) realizations of $\boldsymbol{Y}$, the event E would have occurred whereas for other realizations of $\boldsymbol{Y}$, e would not have occurred. Let $T_e(\boldsymbol{Y})$ represent an indicator function that indicates whether e has occurred or not based on the realization of $\boldsymbol{Y}$, as:

$$T_e(\boldsymbol{y}) = \begin{cases} 1, & \text{if } e \text{ occurs} \\ 0, & \text{if } e \text{ does not occur} \end{cases} \tag{5.2}$$

Then, the probability of the occurrence of e can be expressed as:

$$P(e) = \int_{T_e(\boldsymbol{y})=1} f_{\boldsymbol{Y}}(\boldsymbol{y}) \tag{5.3}$$

In this report, we consider multiple events of safety, as indicated in Fig. 5.4. The computation of likelihood and probability of unsafe events varies from one event to another. These probabilities are calculated for all future time-instants (until a desired look-ahead time), based on information available at the present time-instant. As time keeps evolving, more information is available, and the probabilities for all future safety-related incidents keep evolving as well.

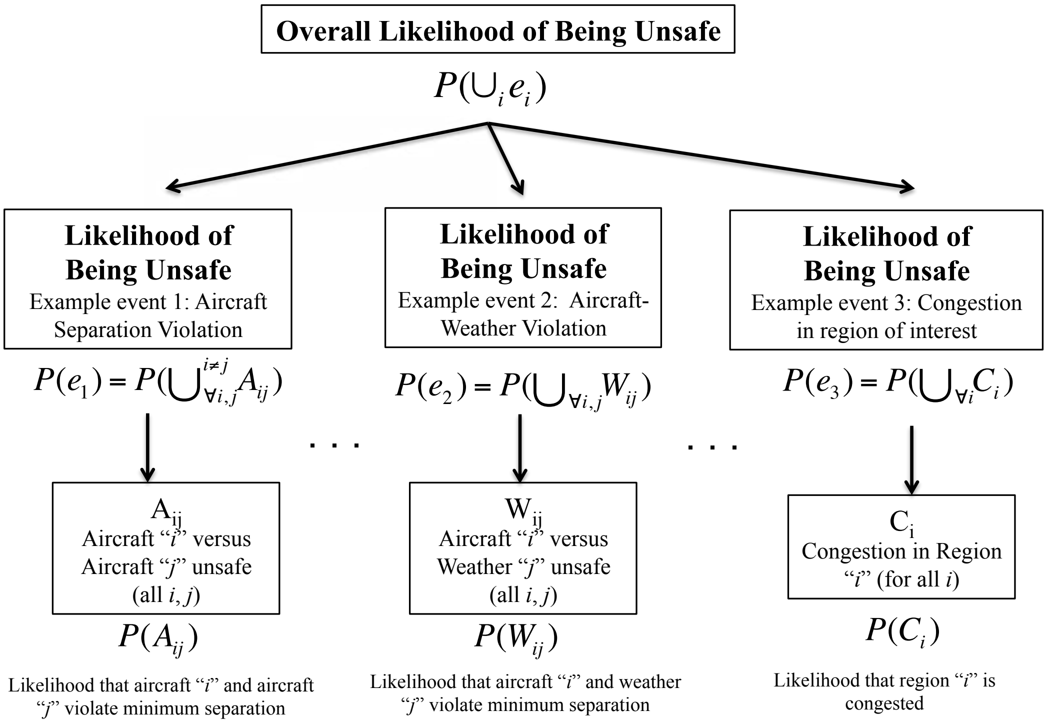


Figure 5.4: Probability Tree: Unsafe Indicators

Multiple safety metrics can be computed and the likelihood of safety in each scenario can be computed using the probability computation in Eq. 5.3.

5.4.1 Computing Overall Safety of the NAS

In order to assess the NAS-level safety, it is important to consider multiple hazards, compute respective safety metrics, and related likelihoods of unsafe events. All of such likelihoods from each event can be combined together in order to compute the overall safety of the NAS.

The NAS is said to be unsafe if any unsafe event occurs. Consider events e_i ($i = 1$ to n) that correspond to multiple safety related events; the occurence of event e_i means that safety has been violated with respect that particular event. Let e denote the event that the NAS is unsafe; hence, e is said to have occurred when any of the events e_i has occurred. Hence, it is possible to calculate the probability that the entire airspace is unsafe, as:

$$P(e) = P(\cup_{\forall i} e_i) \tag{5.4}$$

Note that $P(e_i)$'s and $P(e)$ can be calculated for all future time-instants based on information available at the present time-instant. As explained earlier, time keeps evolving and these probabilities (for occurence of unsafe-incidents in the future) keep evolving too.

Also, note that the above equation simply calculates the probability that any unsafe incident occurs. However, it does not take into account the risk/criticality associated with each safety incident. Future work needs to account for this factor in computing the overall safety of the airspace and develop metrics that not only include the information regarding probability/uncertainty but also important information regarding risk and criticality.

5.4.2 Examples

This section discusses how the aforementioned probabilities, i.e., the likelihoods of safety from multiple events can be combined probabilistically (using Eq. 5.4) for a few safety-related events. For instance, e_1 refers to the occurence of aircraft separation violation (minimum distance requirement not being met), e_2 refers to the occurrence of insufficient distance between an aircraft and an adverse weather region, e_3 refers to the occurrence of congestion in a sector/region of interest, and so on. While this discussion on examples can be potentially extended to an endless list of scenarios, only three are presented in this report, for the sake of illustration.

Example 1: Aircraft Separation

Consider the event e_1; this event is said to occur when any two aircraft in the NAS are "too close" to one another. In this report, we model the behavior of each individual aircraft and hence can compute the distance between any two aircraft. Hence, A_{ij} refers to the event that the i^{th} aircraft and the j^{th} aircraft are too close to each other (obviously, $i \neq j$). Hence, the event e_1 is said to occur when any of the events A_{ij} (i, j are indices referring the numbering of different aircraft in the airspace) occurs. In other words:

$$P(e_1) = P(\cup_{\forall i,j}^{i \neq j} A_{ij}) \tag{5.5}$$

Hence, using the real-time monitoring and prediction framework, all possible A_{ij}'s are considered, their probabilities are evaluated, then Eq. 5.5 is used to compute $P(e_1)$. Typically, the computation of probability of union of events is referred to as system-level reliability analysis [91]; since we use a Monte Carlo algorithm to compute probabilities in this report, union-probabilities can also be computed within the scope of the proposed computational framework.

Example 2: Aircraft-Weather Separation

Similarly, the separation between any aircraft and a region of adverse weather can be calculated as an output quantity. Using a minimum-separation-distance criterion, we can define an event W_{ij}; this event is said occur when the i^{th} aircraft and the j^{th} adverse-weather-region are too close to each other. Hence, the event e_2 is said to occur when any of the events W_{ij} (i, j are indices referring the numbering of aircrafts and adverse-weather regions respectively, in the airspace) occurs. In other words:

$$P(e_2) = P(\cup_{\forall i,j} W_{ij}) \tag{5.6}$$

Similar to the aircraft separation safety-scenario, using the real-time prediction framework, all possible W_{ij}'s are considered, their probabilities are evaluated, then Eq. 5.6 is used to compute $P(e_2)$.

Example 3: Congestion

Another safety-scenario we consider in this report is congestion. Using the prediction framework, it is possible to compute the number of flights present in any region/sector of interest. When the number of flights is greater than a critical number, then the corresponding region/sector is said to be congested. Let C_i denote the event that the i^{th} region is congested. Then, the event e_3 is said to occur when any of the regions/sectors in the airspace are congested. In other words:

$$P(e_3) = P(\cup_{\forall i} C_i) \tag{5.7}$$

Similar to the previous safety-scenarios, using the real-time prediction framework, all possible C_i's are considered, their probabilities are evaluated, then Eq. 5.7 is used to compute $P(e_3)$.

Chapter 6

Case Studies

In this chapter, we describe simulated case studies that demonstrate our overall framework. For each case study, we describe the details of the study, along with the safety modeling, i.e., the safety metrics, events, and thresholds used. The first two examples demonstrate the framework for a single type of an event and take place in the terminal airspace, while the third involves several different events and takes place en-route.

We first describe the selected case studies in Sections 6.1–6.3. The underlying dynamic models used by the framework are described in Section 6.4.

6.1 Scenario 1: Wake Turbulence in the Terminal Airspace

As evidenced by the numerous reports in the ASRS database, wake turbulence is a common hazard for aircraft (see Appendix C). Wake turbulence is caused by the wake vortex produced due to the pressure differences on the wing [92–94]. The weight, wingspan, and speed of the generating aircraft determine the initial strength and motion of the vortices; however, ambient atmosphere (wind, stability, turbulence, etc.) dictates the eventual motion and decay rate of the vortices. The maximum core velocity of the vortex may exceed 300 ft/sec, peaking when an aircraft has a clean wing (i.e., no flaps extended, etc.). The induced rolling moment on an aircraft encountering the wake vortex of another aircraft can exceed its roll control, leading to loss of control. As an example, in 1972, a DC-9 aircraft two miles behind a DC-10 aircraft crashed; it was assumed the crash was caused by a wake vortex encounter, prompting additional wake vortex separation standards for IFR aircraft [95].

Even though controllers may provide wake turbulence advisories in certain situations, pilots are generally solely responsible for maintaining adequate horizontal or vertical separation for wake turbulence avoidance. For arrivals to and departures from controlled airports, the controller follows separation standards to mitigate potential issues, such as the one documented in ASRS report 1201963 describing an experience of a departing CRJ-200 business jet that encountered wake turbulence shortly after takeoff at Atlanta Hartsfield (ATL) airport. According to the flight crew, ATL ATC has implemented new reduced separation procedures that allow controllers to clear aircraft for takeoff before the previous aircraft has rotated. Normally, this situation may not have resulted in a wake turbulence encounter. On this particular day, however, the CRJ-200 was heavy, extending its departure roll and decreasing its climb rate. The CRJ-200 crew writes that "The new separation minimums between takeoffs in Atlanta need to be altered. The company needs to present these issues to local ATC to prevent a major accident in the future."

One approach to improving the situation is to provide additional information about the safety of the airspace in the airport vicinity to both pilots and controllers. If either of these participants had gotten a warning that standard operating rules or perhaps the heuristics that typically work in this situation would not work that day, the encounter could have been avoided.

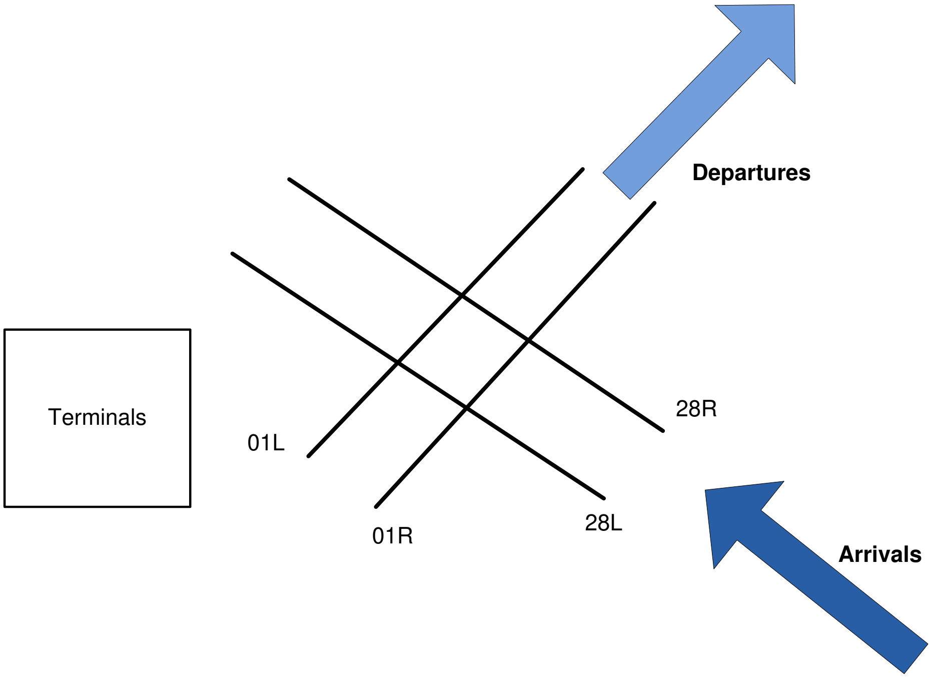


Figure 6.1: Nominal SFO operations.

To demonstrate the type of situation described by the CRJ-200 crew, we consider the terminal airspace of the San Francisco International Airport (SFO), shown in Fig. 6.1. SFO has two sets of intersecting parallel runways. In typical (good weather) operations, aircraft take off from runways 01L and 01R [1], and land on runways 28L and 28R.[2] During inclement weather, the winds typically come from the S or SE, and as a result, SFO operations shift to utilize runways 19L and 19R for departure and runways 10L and 10R for arrivals.

In our demonstration scenario, a light aircraft A1 (e.g. Piper Aztec), is waiting on 01L for takeoff clearance from tower controllers (see Fig. 6.2). A large aircraft A2 (e.g.

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[1] Runway designators are based on the magnetic heading of the runway; thus, aircraft departing from runway 01 are heading 010 degrees, or more precisely, 013 degrees, or NNE). Parallel runways are designated L for left and R for right.

[2] Runways 28L and 28R are oriented at 283 degrees, thus, arrivals are heading WNW, taking advantage of the predominant winds.

Boeing 777) is coming in for a landing on 28L. As the scenario proceeds, the pilot of A2 decides to do a go-around right after touching down because of the difficulties with maintaining directional control due to a strong crosswind (19 knots, coming from the north). As the aircraft accelerates again for the go-around and starts generating lift, a region of wake turbulence is formed behind it. Due to the wind, the vortices will drift onto runways 01L and 01R. Ordinarily, there are no issues with residual wake turbulence in the general area of runway intersection as landing aircraft touch down (and stop generating lift) well before it and departing aircraft rotate (and start generating wake vortices) well after the intersection. In this, somewhat rare, scenario a controller may not consider all of the implications of A2's go-around and clear A1 for departure as soon as A2 is clear of the runway, while the region of wake turbulence is still present (which may be particularly dangerous for the lighter A1 since it may rotate before the intersection of the runways).

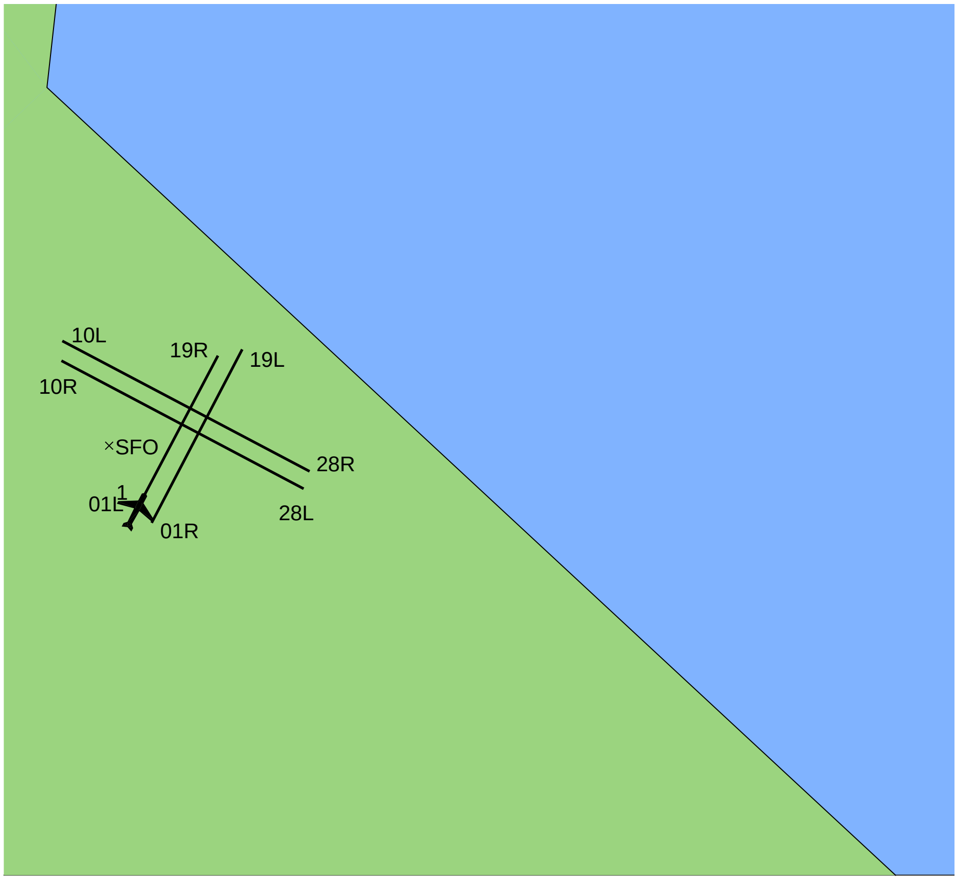

Figure 6.2: Wake turbulence scenario at $t = 0$.

As described above, wake vortices are generated as a byproduct of an aircraft generating lift. These vortices cause wake turbulence for following aircraft. The initial descent rate of the vortices is determined by weight, flight speed, and wingspan of the generating aircraft. The initial rate is approximately 300 to 500 fpm for about 30 sec. The descent rate decreases and eventually reaches zero between 500 to 900 ft below the flight path. For our model, we simplified this behavior and compute the wake turbulence region as follows. Given the aircraft position for the past m minutes (in which the turbulence generated before $t - m$ has dissipated), we compute points at the wingtips at each time step, and extend them along the line between the wingtips proportional to $t - t_{prev}$ for $m \leq t_{prev} \leq t$, and then shift them in the direction of the wind at t_{prev}. The wake turbulence region is then defined by these points; this procedure is summarized in Fig. 6.3, where the wake region at time t is computed based on the aircraft position at times t, $t - 1$, and $t - 2$ (p_t, p_{t-1}, and p_{t-2}, respectively). At p_t, the width is equal to the distance between the wingtips and the wake region points are placed there. At p_{t-1}, the width of the region has become larger than the original wingtip distance and shifted in the direction of the wind. At p_{t-2}, the turbulence has spread still wider and shifted further by the wind from its original location, and this continues for each past time step (the finer the sampling time, the finer the resolution of the region). This region extends below for 1000 feet. This approximation of the wake region is meant to be more realistic than a simple region computed based on separation standards, but simple enough for demonstration purposes. More advanced models, such as those in [92–94] can be used in future work.

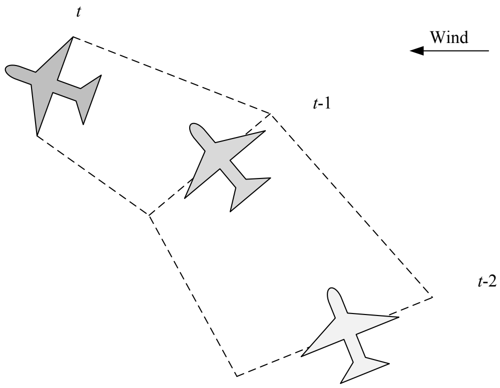

Figure 6.3: Computation of wake turbulence region.

Connecting the description of this scenario to our framework, the event e we are concerned with is whether an aircraft enters a region of wake turbulence created by another aircraft. Given two aircraft, T_e is defined to be true when the position of the first aircraft is within the wake turbulence region of the second aircraft. Since we have two aircraft, there are 2 different wake turbulence events we want to predict (A1 in wake of A2, A2 in wake of A1). The safety metric in this case is computed as the distance between an aircraft and the wake region of another aircraft.

Initially, A1 is on the runway. The time of takeoff clearance is unknown, and will be given once the approaching aircraft on the intersecting runways is clear. A2 is lined up for approach at about 150 knots. As mentioned earlier, there is a wind coming from the north of 19 knots, that will be pushing the wake turbulence region south toward A1.

The safety metric is constantly monitored, and predictions are made up through 5 minutes into the future at a discrete time step of 10 s. From the pilot's perspective, we compute the probability that a wake turbulence event will happen in the next 5 minutes. Fig. 6.4 shows the computed probability of A1 being in the wake region of A2 within the next 5 minutes, computed at each time. Initially, since the takeoff time is unknown, the probability is zero. At 195 s, takeoff clearance is known and immediately the prediction algorithm computes a high probability of encountering wake turbulence, since we know that A2 is not landing.

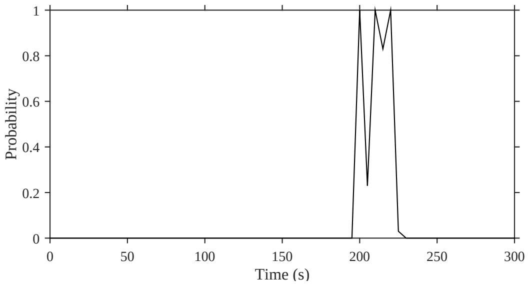

Figure 6.4: Probability of A1 being in the wake of A2 within the next 5 minutes as a function of time.

From the controller's perspective, we can compute the probability of a wake turbulence event happening in the next 5 minutes at every spatial position. Aggregating all that information, we can overlap trouble spots on the controller's view of the map. This is shown in Fig. 6.5 at $t = 220$ s. The yellow region is the region of wake turbulence created by A2 after its missed approach, and the marked red region indicates future locations of a wake turbulence event within the next 5 minutes.

Figure 6.5: Wake turbulence scenario at $t = 220$ s.

6.2 Scenario 2: Compression in the Terminal Airspace

Efficient airspace operations require the cooperation of all pilots and controllers. Operations go more smoothly when pilots and controllers know what to expect of each participant and each participant conforms with that expectation. One such expectation (and regulation) is that pilots will maintain cruise airspeed as specified in the flight plan and will inform ATC of airspeed changes greater than 5%. Moreover, ATC expects certain approach speed profiles, depending on aircraft type, and anticipates speed decreases of leading aircraft with extra separation from following aircraft. This ensures that separation standards are not violated as the leading aircraft slows for landing. There are situations under which the leading aircraft slows more than anticipated by ATC. This leads to the follower aircraft closing the gap with the lead aircraft. As each follower slows, the gap with its corresponding follower also closes, leading to what is referred to as "compression" of the flights. Compression can occur in any airspace, not just near the airport, given the right (or wrong) circumstances. In these circumstances, ATC must be aware and protect against loss of separation.

We demonstrate the application of our framework on a compression scenario by simulating an approach to SFO's runway 28L of four in-trail aircraft, A1 through A4, each separated by 5 miles from the preceding aircraft. As the simulation begins, the first aircraft, A1, flies at a slower than expected approach speed.

The unsafe event e of interest is loss of standard separation (LOSS) between any aircraft. Given two aircraft, T_e is defined to be true when the horizontal distance between them is less than 3 nautical miles and the vertical separation is less than 1000 ft for in-trail under IFR. Since we have four aircraft, there are 6 different LOSS events we want to predict (A1 conflict with A2, A1 conflict with A3, etc.). The safety metric in this case is the distance between two aircraft. In this scenario, aircraft position is uncertain due to sensor noise, slow radar update rates, etc.

Fig. 6.6 shows the predictions from the controller perspective 50 s into the scenario. The marked red spots show the predicted locations of A2 when it will be in conflict with A1.[3] Fig. 6.7 shows the same situation at $t = 80$ s (the true time of conflict is 85 s). Here, the predictions are more precise, and the predicted locations of conflict are concentrated into a smaller region of airspace than at the earlier prediction time.

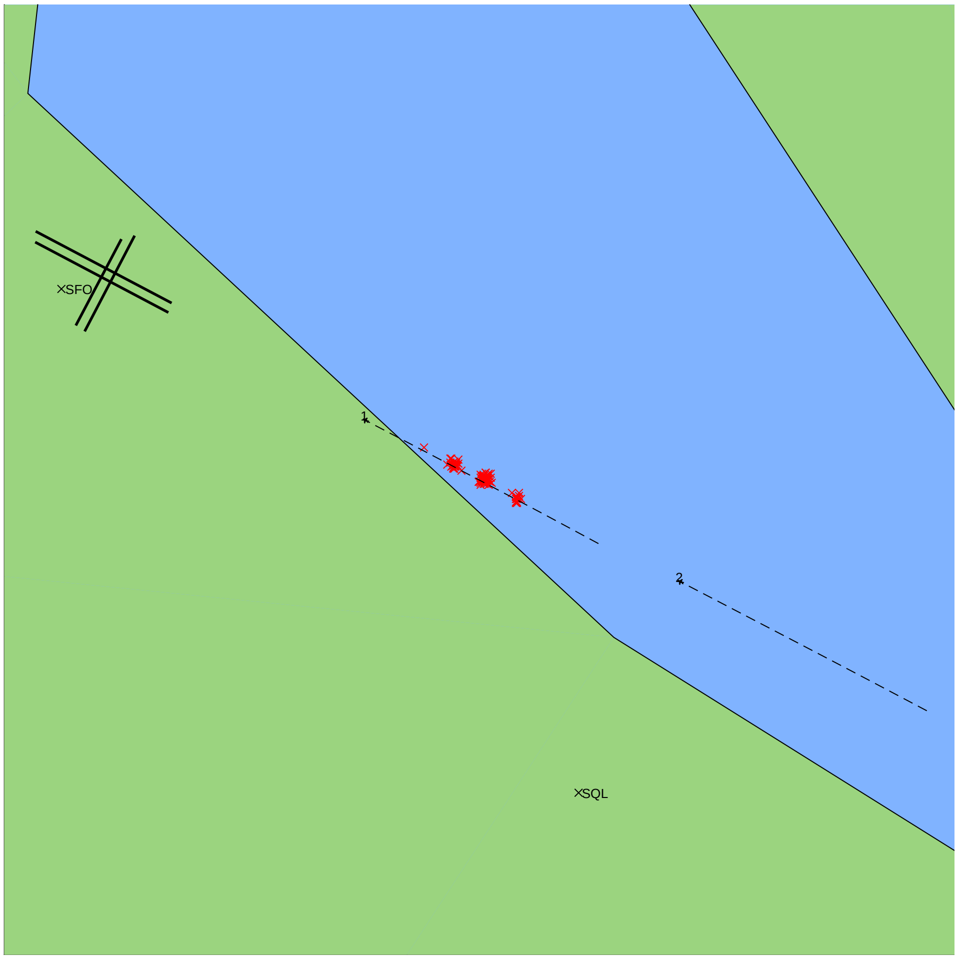

Figure 6.6: Compression scenario at $t = 50$ s.

Fig. 6.8 shows the probability of conflict between A1 and A2 at different prediction

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[3] The three separate regions shown are due solely to the sampling time of the simulation, which is 10 s.

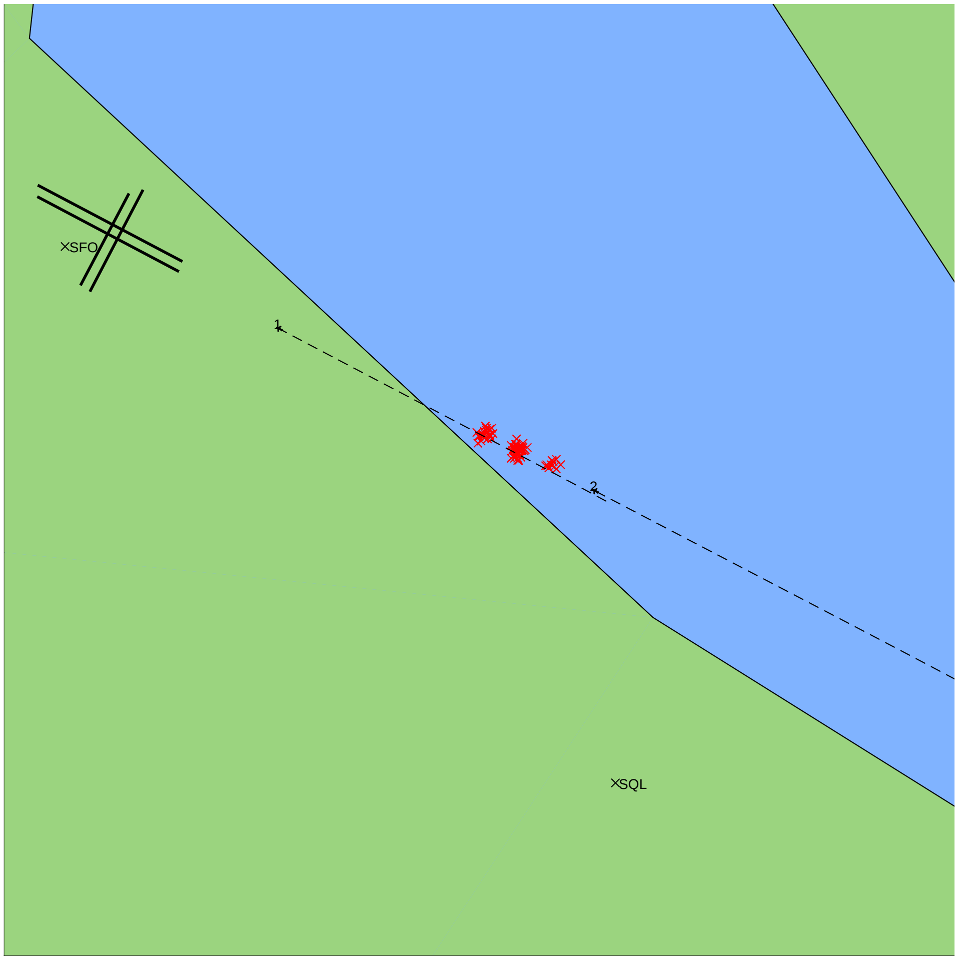

Figure 6.7: Compression scenario at $t = 80$ s.

times. For example, at 10 s the prediction is that the probability of a conflict at $t = 50$ s is around 30%, and around 100% by about 60 s. As we get closer to the actual time of conflict, the predictions become more accurate (the curve becomes shifted to the right), and the actual time of conflict is predicted to be later (at $t = 85$ s). From the perspective of A2, it is predicted from $t = 0$ that there is a 100% probability of conflict with A1 within the next 5 minutes.

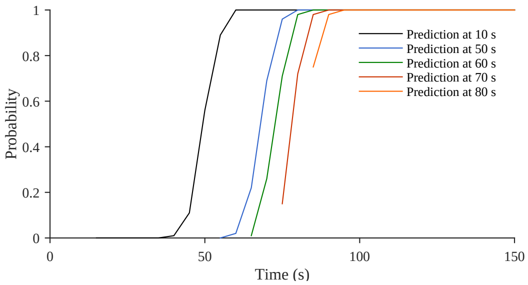

Figure 6.8: Predictions of probability of conflict between A1 and A2 at different prediction times.

6.3 Scenario 3: Weather in the En-route Airspace

Arguably, the most disruptive hazards to aviation are weather related. Convective weather in particular has the potential to wreak havoc on aircraft operations depending on its timing and extent. There are numerous ASRS reports documenting unsafe events due to weather and weather is a contributing factor in many accidents and incidents; many passengers have first-hand experience with its effects.

In this scenario, there is a large convective weather system moving north to south east of SFO, and there are several aircraft approaching SFO from the east. The weather is moving faster than the provided forecast and is in direct conflict with the planned route of most of the aircraft, forcing them to deviate.

The safety metrics of interest in this scenario are LOSS, low fuel, congestion, and distance from the weather. For this scenario, we use a standard separation of 5 nm; a low fuel event occurs if an aircraft's fuel mass, m_f, decreases below a level where reserves would need to be used to reach the destination; congestion (and hence, higher controller workload) occurs when the number of aircraft in a region (e.g., a sector, but in this case we consider a specific multi-sector portion of Oakland Center, ZOA) reaches an upper limit on the number of aircraft corresponding to the maximum workload for that region, and the distance from weather goes below a required distance, as summarized in Fig. 6.9.

The uncertainties considered arise from the movement of the wind and weather, position of the aircraft, and fuel usage of each aircraft.

As the aircraft approach the weather system, they are forced to deviate around it. Fig. 6.10 shows for A9 the probability of encountering weather in the next 5 minutes, and Fig. 6.11 shows the same but computed for the probability of getting a low fuel warning. Because the forecast is wrong and the aircraft is forced to reroute around the storm, the distance traveled is lengthened and the probability of having low fuel drastically increases once the new path is known (at 480 s). The probability of weather increases once it is known that it will hit the weather system, and drops off after routing around it. Fig. 6.12 shows the predictions of A2 encountering weather. As time advances, the predicted time of encountering the weather system moves earlier since the forecast is that the weather will move more slowly than it actually is.

From the controller perspective, the locations of aircraft encountering the weather system are shown as the marked blue regions in Figs. 6.13, 6.14, and 6.15. For congestion, the

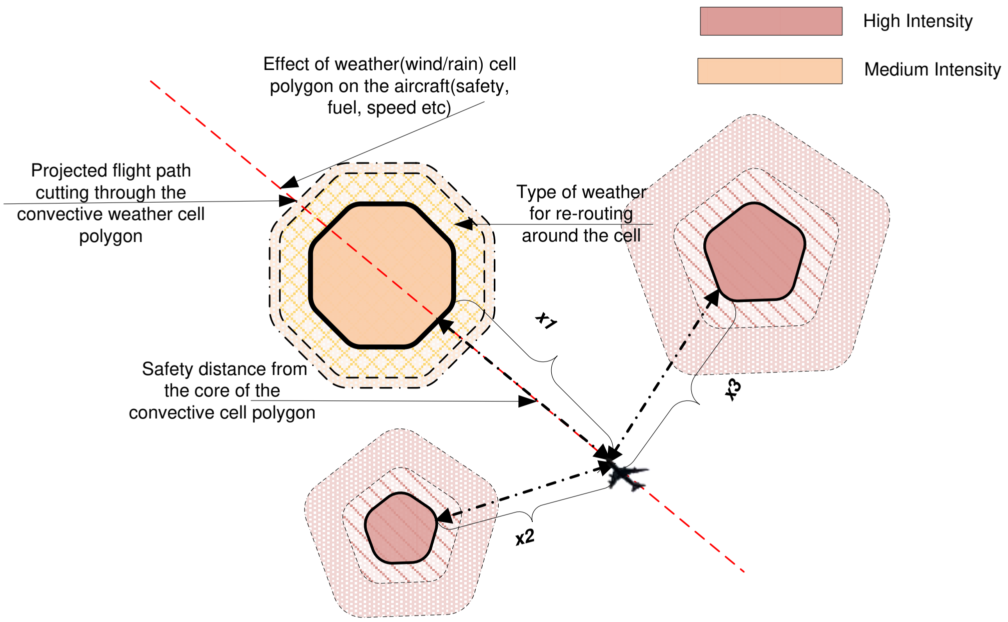

Figure 6.9: Safety distances from core of convective weather avoidance polygons.

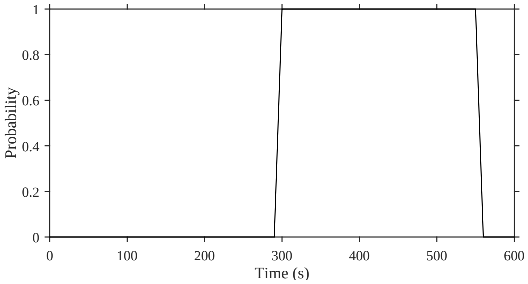

Figure 6.10: Predicted probability of A9 encountering weather within the next 5 minutes, as a function of time.

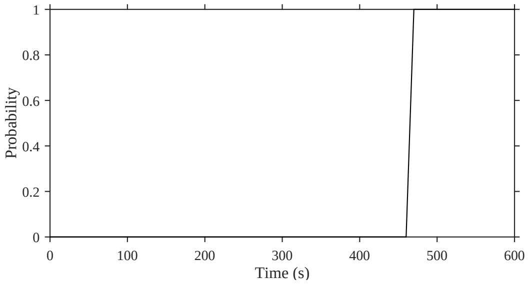

Figure 6.11: Predicted probability of A9 encountering low fuel within the next 5 minutes, as a function of time.

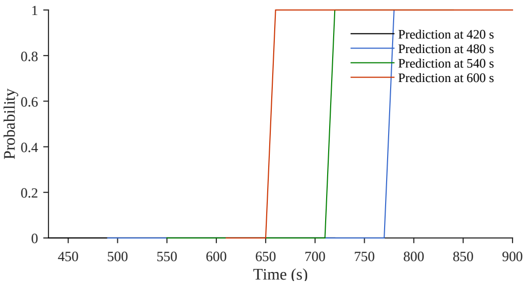

Figure 6.12: Predictions of A2 encountering weather at different prediction times.

region of interest (ZOA) has a red overlay with its intensity matching the magnitude of the congestion safety metric.

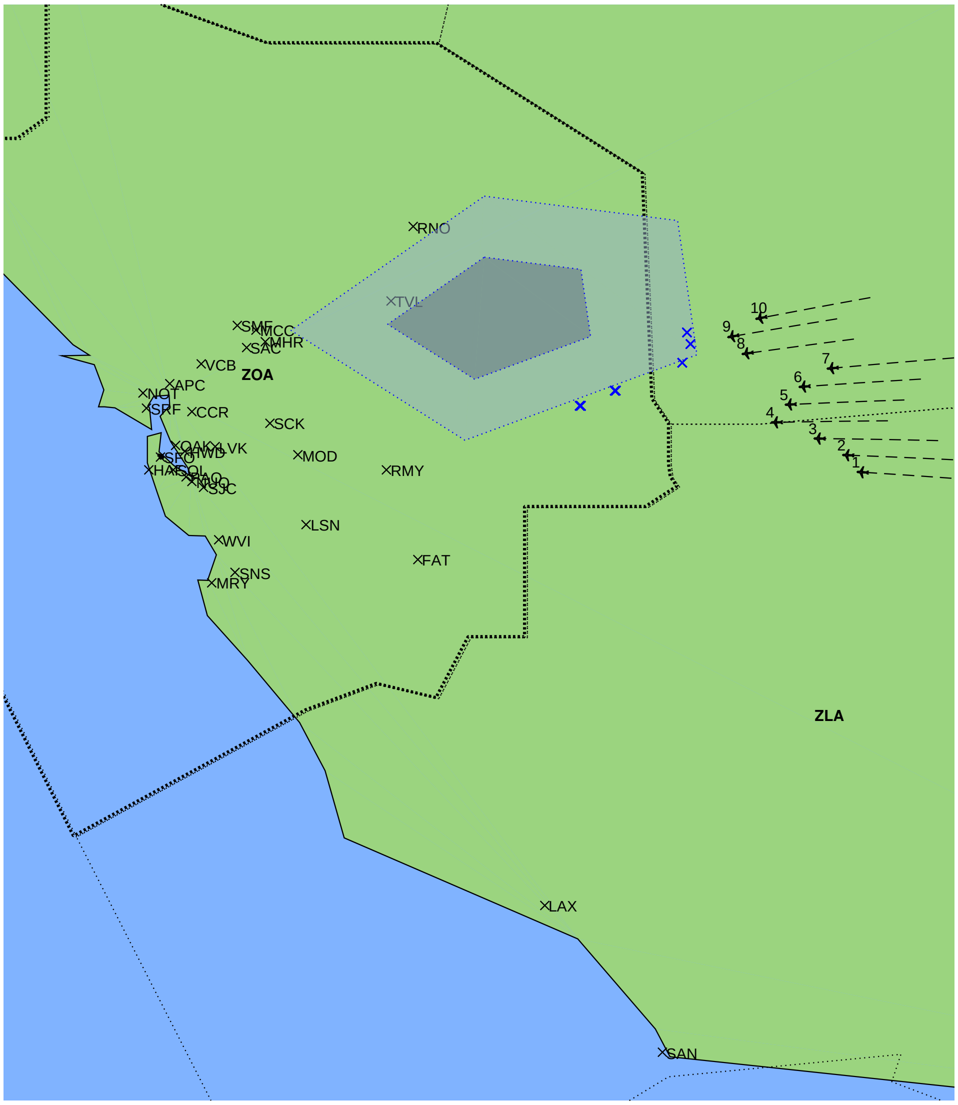

Figure 6.13: En-route weather scenario at $t = 400$ s.

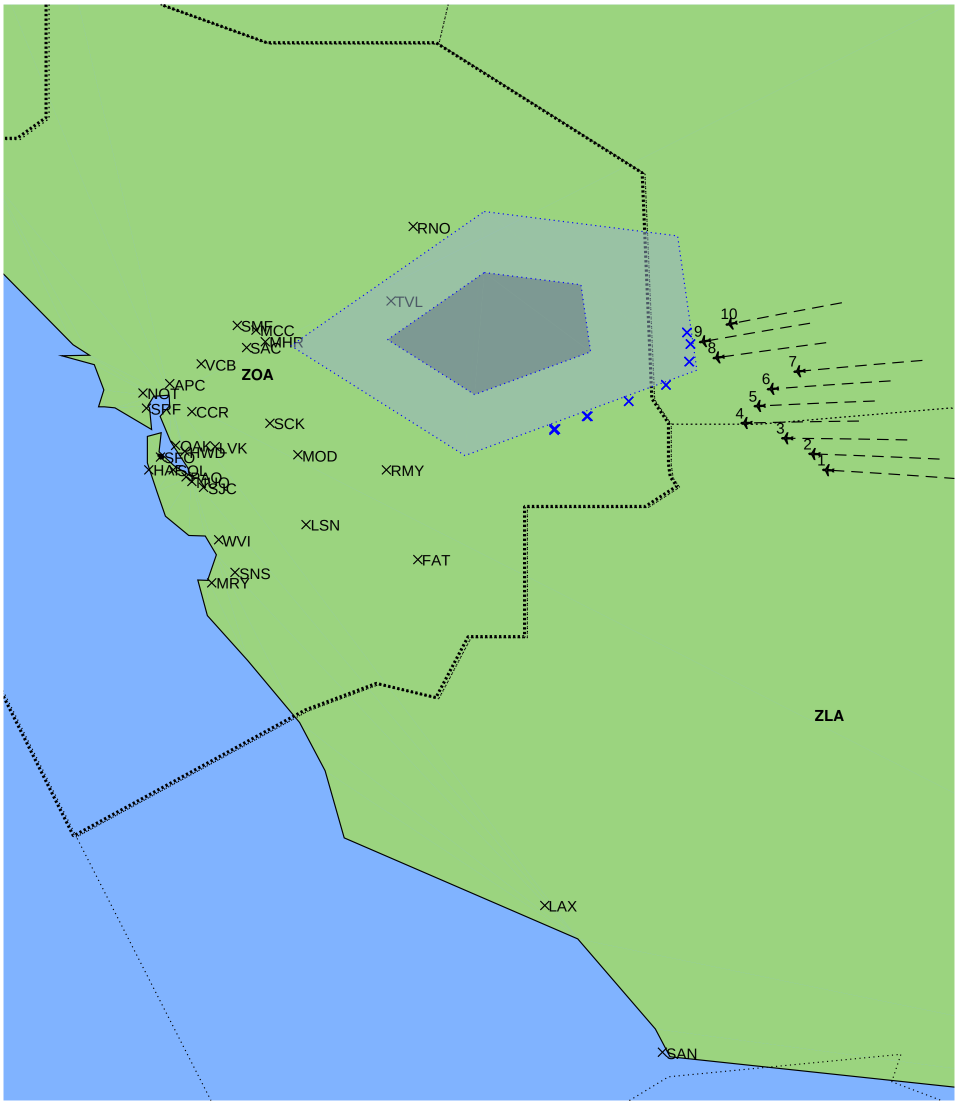

Figure 6.14: En-route weather scenario at $t = 440$ s.

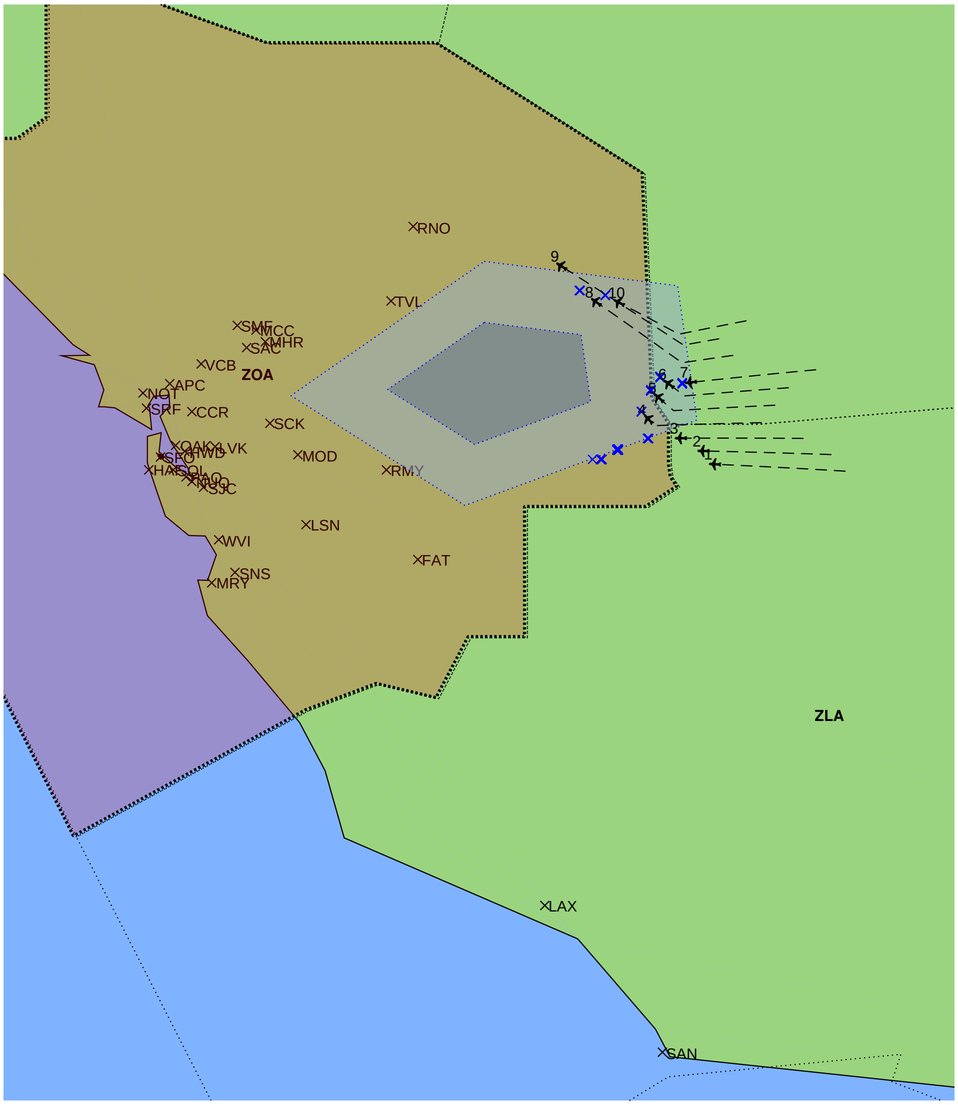

Figure 6.15: En-route weather scenario at $t = 570$ s.

6.4 Prediction Models

We have implemented models of aircraft dynamics, models of pilot and controller behavior, and weather models. Because our approach is model-based, these models can be replaced with higher fidelity models to improve prediction performance. In order to demonstrate the approach, we have used medium-fidelity models similar to those used in FACET.

In the following, we present the models used for the example scenarios. We describe the models in continuous time; note that they are converted to discrete-time for a given sampling rate for use in the simulation and prediction algorithm.

6.4.1 Aircraft Modeling

We use kinematic models of aircraft navigation with simplified dynamics and control, similar to the models developed in [80]. The aircraft state vector is defined as

$$\mathbf{x}(t) = \begin{bmatrix} V_a(t) \\ V_h(t) \\ \chi_a(t) \\ h(t) \\ \lambda(t) \\ \tau(t) \\ m_f(t) \end{bmatrix}, \tag{6.1}$$

where V_a is the indicated airspeed, V_h is the vertical speed, χ_a is the aircraft heading, h is the mean sea level (MSL) altitude, λ is the latitude, τ is the longitude, and m_f is the fuel mass. Note that we assume there is no roll and the aircraft may rotate only along the other two axes.

The well-known velocity triangle is shown in Fig. 6.16 [72], and consists of three velocity vectors: the airspeed vector, with magnitude V_a and heading χ_a, the wind vector, with magnitude V_w and heading χ_w, and the groundspeed vector, with magnitude V_g and heading χ_g. The groundspeed vector is the vector addition of the airspeed and wind vectors. In order to follow a given ground track, the commanded heading must be corrected for the wind.

For our purposes, we assume that each aircraft has a set of waypoints or fixes which it must navigate to, each defined by a latitude λ^*, a longitude τ^*, an altitude h^*, and a time t^*. The control is such that the commanded airspeed, climb rate, and heading are set to reach the desired position at the desired time, using great-circle bearing (χ_{GC}) and distance (d_{GC}) calculations:

$$d_{GC} = 2R \arcsin\left(\sqrt{\sin^2\left(\frac{\lambda^* - \lambda}{2}\right) + \cos(\lambda)\cos(\lambda^*)\sin^2\left(\frac{\tau^* - \tau}{2}\right)}\right), \tag{6.2}$$

$$\chi_{GC} = \arctan \frac{\sin(\tau^* - \tau)\cos(\lambda^*)}{(\sin(\lambda^*)\cos(\lambda) - \sin(\lambda)\cos(\lambda^*)\cos(\tau^* - \tau))}, \tag{6.3}$$

where $R = R_E + h$, with R_E being the MSL radius of the Earth. Then, commanded

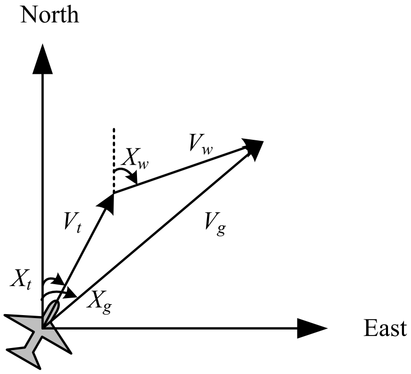

Figure 6.16: Velocity triangle.

airspeed V_a^*, commanded heading χ_a^*, and commanded climb speed V_h^* are described by

$$V_a^* = \frac{d_{GC}}{t^* - t} - V_w \cos\left(\chi_w - \chi_a\right), \tag{6.4}$$

$$\chi_a^* = \chi_{GC} - \arcsin\left(\frac{V_w}{V_a}\sin(\chi_w - \chi_g)\right), \tag{6.5}$$

$$V_h^* = \frac{h^* - h}{t^* - t}, \tag{6.6}$$

where $V_w \cos\left(\chi_w - \chi_a\right)$ is the wind correction term to the commanded airspeed, and the arcsin term is a wind correction term to the commanded heading [72].

The latitude, longitude, and altitude evolve in time as described by

$$\dot{\lambda}_t = (V_a \cos\gamma \cos\chi_a + W_N)/R, \tag{6.7}$$

$$\dot{\tau}_t = (V_a \cos\gamma \sin\chi_a + W_E)/(R\cos\lambda), \tag{6.8}$$

$$\dot{h} = V_h, \tag{6.9}$$

where γ is the flight path angle, approximated by

$$\gamma = \arcsin(\dot{h}/V_a), \tag{6.10}$$

and W_N and W_E are the north and east components of the wind vector.

We assume some simplified dynamics, where the airspeed, climb rate, and heading all change to the commanded values with some "inertia":

$$\dot{V}_a = (V_a^* - V_a)/J_t, \tag{6.11}$$

$$\dot{V}_h = (V_h^* - V_h)/J_h, \tag{6.12}$$

$$\dot{\chi}_t = (\chi_a^* - \chi_a)/J_\chi, \tag{6.13}$$

where the J parameters are represent the inertia.

We assume a simplified model of fuel consumption where the fuel loss rate is proportional to airspeed:

$$\dot{m}_f = P_f V_a. \tag{6.14}$$

The inputs to this model include the wind and desired position variables:

$$\mathbf{u}(t) = \begin{bmatrix} V_w \\ \chi_w \\ \lambda^* \\ \tau^* \\ h^* \\ t^* \end{bmatrix}. \tag{6.15}$$

6.4.2 Pilot Modeling

Pilots behave in different ways, and we assume that for the most part the commanded speeds and headings as computed above are followed. We consider two cases in which the pilot will take specific reactive control actions, which are represented through a change in the set of waypoints an aircraft is to follow.

The first situation is for a missed approach. We cover three versions. A missed approach, and subsequent go-around, will be executed if the aircraft is going too fast for its current altitude a specified distance from the runway, or if there is a strong crosswind preventing a safe landing. This model is incorporated into the predictions, so if the conditions for a missed approach are predicted then the prediction algorithm will predict a missed approach and the subsequent changes to the waypoints that would result from it.

The second situation is for approaching an unplanned-for convective weather region. If the pilot approaches a weather region and comes too close, then a waypoint will be added in order to travel around the convective weather cell. The waypoint selection is made reactively, so is not available to the prediction algorithm.

6.4.3 Weather Modeling

We assume that a region of convective weather is modeled as a polygon with a moving center, and with no floor or ceiling. The state of a weather region is defined by its latitude, longitude, and heading

$$\mathbf{x}(t) = \begin{bmatrix} \lambda(t) \\ \tau(t) \\ \chi(t) \end{bmatrix}. \tag{6.16}$$

We consider the inputs to be the linear velocity $V(t)$ and rotational velocity $\omega(t)$. The position evolves in time using

$$\dot{\lambda} = V\frac{\sin\chi}{R_E}, \tag{6.17}$$

$$\dot{\tau} = V\frac{\sin\chi}{R_E\cos\lambda}. \tag{6.18}$$

$$\tag{6.19}$$

6.4.4 NAS Modeling

The overall model of a given region of the NAS is composed of the aircraft models, pilot models, and weather models. The system-level inputs are the winds, weather system speeds, and waypoint sets for each aircraft. The modeling framework is general, in that an arbitrary number of aircraft and weather systems can be included. Higher-fidelity models can also replace the low- to medium-fidelity models used in this work.

Chapter 7

Summary and Future Work

National Airspace System (NAS) operations continue to grow. Although aviation safety is now at unprecedented high levels, with the expected growth in operations, additional methods are required to further boost it. Consequently, there are many efforts underway by the various stakeholders to develop technologies to improve the different aspects of operations, from building safer aircraft and improving ground infrastructure to enacting and enforcing additional rules and regulations. Our efforts take the perspective of providing additional information to pilots, controllers, and other decision makers to enable more informed decisions and preemptive actions to deal with forecast hazards.

In this report, we presented a methodology and framework for computing the *safety* of the NAS, defined by the FAA as *Freedom from those conditions that can cause death, injury, occupational illness, or damage to or loss of equipment or property, or damage to the environment.* Our approach utilizes a model-based prediction framework developed at NASA Ames Research Center. Applying the framework first requires offline analysis and modeling. The models are then utilized for (online) real-time monitoring and prediction.

Offline, we first performed a safety analysis, scrutinizing pilot and controller reports submitted to NASA's ASRS, NTSB accident investigation reports, and a variety of stakeholder reports. The result of this step was an extensive list of airspace-related, environmental, and human-related hazards, including among them such hazards as airspace congestion, convective weather, and zones of increased human workload. These hazards were then transformed into *safety metrics* – factors that measure airspace safety and can be monitored and predicted.

Next, these safety metrics were used to focus our modeling efforts. Models of airspace operations and aircraft dynamics were built. The fidelity of our models were intended only as an example of the application of the framework to monitor and predict safety metrics; higher fidelity models can be substituted as required by user requirements. For real-time assessment of whether the results of the model signify safe or unsafe airspace, thresholds were determined through analysis and consultation with SMEs. Thresholds can also be learned through data mining of archived operations data or other means.

Using this information, we are then able to monitor and predict the safety of the NAS in real time operations. In order to estimate the current level of safety, the state of the NAS must first be estimated using the dynamic models of the NAS. Given the state estimate and a probability distribution of future inputs to the NAS, the evolution of the NAS – the future state – and the occurence of hazards or *unsafe* events can then be predicted. For robustness to actual operations, which are highly stochastic, the monitoring and prediction algorithms rigorously take into account uncertainty.

We demonstrated the full framework through three case studies that compute the effects on airspace safety of *(i)* wake turbulence, *(ii)* "compression" of aircraft on final approach due to unexpected leading-aircraft pilot behavior, and *(iii)* a combination of convective weather and congestion. In the case studies, we consider the uncertainties introduced due to convective weather movement, wind speed, and pilot behavior.

We believe that our real-time monitoring and prediction framework will benefit many of the diverse NAS operators. At the small-vehicle end of the scale and occupying airspace close to the ground (mostly below 500 ft), small UAS are being utilized for pipeline, real-estate, disaster and other inspections and are being considered for package delivery. They typically do not use established airports. However, they need access to the NAS to accomplish their work and need access to flight hazards (including congestion information) that affect low-altitude operations. An application targeting small UAS may consider a subset of the hazards identified in this report, perhaps adding UAS-specific hazards not identified through the current analysis. The framework is general and can handle any hazards that can be modeled and predicted.

Next on the performance scale above small UAS are "low and slow" general aviation (GA) aircraft which typically operate between 1000 ft and 12,000 ft and at almost all airports, from very short grass or gravel fields to major metropolitan airports. (The term "aircraft" includes hot-air balloons, gliders, and helicopters.) These aircraft require only a single pilot whose capability and proficiency ranges from the recreational, sporadic pilot who flies only in good weather, to very proficient airline transport pilots who regularly make use of the ATC system. Aircraft are flown under either Visual Flight Rules (VFR) or Instrument Flight Rules (IFR). Under VFR, pilots can fly any trajectory they deem desirable as long as they remain outside restricted airspace (including controlled airspace, unless permission is received). With the proliferation of GPS navigation devices, IFR pilots often fly direct (i.e., following a great-circle route) when in uncongested and unrestricted en-route airspace. Access to a real-time prediction of safety metrics could potentially significantly reduce the accident rate, which tends to be highest in this category of NAS users, partially due to pilot capability and partially due to the hazards of low-level flight.

General aviation also includes some very capable aircraft that can fly at the "flight levels", that is, above 18,000 ft. Performance and equipage in this category can vary significantly, from 200 kt aircraft with a maximum altitude not much higher than 18,000 ft to business jets that are better equipped and can go higher and faster than most airline jets. One of the main differences between these high performance aircraft and the airlines is the flight routes. GA flights can avoid congested airline-serviced airports and, as a result, also avoid congested flight routes, providing them the freedom to select advantageous trajectories. A secondary difference is the pilot(s). Many aircraft are flown by one pilot and oftentimes that pilot is not a professional pilot who undergoes the same rigorous flight reviews imposed on airline pilots. Real-time prediction of safety metrics could assist these pilots in optimizing trajectories while avoiding hazardous situations.

The final user of the NAS that we will describe is the airlines. Except for restricted airspaces, otherwise controlled airspaces are configured to maximize safety for the largest number of the public, implying, for the benefit of the airliners. Airliners are (for now) flown by two-person professional pilots who undergo extensive training and recurrency checks. Airliner equipage has improved over the decades, incorporating many automated systems, but still varies to suit the business model of each airline. Their advanced avionics provide insight into many potential hazards. There is still room for improvement, however, with regard to prediction of safety metrics, especially predictions that help decrease the uncertainty of operations. Predictions will help flight dispatchers and/or pilots select safe and efficient trajectories; minimize larger diversions required by last-minute decisions; and anticipate large disruptions to airline operations, enabling earlier planning and more predictable operations.

In addition to the users of the NAS, stakeholders for our work are the service providers of the NAS – the controllers and traffic managers at airport control towers, TRACONs, and ARTCCs ("Centers"), as well as the ATCSCC ("Command Center") traffic managers in charge of the integrated system The controllers at the various facilities take a tactical approach to managing traffic, typically following the first-come first-served paradigm, modifying the order only when it results in greater efficiency without too adversely affecting fairness. Their first priority, of course, is safety. They must keep aircraft a certain distance apart (3 mi or more depending on circumstances), away from terrain, outside restricted airspace, and expeditiously moving toward their destination. Uncertainties in aircraft position, pilot intent, and weather movement result in greater separation distances, less efficient operations, and increased workload. Further, their narrow perspective of the situation sacrifices the end result for the immediate journey. For example, if a flight is delayed for flow management purposes, without the knowledge of the end game, one controller may shorten the flight's path only to cause additional path stretching by a downstream controller, resulting in a less fuel efficient or less safe trajectory and extra work for both pilots and controllers. Another example, a controller may keep a flight along its current path, only to cause a downstream controller to send the flight around an impermeable airspace (for instance, due to severe thunderstorms) when much closer to the issue. Predictions of safety metrics in the current NAS will allow controllers to better understand all the constraints and control traffic with downstream effects in mind.

Unlike tower, TRACON, and Center, the traffic managers at the Command Center take a more strategic view. In current operations, traffic managers need to account for considerable uncertainty in how the traffic situation will evolve. First, departure time is uncertain, due to the uncertainties of push-back (from the gate) times and taxi times. Next, the TRACON controller's approach to managing traffic add uncertainty in when a flight will reach the en-route portion. While en-route, pilots and controllers may negotiate a shorter route, faster airspeed, lower altitude, etc., to account for flight circumstances. Or dispatchers and controllers may negotiate priority for a flight. Or pilots may deviate around severe weather in unexpected ways. Once in the approach TRACON, conditions at the airport may necessitate different actions than anticipated by the traffic managers many hours in advance, introducing yet more uncertainty. Thus, flow management initiatives that are issued to deal with an expected situation may not manage the actual situation. Accurate predictions of safety metrics far enough in advance for the traffic managers to take action may decrease some of the uncertainties for a better match between anticipated and actual conditions, leading to more predictable operations without sacrificing safety.

Finally, the different safety metrics described in Chapter 4 can also be integrated into automated decision-making systems. One way to do that is to use them in forming a set of constraints that limit the space of possible solutions to a decision making problem and for composing a relevant cost function that can then be used in evaluation of the remaining candidate solutions. For instance, if the decision-making system is being designed to generate optimized routes for airliners, it may use hard thresholds on some of the metrics (such as distance from SUA, time to nearest traffic, probability of fuel exhaustion, etc) to eliminate potential solutions that do not satisfy one or more constraints, then use different safety metrics such as congestion and density in combination with other types of metrics (e.g. fuel cost, probability of departure delay) to evaluate the remaining solutions and pick one (or several) that have the best combined score.

In conclusion, the real-time monitoring and prediction of airspace safety metrics can improve shared situational awareness through automated assessment of multiple factors for potential flight routes, diminish the need for but advance the initiation of en-route diversions, and support strategic planning between users and the ATC system. Through predictive safety computation that includes rigorous handling of uncertainty, pilots and ATC controllers can receive advance warning of precursors to unsafe events. This enables preemptive actions that have a higher chance of avoiding unsafe events rather than having to mitigate them. Additionally, the computed time-to-unsafe-event can be used to improve current operations to accommodate more demand without compromising overall system safety. Further, predicted safety can be incorporated into automated decision-making tools, perhaps providing pilot-in-command capability to UAS. Finally, global/local sensitivity analysis techniques can be used to identify quantities that pertain to safety, use risk analysis methods to incorporate criticality of multiple events, and calculate likelihood of unsafe events in specific contexts.

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Appendices

Appendix A

Acronyms

ADS-B Automatic Dependent Surveillance - Broadcast

AEA Association of European Airlines

ALPA Air Line Pilots Association, International

ANSP Air Navigation Service Provider

AOPA Aircraft Owners and Pilots Association

ARTCC Air Route Traffic Control Center

ASOS Automated Surface Observation Station

ASRS Aviation Safety Reporting System

ATC Air Traffic Control

ATCSCC Air Traffic Control System Command Center

ATIS Automatic Terminal Information System

ATM Air Traffic Management

AWOS Automatic Weather Observation System

CAA Civil Aviation Authority

CASA Australia’s Civil Aviation Safety Authority

CAAC Civil Aviation Administration of China

CFR Code of Federal Regulations

DLR German Aerospace Center

EASA European Aviation Safety Agency

EICAS Engine Indicating and Crew Alerting System

FAA Federal Aviation Administration

FAR Federal Aviation Regulation

FL Flight Level

GA General Aviation

GDP Ground Delay Program

GPS Global Positioning System

GPWS Ground Proximity Warning System

IAOPA International Council of Aircraft Owners and Pilots Association

IATA International Air Transport Association

ICAO International Civil Aviation Organization

IFATCA International Federation Air Traffic Controllers' Association

IFR Instrument Flight Rules

ILS Instrument Landing System

ITSA International Transportation Safety Association

JTSB Japan Transportation Safety Board

LOA Letter of Agreement

LOS Loss of Separation

LOSS Loss of Standard Separation

LUAW Line-Up and Wait

MIT Miles in Trail

MOA Military Operations Area

NAS National Airspace System

NASA National Aeronautics and Space Administration

NATA U.S. National Air Transport Association

NATCA National Air Traffic Controllers Association

NBAA National Business Aviation Association

NDB Non-Directional Beacon

NextGen Next Generation Air Traffic Management System

NTSB National Transportation Safety Board

NWS National Weather Service

OPD Optimized Profile Descent

PAPI Precision Approach Path Indicator

PBN Performance Based Navigation

RA Resolution Advisory (as issued by TCAS)

RAA U.S. Regional Airline Association

RAPCON Radar Approach Control (military version of TRACON)

RNAV Area Navigation

RNP Required Navigational Performance

RVSM Reduced Vertical Separation Minimums

SA Situational Awareness

SID Standard Instrument Departure

STAR Standard Terminal Approach Route

SUA Special Use Airspace

TA Traffic Advisory (as issued by TCAS)

TBM Time Based Metering

TBFM Time Based Flow Management

TBO Trajectory Based Operations

TCAS Traffic Collision Avoidance System

TRACON Terminal Radar Approach Control

TSB Transportation Safety Board

UAS Unmanned Aircraft Systems

UAV Unmanned Aircraft Vehicle

VASI Visual Approach Slope Indicator

VFR Visual Flight Rules

VOR VHF (Very high frequency) Omnidirectional Range

Appendix B

Hazards

The following tables provide additional details on how each predictable hazard affects flight operations.

Table B1: Airspace: Characteristics

Hazard	Potential Issues / Comments
Obstacles near an airport	CFIT.
Active SUA (MOA, restricted, alert, aerobatics, parachute jumping)	Increased congestion. Unpredictable operations. Jumpers over airport. Jump planes descend very rapidly.
TFRs, especially near instrument approach	
Noise sensitive areas	
Training areas – Controller	Need real-time source for information on known training areas. Could also incorporate knowledge of current activities if data is available.
Airport hotspots	Identified in taxi diagrams.
Controller blind spots of airport surface	Cannot see some aircraft movements.
Similar sounding intersections (e.g., BLUZZ and BLEWS)	
Two RNAV points that are in the same in space but with different names	
Diverse traffic mix (small, large, heavy, helicopters, etc.)	
Airspace complexity – merging traffic paths	Higher workload to manage more merging paths.
Airspace complexity (number of sectors that intersect in an area	ASRS 1192232.

Sector change	Extra coordination required to assure both controllers know what aircraft near their airspace are expected to do. Added handoff workload for pilots and controllers.
Flight path precision	Increased likelihood of hitting wake if following precisely in leader's path.
Aircraft separation	Increased likelihood of wake turbulence. Could lead to: Loss of control of following aircraft. Reduced separation could occur due to: ATC technique, lead aircraft slows down for approach, following aircraft increases speed, different approach speeds of two aircraft. Existing separation standards may not be adequate as defined – out of scope for this work.

Table B2: Airspace: Airport

Hazard	**Potential Issues / Comments**
Runway – closed	Especially problematic if tower or TRACON is unaware.
Lights – inop	
Navaids – inop	
Glideslope aids (e.g., VASI, PAPI, ILS glideslope) – inop	
Communication facilities – inop	
Airport configuration – recently changed or imminent change	Could lead to 'minimal fuel if expected to take 15 min. Crew distraction programming FMS.
Airport configuration – parallel runways	Increased probability of wake turbulence due to inadequate lateral separation.
Airport configuration – aircraft taxi paths	Jet blast from aircraft parked perpendicular to runway.
Approach – changed	Crew distraction programming FMS.
Intersecting runways	Potential LOSS for double go-arounds, potential for go-around during departure.

Intersecting flight paths to/from independent runways	Example: LAS 25L/19L.
Parallel runways, especially with GA traffic in the mix	
Non-controlled airport with IFR/VFR mix.	
Proximity of arrival routes to departure routes	Via analysis or mine for pertinent areas.
Bright lights near terminal that look like PAPI	Confusing, CFTT/CFIT.
Misplaced signs or incorrectly placed signs or missing signs at terminals – known areas	ASRS 1130184.

Table B3: Airspace: Mechanical Issues (OTS)

Hazard	**Potential Issues / Comments**
Radar – OTS	
Radar – known spotty in area	
Communication frequency – known blind spots or poor in area	
Glideslope OTS	
New style bright LED runway and approach lights	Crew distraction.
Handoff (communication) equipment failure	ASRS 1192183.

Table B4: Airspace: Congestion

Hazard	Potential Issues / Comments
VFR traffic – known routes, practice areas	May be able to mine for activity areas.
VFR traffic – self-created IFR approach routes near high density arrival corridors, especially if conflicting traffic is capable of high performance climb/descent	Mine for threshold. ”Uncontrolled” instrument approaches (not coordinated with ATC or other nearby aircraft).
Unpredictable traffic nearby	ASRS 1192232.
UAS operations	
Training areas – Flight	Known congested areas, from SME or can be mined. Real-time congestion status can be determined from radar tracks. Example areas: VFR corridors, class B cutouts, traffic pattern, airways, jet routes, STARs/SIDs, navaid proximity (e.g., VORs).
Constricted airspace (lots of traffic in all directions in a small area)	Mine for threshold.
Congestion – high volume of traffic	Taxes situational awareness. Mine for threshold.
Congestion – high density (high volume, narrow corridors)	Mine for threshold.
Congestion – concentration of traffic in small volume of controller’s airspace	Traffic outside that area may get ignored. Mine for threshold.
Aircraft separation – crossing traffic at similar altitude	Likelihood of altitude loss of separation (level).
Aircraft separation – nearby climbing/descending traffic	Likelihood of altitude loss of separation (climb/descend).

Pre-departure re-routes resulting in significantly longer flight path than original	ASRS 1192182; Can affect release times as aircraft load more fuel. Could be caused by weather, closed runways, special events, etc.
Delayed takeoff	Example: almost an hour sitting in line; potential fuel issues.

Table B5: Environment: Weather

Hazard	**Potential Issues / Comments**
Weather conditions significantly worse than forecast	Fuel issues; VFR into IMC for GA; unexpected turbulence, etc.
Convective weather – enroute	Avoidance required for moderate or severe. Beware gust front and wind shear preceding a thunderstorm. En-route deviation for weather could result in fuel issues and can interfere with crew rest period.
Convective weather – near airport	Airport closure, windshear, microbursts. Could lead to comm frequency congestion due to increased communications with ATC. Could lead to missed calls due to increased communication with Dispatch (requires earlier issuance of control instructions). Comm congestion and comm issues can be inferred based on number of flights and amount of maneuvering, but can it be measured?
Convective weather – embedded	Inadvertent entry due to difficulty of seeing it.
Convective weather – developing	Severe turbulence if near the tops of rapidly developing area of convective weather.
Convective weather – line of storms	In-flight re-routing on the wrong side from destination airport of a solid line of thunderstorms could lead to fuel issues.
Hail	Structural damage.

Rain – moderate	Downdrafts, engine out, wet runway, hydroplaning.
Icing – enroute	structural icing (performance, increased stall speed, incorrect airspeed indications [pitot icing]).
Icing – on takeoff	Damaged engines, compressor stalls.
Icing – of runway	Runway excursion.
Turbulence – low level, near airport	
Turbulence – enroute,	Especially if severe or with significant updrafts or downdrafts.
Turbulence – mountain wave	
Turbulence – rotor	
Turbulence – clear air	
Wind – surface, strong	Available via SIGMET. Turbulence.
Wind – surface, tailwind	Longer runway required (ex: 15 kts max).
Wind – surface, crosswind	May lead to loss of control by exceeding aircraft or pilot ability.
Wind – surface, crosswind on parallel approaches	Traffic may overshoot final approach course.
Wind – approach, tailwind	Difficult to get stabilized approach. May require too steep a descent gradient to meet crossing restrictions.
Wind – enroute, tailwind	At least one operator specifies that pilots slow down when tailwinds are strong (ex: 135kt), causing additional vectoring to let others on same route pass.
Wind – enroute, headwind	Fuel issues.
Wind – approach/surface, windshear	Must protect for go-arounds; one example: +25 kts.
Wind – microburst	Downdrafts of 100 kts vertically possible. Immediate go-around required. (6000 fpm in a 1mi, 1000’ area.)
Wind – updrafts / downdrafts	Altitude deviation of own aircraft or nearby aircraft.
Visibility – VMC	Increased risk of NMAC, especially if SCT clouds, due to VFR and IFR traffic mix. Increased complacency.
Visibility – low IMC	Missed approach, CFIT. Could be caused by haze, fog, volcanic ash.

Temperature – low	Runway or taxiway ice. Also, potential incorrect altimeter setting if cold-ops procedures for correcting barometric altitude ignored.
Temperature – high	High density altitude, reduced performance.
Temperature – extreme	Aircraft systems may fail.

Table B6: Environment: Time of Day / Time of Year

Hazard	**Potential Issues / Comments**
Night	More difficult to see obstacles or terrain if VFR or on visual IFR approach. More difficult to avoid convective weather.
Early morning	Very early ops contribute to fatigue.
Sun angle – Low	Controller looking into the sun, pilot landing into the sun.
Animal (bird, other) activity	Time of day and seasonal effects.

Table B7: Environment: Animals, FOD, Other

Hazard	**Potential Issues / Comments**
Birds en-route or around airport	Relevant safety metrics: location, direction of travel, and speed of flock. Can get from real-time reports from pilots, from radar, from airport perimeter motion sensor alarm. Also safety metric: likelihood from seasonal patterns. Can cause structural or engine damage.

Animals (non-bird) on airport	Safety metric: likelihood from seasonal patterns. Can cause structural or engine damage.
FOD on runway	Can get from runway FOD sensor alarm.
Wake turbulence	Can lead to loss of control.
Volcanic ash	Visibility restrictions and can cause engine problems.

Table B8: Human: Workload

Hazard	**Potential Issues / Comments**
Multiple speed changes on approach	Disruptive to pilots, especially of unequipped aircraft.
Multiple runway changes on approach	Too time consuming to reprogram FMS.
Complex descent via RNAV clearances	Increased workload, especially for aircraft without VNAV and auto throttles.
Excessive vectoring for weather	
Avoiding convective activty en route	Increased fatigue.
Low traffic and infrequent radio transmissions	Increased complacency.
Emergency/non-nominal situations	E.g., Disabled aircraft. Can lead to increased pressure. Some airspace may be available only to the disabled aircraft.
Required procedures (tasks)	Increased crew workload due to required tasks during a flight phase (e.g., setting up for an instrument approach).
Aborted approach (botched approach)	Potential fuel issues. Added workload.
Coordination between sectors or facilities, especially in terminal airspace	Increases workload, multi-tasking.
Coordination between sectors, in en-route airspace	Increases workload, multi-tasking.
Number of restrictions (like MIT to an adjoining Center)	Increases workload.

Communication issues (multiple languages, lack of command in English, multiple frequencies, etc.)	Increases attention required.
Excessive delaying vectors for congested airspace (or for disagreeing with controller)	Potential fuel issues (Safety metric).
In-flight re-routing, especially multiple or distant re-routes	Potential fuel issues to fly new route (Safety metric).

Table B9: Human: Operations

Hazard	**Potential Issues / Comments**
Incorrect operations/procedures	Second-in-command capability evaluates deviation from expected (current and control of): airspeed, altitude, heading/navigation; Examples: Pilot deviation from explicit or implied clearance (standard operating procedure). Climbing too slowly to clear terrain ahead; Descending too slowly to meet crossing restriction; Descending too low for obstacles in area (below minimum safe altitude); Descending below approach minimums; Descending below decision altitude; Deviating from approach procedure; Unstabilized approach – too aggressive a descent, high sink rate.

Appendix C

Incidents and Accidents Reported in ASRS and NTSB Databases

C.1 Extracting Safety Factors from Controller ASRS Reports

Surface Issues

- Cognitive: Lost SA, multitasking: 1197092: controller forgot about aircraft that is departing; clears another aircraft to cross same runway; meanwhile, another aircraft is on final for same runway. Distracted by making ATIS recording.

- Cognitive: Fatigue/understaffing: 1196529: Controllers on shift for too long, mistakenly clear aircraft to depart on closed runway. Everyone involved forgets runway is closed, including pilots who initially requested the closed runway.

- Cognitive: Understaffing: 1193526: One controller was working tower, ground, flight data, clearance delivery. Traffic was 2 jets in local pattern, 4 airport vehicles on Ground frequency with 3 vehicles on an active runway.

- Airspace: 1195892: Hot spots on airports contribute to runway incursions, causing go-arounds (ex: DEN 17R).

- Cognitive: Anticipated separation: 1194087: tower clears flight to LUAW when another flight is on very short final, but not yet past the departing flight.

- Cognitive: Distraction: 1192249: Pilot distracted with checklist items misses turn and ends up crossing hold short line for runway without clearance.

Terminal Issues

- Environmental: Precip, turbulence:1197077: windshear, microbursts, heavy precipitation (and resulting turbulence) caused autopilot to disengage & aircraft to deviate into non-transgression zone for parallel approach.

- Cognitive: Congested airspace: TCAS RA turned safe situation unsafe: 1195620: air carrier at 4000, VFR traffic at 3500 and another at 4500 , both opposite direction. TCAS issued RA to climb to avoid the 3500 guy, putting air carrier at 4400 with 4500 VFR oncoming traffic.

- Cognitive: Congested airspace and airspace structure: 1195320: SoCal TRACON allowed to climb flights into airspace owned by ZLA (per LOA). TRACON did not see the VFR traffic; flight got TCAS RA to descend to avoid traffic.

- Cognitive: Congested airspace, controller workload: 1194076: weather delayed arrivals into the short-staffed midnight shift; mx went ahead with planned work even though there was lots of traffic; bad comm with pilots (who were talking with dispatch) and tower (who switched airport config without adequate comm to everyone involved).

- Cognitive: complexity: 1194035: two arrivals, a departure, sky diving operation, and a VFR flight following target at same time as an aircraft departs later than his void time & conflicts (LOS) with arriving aircraft. Airspace should have been protected for departing aircraft by slightly vectoring arriving aircraft.
- Cognitive: ATC coordination: 1193516: different interpretations of procedures between TRACON and tower lead to controllers getting upset on handoff.
- Environmental: weather: 1192247: Level 4-6 thunderstorm cell on departure path.
- Environmental: ceiling AND Cognitive: ATC-to-ATC coordination: 1192225: VFR aircraft descended (with clearance from TRACON) into airport airspace to remain VFR (ceiling), had a NMAC with departing aircraft (with clearance from tower). Tower and TRACON coordinated, but not well.

En-Route Issues

- Environmental: Icing: 1195614: multiple helicopters on a similar mission affected by icing, unable to maintain altitude; in the mountains; loss of SA, confusion, bad communication.
- Environmental, weather deviation into SUA: 1195051: between a rock and a hard place.
- Pilot deviation: 1195324: flight cleared at FL360 was actually flying at FL380 as reported by ADS-B and later confirmed by pilot. Pilot was initially saying he was at FL360, the cleared altitude.
- Cognitive: SA & Airspace: SUA: 1195052: ATC forgot Warning area was active & transitioned flights into it without coordination with RAPCON.
- Cognitive: congestion: 1193812: 3 IFR aircraft handed off to adjoining sector without adequate coordination and spaced too close to each other.
- Cognitive: Congestion: 1193796: Two VFR aircraft nearby airport doing practice ILS approaches, one controlled by TRACON and one by the tower (unbeknownst to each other).
- Cognitive: Coordination: 1193795: Aircraft were re-routed without complete coordination of all parties (controllers) involved in the multiple (adjoining) sectors, leading to LOS. Making decisions without all the information.
- Cognitive: Congestion: 1192232: conflict in area of sector not as populated as where center of attention was with moderate traffic in middle of sector.
- Environmental: Turbulence: 1192232: frequency congestion due to traffic volume and ride conditions

Unsafe Situation Indicators

- Airspace deviation
- Loss of separation
- Accidents
- Go-around
- Aborted takeoff

Features - Predictable

- Active SUA
- Congestion - high volume of traffic
- Congestion - high density (high volume, narrow corridors)
- Congestion - concentration of traffic in small volume of controller's airspace (traffic outside that area may get ignored)
- Inadequate staffing
- Convective weather
- (Favorable PIREPs can be used to decrease extent of weather impact; ASRS 1192247)
- Windshear - must protect for go-arounds
- Icing
- Airport hotspots
- Potential double go-around on intersecting runways
- VFR traffic (known routes, known practice areas; may be able to mine for activty areas)
- Coordination between sectors or facilities, especially in terminal airspace
- Coordination between sectors, in en-route airspace
- Airspace complexity (number of sectors that intersect in an area; ASRS 1192232)
- Congestion plus weather (turbulence) – comm frequency congestion
- Unpredictable traffic nearby (ASRS 1192232)
- Amount of student traffic (ASRS 1192220)
- Handoff (communication) equipment failure (ASRS 1192183)

- Reroutes resulting in significantly longer flight path than original (ASRS 1192182) (can affect release times as aircraft load more fuel)
- Number of restrictions (like MIT to an adjoining Center)
- Pilot deviation from clearance (match flight path to clearance; predictable perhaps at coarse granularity)

Features - Not Predictable

- Fatigue/staffing
- Multi-tasking
- Technique (e.g., anticipating separation when issuing LUAW instruction)

Revealing Quotes

- The controller working both aircraft was busy with successive arrivals and the potential for operational errors rose drastically.
- Complexity increased at JAC with two arrivals, a departure, a VFR sky diving operation, and possibly another VFR flight following target.
- Aircraft were able to pick their way through (weather) but we needed to reduce volume to help with complexity.
- Monitor Alert is not being watched for areas that have volume issues.
- Towers are calling to cancel release times because aircraft need more fuel to fly the new routes.

C.2 ASRS: Bird or Animal Strikes

Surface Issues

- Environmental: Animal damage to aircraft: 1177530: An EMB-145 First Officer refused to fly an aircraft after he saw a mouse disappear under the First Officer's instrument panel. The aircraft flew a round trip with another pilot and then was removed from service.

Terminal Issues

- Environmental: Bird strike (structural): 1138617: C210 pilot reports striking at least one Canadian goose at 1700 feet after takeoff. The windscreen is badly damaged but neither front seat occupant is injured. The flight returned to the departure airport.
- Environmental: Bird strike (propulsion): 1137650: Bird strike (likely geese) disabled one engine of a B737-300 on take-off. Significant damage to the leading edge of the wing also occurred. Flight returned safely to departure airport.

- Environmental: Bird strike (structural): 1117541: C172 windshield shattered due to bird strike. Pilot and passenger injured, but able to land at the planned destination airport.

- Environmental: Bird strike (propulsion): 1115153: Tower controller described a momentary loss of MVA separation when an air carrier departure experienced an engine bird strike, entered a wide down wind, and returned to the airport.

- Environmental: Bird strike (propulsion): 1113186: B737 ingested a goose at V1 during takeoff. Loud compressor stalls are heard from the left engine. Captain assumes control at approximately 100 FT AGL, but the positive rate call is not made and the gear is not retracted. After the engine is shut down the gear is noticed and retracted. Flight returns for a single engine landing.

- Environmental: Bird strike (sensor): 1099087: HS125 captain experiences unreliable airspeed indication climbing through 3500 ft resulting in an overspeed upon leveling at 8500 FT. Post flight reveals that a small bird may have impacted the pitot tube.

- Environmental: Bird strike (controls): 1050685: A commuter departure encountered a flock of circling birds, one of which was struck by the right wing damaging the slat system. The flight crew declared an emergency and diverted to a nearby airport.

- Environmental: Animal strike (runway): 1108430: C172 pilot performing night landings reports hitting a coyote at touchdown causing the right gear to break off and the aircraft to depart the runway.

En-Route Issues

- Environmental: Bird strike (propulsion): 1045876: B757-200 flight crew reported they struck a large bird or birds, possibly Canadian geese, while climbing through 15,000 feet. With indeterminate damage to nose and right engine, they declared an emergency and returned to departure airport.

Unsafe Situation Indicators

- Go-around

- Aborted take-off

- Rapid descent

- Unanticipated evasive maneuvers

- Unanticipated decrease in airspeed

- Loss of separation

Features - Computable

- Location, direction of travel, and speed of large flocks of birds
- Likelihood of bird activity at altitude based on pilot reports or radar
- Likelihood of bird activity in the vicinity of an airport based on seasonal patterns, time of the day, etc
- Likelihood of animal activity in the vicinity of an airport based on seasonal patterns, time of the day, etc
- Runway FOD sensor alarms
- Airport perimeter motion sensor alarms

Features - Not Computable

- Extent of the damage (from bird strike, etc)
- Presence of animals on the runway (true/false)
- Extent of damage to aircraft systems from rodents and similar animals on the ground

Revealing Quotes

- Report 1033063: An MD-83 hit a flock of seagulls on takeoff damaging the right engine, but the flight returned to land with both engines running. The Captain felt stressed by post flight notifications and paperwork.
- Report 1115153: "While this situation was going on, there was an extreme amount of **coordination** for both the Local Controller and the Ground Controller. I feel that in the RADAR room, there should be a designated person who is doing all the coordination with the Tower, instead of different people calling at different points for different reasons. Also the Local Controller had not been tested or briefed on the MVA in the area before his certification, in the event of the emergency I feel we both did a good job of getting the proper assistance to the aircraft."
- Report 1172873: "On the way back to my home airport, I heard a loud bang and using a flashlight I realized that I had hit a bird. This caused a massive increase in pilot workload. I continued my flight to my destination and there seemed to be no control issues on the aircraft. Due to the **increased workload** I forgot to complete the decent and landing checklists. This caused the mixture and boost pump to remain in the cruise setting."
- Report 1113186: We saw the geese approximately 150 yards prior to impact. I was very concerned about ingesting multiple birds in at least one engine, and I continued to watch them until we hit them. The geese remained sitting on the runway until we were almost on top of them, when two or three flew up and towards the Captain's side of the runway. This **distraction**caused me to not make the rotate call. At very close to

rotate speed, I felt multiple impacts with the plane's left side, followed immediately by loud, continuous compressor stalls, and accompanied by erratic engine indications on the number one engine.

- Report 1016862: The two largest obstacles with this emergency was **dealing with distractions** and **prioritizing**. I believe that I should have communicated more clearly with ATC initially to avoid further distractions. I should have let them know that we needed radio silence and they were distracting by asking for unnecessary information. Another possible solution could have been to turn the radio off altogether. If I had buried the distraction of ATC early on, I believe that I could have communicated and listened much better with my First Officer and flight attendants. I could have devoted the initial climb out phase to helping the First Officer fly the aircraft rather than diverting attention to unnecessary ATC things.

C.3 Extracting Safety Factors from Commuter and Corporate Fatigue ASRS Reports

Surface Issues

- Cognitive: management pressure, insufficient staffing: 1195312: One of the bolts that secure the Tail Rotor Control tube on a Bell-206L helicopter not tightened. Technician noted that pressure from supervisors to get the job done and the use of pilots to look over major maintenance work accomplished by mechanics were contributors.
- Cognitive: complacency, insufficient staffing, lack of adequate procedures: 1130027: Four AMT reports about working conditions at an FAR 135 repair facility that included fatigue, complacency, the lack of an Inspection Department and the lack of adequate maintenance procedures that eventually led to one of their pilot's performing a precautionary landing of a Bell 206L helicopter.

Terminal Issues

- Cognitive: fatigue: 1181675: G200 flight crew reports getting very low during a night visual approach after a 12 hour duty day and five legs. The Captain recognizes that he is only 500 FT above the field elevation at the same time the tower issues a low altitude alert.
- Cognitive: fatigue: 1180378: A fatigued flight crew landed at CMH during late night operations without clearance. Fatigue and distractions including bright LED approach lights and a lull due to the lack of frequency activity.
- Cognitive: fatigue: 1165981: C172 pilot reports a NMAC with another pilot in the traffic pattern due to mistakenly entering right traffic for Runway 1 while attempting to join left traffic for Runway 19.
- Cognitive: fatigue, inattention: 949134: A crew flew the VGC RNAV Z Runway 17 LPV approach, descended below the vertical path and received a terrain warning because they did not realize the approach was not a RNAV GPS LNAV approach.

- Cognitive: fatigue, inadequate CRM procedures: 998731: A CE560XL departed on the TEB RUUDY 4 SID and failed to level at 1,500 FT because of confusion, fatigue and the First Officer not calling the aircraft approaching the level altitude.

- Cognitive: fatigue, illness: 1056821: A turboprop pilot requested 360 gallons of fuel departing Canada but was fueled with 360 liters instead. This error was confirmed when airborne and the reporter diverted for fuel. Illness, fatigue, and maintenance delays were cited as factors.

En-Route Issues

- Cognitive: Toxic substance exposure: 1191512: A mechanic tasked with a 1.5 hour C208 deadhead flight felt ill, developed an intoxicated feeling, a sore throat, burning sinus and headache following prolonged TKS fluid exposure during the flight.

- Cognitive: fatigue: 1180378: EMB110 Captain reports departing without checking the fuel, causing both engines to quit enroute. A successful dead stick landing on a 2,500 foot runway is accomplished with only the main gear tires the worse for wear.

- Cognitive: distraction: 976008: An SA227 Pilot suffered an altitude excursion when the autopilot failed to maintain his assigned altitude. The pilot's immersion in a book prevented earlier detection of the autopilot's failure to do his job.

- Cognitive: fatigue, excessive workload, inexperience: 1083692: A DA-50 annunciated TRIM and MISTRIM while climbing to 11,000 FT and so the autopilot did not automatically capture the altitude, but overshot by 800 FT. Fatigue, task saturation and inexperience were all elements in this event.

- Cognitive: fatigue, coercion: 992723: An HS-125 Captain for a fractional operator alleged coercion of some pilots to fly fatiguing schedules and preferential treatment for others to avoid the same, resulting in flight crews being compelled to fly when not fit to do so.

- Cognitive: fatigue: 980747: G150 Captain reports being assigned 11,000 FT by Departure Control but setting 12,000 FT in the altitude select window. This is detected passing 11,400 FT but 12,000 FT is reached before the climb is stopped. Fatigue and a very high climb rate were cited as factors.

- Cognitive: fatigue, coercion: 1007581: A C560XL Captain for a fractional operator addressed debilitating scheduling practices that force flight crew members to refuse flights due to fatigue or to accede to them and risk violation of regulations requiring they fly only when fit for duty.

Unsafe Situation Indicators

- Misunderstood clearances

- Altitude deviations

- NMAC (near mid-air collision)
- CFTT (controlled flight toward terrain)
- Fuel mismanagement
- Miscommunications
- Inadequate crew situational awareness
- Unexpected control inputs
- Wrong runway or taxiway used
- Delayed communication responses

Features - Computable

- Staffing level
- Crew rest period between flights
- Crew duty hours
- Crew level of experience (hours in the type, hours PIC, etc)
- Crew currency in the type

Features - Not Computable

- Crew fatigue level
- Crew wellness
- Adequacy of corporate procedures
- Management pressure and coercion
- Company culture
- Distractions / inadequate CRM
- Crew workload level

Revealing Quotes

- 1015350: “My crew was briefed to do ”ready spare” beginning at 2100E ending at 0400E. (Interestingly enough, the evening before the tentative brief was ”ready spare” from 1900E to 0200E, but after I **fatigued** the night before the brief changed to 2100E to 0400E ”ready spare.” There is no doubt in my mind that this was changed as **“punishment”** for having called in fatigued. Confirming evidence to this was that upon arrival at the airport that evening, there were no scheduled flights out after our arrival.”

- 1007581: “Specific recommendations: 1) **use available fatigue abatement software to force scheduling into a safer operation. Build in constraints for duty time and rest periods based on normal wake/sleep cycles.** 2) When crews advise that the planned rest/duty cycle doesn’t look doable, require an immediate review of the situation by a flight operations supervisor to determine if this is the best available plan. Lip service of ”do your best” isn’t adequate. 3) Give a greater heads up on planned duty times for Day 1. Getting a brief at 1800L the night prior doesn’t allow any [necessary sleep/rest cycle] modifications to be made for early or late operations.”

- 989705: “I am not sure why I missed this very important step, but I did. It may have been the unwinding effect of finishing up a sixteen hour day. It might have been the time of day. It might have been the pressure to close out our duty day before our normal one hour duty on the ground. **It probably was a bit of the three.**”

- 976008: “I fully understand the gravity of the situation. Had there been traffic or any other number of things the results could have been bad. Going forward I have realized the need to **eliminate distractions in the cockpit**. I had only recently started to read in the cockpit in an effort to help keep my brain active so as to avoid being overly drowsy or tired during the long cruise, something that naturally occurs with such long overwater flights with **little external stimuli**.”

- 1099042: “Because the pilot not flying was younger than I, with less total time, and because I was the “Captain”, I feel that he deferred to me, even though he knew I was not correct. **Neither of us thought to call ATC to resolve the confusion**. This may be due to the fact that we were both **fatigued** and **anxious to get home**.”

- 992723: “Management’s practice of calling people into Headquarters about **fatigue** calls has also created a **social stigma** among the pilot group where, if one deviates from the statistical average of fatigue calls, he/she is deemed an ”abuser” of the policy. Because our company is an unscheduled operation and pilots cannot bid trips ahead of time, Schedulers often give certain pilots “preferential treatment” with their schedules thereby skewing the fatigue numbers. This helps the company justify that only a few “abuse” the fatigue policy by giving just a few the most “fatiguing schedules.”

C.4 Extracting Safety Factors from Near Mid-Air Collision Event (NMAC) ASRS Reports

Surface Issues

- Not applicable

Terminal Issues

- Cognitive: Congestion: 1183676 : Aircraft under radar vectors for practice approach flew too close above VFR aircraft in known congested area of flight training. Radar alert prompted controller to issue a climb, perhaps later than he should have.

- Cognitive: Clearance adherence: 1182746 : IFR aircraft departed rwy 16 and turned left per clearance. VFR aircraft departed rwy 11 previously and turned right, against standard procedure of straight out or left turn out from that runway.

- Cognitive: Clearance Adherence: 1179561 : Arrival aircraft did not follow arrival procedure and nearly collided with departing aircraft following departure procedure from same airport.

- Cognitive: Clearance Adherence: 1178663 : (Student) Pilot overshot turn to final and conflicted with traffic on parallel runway.

- Cognitive: Clearance Adherence: 1170587 : VFR pilot climbed into IFR aircraft. The two aircraft were talking to two different controllers. The VFR aircraft was not cleared to climb; it was given an altitude 500' than the inbound IFR aircraft.

- Cognitive: Clearance Adherence: 1176553: IFR aircraft not practicing see & avoid on visual approach. ATC had no altitude readout for aircraft; airliner saw altitude (and potential collision) on TCAS yet continued toward collision.

- Cognitive: Clearnace Adherence: 1171767 : Aircraft cleared to land did touch-and-go instead. (Opinion: Aircraft may have to do a go-around on any approach, so the controller was also at fault for not thinking it through all the way.)

- Cognitive: Unexpected behavior : 1171744: Aircraft on VFR flight following descended, then unexpectedly climbed back up to cancel flight following. Weak radio reception at lower altitudes.

- Cognitive: Congestion: 1181742 and 1174533 and 1173647: ATC called out VFR traffic 500' above to airliner. TCAS indicated 400' separation. Airliner descended to increase separation.

- Cognitive: Inexperienced controller, distraction, complacency: 1181401 and 1172405: Two VFR aircraft. One was getting radar vectors to approach. Other was departing. Controller misjudged closure rate and was distracted reviewing the approach plate. Pilot believes controller was inexperienced. Airport used for training new controllers because it's not busy. Complacency due to CAVU weather and not much traffic.

- Cognitive: Congestion: 1181389: Multiple sectors combined, no D side. Busy sectors. Approach controller was working 3 IFR aircraft heading to airport, near tower quiting time. Airport tower closed while first was on approach (meaning airport airspace becomes one in, one out.) VFR traffic pointed out to first IFR aircraft, but aircraft released to CTAF before pilot had traffic in sight.

- Airspace: Structure : 1180101 : VFR GA aircraft overtaken by air carrier on approach at 8500'. Air carrier crew took no evasive maneuvers.

- Airspace: Structure : 1178698 : VFR aircraft on self-made practice approach not yet talking to tower nearly collides with departure.

- Cognitive: Procedure? : 1172902 : Two aircraft flying practice approach into same airport, not talking on the radio enough to coordinate with each other or another aircraft in the pattern for the opposite direction runway.

- Environment: Noise : 1176434 : Noise complaints around the airport are causing helicopters to fly close to pattern altitude, causing increased collision risk with fixed wing aircraft.

- Airspace: Congestion, structure? : 1174905 : Inbound aircraft comes head on with aircraft setting up for an approach in same area (4-5 nm from airport). Moderate traffic, but no holding outside class D.

- Airspace: Procedure? : 1174904 : NMAC with UAS flying at 800' within 1.5 mi from airport.

- Cognitive: High workload : 1172998 : Controller had high workload, dropped the ball in separating parachute jump plane from traffic he was not talking to. Reason he was not talking to other plane was poor radar coverage results in late handoffs in that area, making it easy for both controllers to lose track of planes in that area.

- Cognitive: Procedure : 1172931 : Two VFR aircraft setting up for landing came very close. One aircraft was not making frequent radio calls.

- Airspace : TFR near instrument approach : 1172042 : Aircraft on ILS came very close to firefighting aircraft departing a fire TFR.

En-Route Issues

- Not applicable.

Unsafe Situation Indicators

- TCAS TA alert
- TCAS RA advisory
- Evasive action
- Loss of Separation
- Go-around
- Missed approach

Features - Predictable

- Known congested area of flight training
- Known area of controller training
- Pilot deviation from explicit or implied clearance (standard operating procedure)

- Nearby crossing traffic close enough in altitude to trigger TCAS advisory
- Nearby climbing/descending traffic climbing/descending at a rate that triggers immediate response required TCAS advisory (no precursons)
- Complacency due to CAVU weather
- Complacency due to low traffic
- Non-controlled airport with IFR/VFR mix
- VFR aircraft on IFR approach route (high density arrival corridors), especially high performance climb/descend conflicting traffic
- Constricted airspace (lots of traffic in all directions in a small area)
- Parallel runways, especially with GA traffic in the mix
- Noise sensitive areas
- UAS operations
- Congested airport area, taxing good situational awareness
- Unusual operations, such as parachute jumping (jumpers over airport plus jump planes descend very rapidly)
- Spotty radar coverage in area
- Spotty radio coverage in area
- Uncontrolled instrument approaches (not coordinated with ATC or other nearby aircraft).
- TFRs near instrument approach
- Sector change (extra coordination required to assure both controllers know what aircraft near their airspace are expected to do)
- VMC
- VMC with SCT clouds.

Features - Not Predictable

- Controller technique (miscalculating closure rates)
- Controller on position for extended time (2 hrs 48 min) without a break
- Pilot error (not querying controller when confused by situation)

Revealing Quotes

- None.

C.5 ASRS: Air Carrier (FAR 121) Flight Crew Fatigue

Constraint themes: Environmental, Mechanical, Cognitive

Surface Issues

- Cognitive: ACN 1130184: A crew entering the cargo ramp at night nearly turned onto the old Taxiway BB because the taxiway signage was located near the old taxiway and there were no Xs painted on the old taxiway indicating it was closed.

- Aircraft: ACN 1106510: After a return to gate for a previous maintenance issue, the flight attendants notice fluid streaming from first engine. Maintenance wants to board, because they are trying to avoid a "timing out" of the flight attendant crew, near end of their duty time limit.

- Cognitive: ACN 1103273: A very early morning's pilot crew misread instructions and mis-programmed the FMS because of fatigue and circadian rhythm effects.

- Cognitive: ACN 1094452: First Officer describes errors made during taxi out and takeoff from JFK after a continuous duty overnight, during which minimal rest was obtained.

Terminal Issues

- Cognitive: ACN 1170226: At Kansai International Airport, ATC suggestions were misinterpreted by the captain, due to discrepancy in instructional/procedural charts/publications, and also due to fatigue and sickeness (caused due to cold, for both the pilots). The pilots claim that the procedures were explained very poorly.

- Cognitive: ACN 1165552: Pilot lands without clearance due to being fatigued (in general, there are quite a few reports of landing without clearance).

- Cognitive: ACN 1158337: Pilots assume that they received clearance for landing, but the tower says otherwise.

- Cognitive: ACN 1154201: B737 flight crew laments ATC handling of an approach to Runway 19R at SFO and a NMAC with an Airbus on the Runway 19L approach.

- Airspace: ACN 1154057: A321 Captain describes a trip paring assignment that does not meet the new FAR 117 rules and the lack of any guidance from the Chief Pilot's Office.

- Cognitive: ACN 1152927: Airline scheduling contains no rest possibility during a normal sleep cycle.

- Mechanical: ACN 1151981: Multiple factors assailed the flight crew of a B767-300ER which resulted in flawed performance data and a tail strike on takeoff due to a planned takeoff gross weight much below the actual.
- Weather: ACN 1150371: Captain reports being intimidated by his duty Manager into accepting a two hour extension to his duty day under FAR 117 without the Captains consent, necessitating a fatigue call. This had to be done in order to mitigate certain weather challenges.
- Weather: ACN 1149011: Captain describes a long duty day caused by two de-icings and maintenance. The flight eventually departs from a slushy runway with snow falling. During descent for landing the spoilers will not deploy symmetrically and the handle is stiff. Upon landing a main gear tire fails immediately. Frozen brakes are suspected.
- Cognitive: ACN 1111719: Captain is fatigued and a last minute runway-change instruction is very confusing and he gets very exhausted.

En-Route Issues

- Cognitive: ACN 1167986: Captain becomes unresponsive to ATC and hands over control to First Officer.
- Cognitive: ACN 1162404: Relief pilot shows up fatigued for a flight, and "expects" to get a break for the first six hours (apparently, a standard for relief pilots). But the captain has a different say since he wants a continous sleeping period of 6 hours, instead of the standard 2 sleep-sessions of three hours each.
- Cognitive: ACN 1150036: EMB-145 First Officer contends that company policy regarding the two hour flight time extension under FAR 117.19 is incorrect and that pilots who do not comply are unfairly pressured to accept flights.
- Mechanical: ACN 1145963: Shortly after takeoff, a B737-800 left engine had two compressor stalls, so an emergency was declared, the QRH completed and the flight returned to the departure airport.
- Mechanical: ACN 1143167: After an all-night turn-around, pilots received flap configuration warning. There was confusion regarding whether the conduct of the approach was optimum.
- Mechanical: ACN 1142138: A B747-400 flight crew dumped fuel and returned to their departure airport after experiencing compressor stalls and eventual failure of the number one engine.
- Mechanical: ACN 1139039 :A CRJ-900 First Officer believes fatigue was a primary contributor to his willingness to concur with the Captain that a cargo door warning light discovered just prior to takeoff was a false warning and acquiesce to continuing the flight. The door opened on rotation and the flight returned to the airport and the gate for maintenance.

- Mechanical: ACN 1131086: Inadvertent operations leading to excursion from assigned altitude - fatigue was cited as reason.

- Airspace: ACN 1123215: Carbon monoxide poisoning renders the pilot and first officer physically and mentally sick, and unfit for flying.

- Mechanical: ACN 1113455 : Did not pay sufficient attention to EICAS (Engine alerting and crew alerting system).

- Cognitive: ACN 1111985: Pilot is asked to make a round due to a cat on the runway, and when he comes back, he goes to a nearby airport (Chicago).

- Environment: ACN 1109148: Fatigued crew, after a 12 hour flight and avoiding typhoon weather, failed to reset their altimeters in a timely fashion. As a result, they descended below their cleared altitude.

- Environment: ACN 1108392: In the presence of turbulence and rain, the flying captain inadvertently selects wrong flying options due to fatigue.

- Environment + Aircraft: ACN 1104057: Crew goes crazy because of an inoperative autopilot, and being forced to maneuver in extremely critical weather conditions, ultimately leading to diversion.

- Airspace: ACN 1103276: Two aircrafts were directed to enter into the same “hold” area. Rapid sequential commands prevented collision.

- ACN 1097909: Even after receiving alert from Tower, Captain elected to continue the approach contrary to company guidelines and First Officer recommendation.

- ACN 1097785: Extreme workload of a two man flight crew operating nearly 8 flight hours at night between the Middle East and Asia while communicating with controllers in poor English, at times on two frequencies.

Unsafe Situation Indicators

- Instructional/procedural charts being misinterpreted
- Confusion due to various policies regarding operation
- Landing without clearance
- ATC/Tower instructions not being understood or incorrectly assumed
- Pilots being pressurized into working late, into “unsafe” hours
- Alerts on EICAS (Engine indicating and crew alerting system)
- Bad weather (usually amplifies other factor significantly)
- Multiple aircrafts in the same “area”
- Crew misreading instructions and incorrectly programming the flight systems

- Circadian rhythm disruptions
- Failing Flaps
- Communication issues (multiple languages, lack of command in English, multiple frequencies, etc.)
- Single relief pilots for long flights (E.g. 1097760)

Safety Factors - Predictable

- Misinterpretation of instructions that may happen due to fatigue/sickness
- Navigation Deviation
- Altitude deviation resulting in clearance issues
- Fatigue/tiredness
- Pilots are not happy with company policies (involving scheduling rest times, operating flights, staffing)
- Insufficient and irregular lay-off times for pilots

Safety Factors - Not Predictable

- Instructional/Procedural charts lacking clarity of explanation.
- Crew becoming unresponsive
- Certain company policies not giving safety priority (E.g., ACN 1154057)
- Increased Pressure under emergency/non-nominal situations (E.g., ACN 1145963)
- Unanticipated or miscalculated fatigue
- Incorrect inspection and/or mistaking alarms to be false alarms (e.g., ACN 1139039)
- Misplaced signs or incorrectly placed signs or missing signs at terminals (e.g. ACN 1130184)
- Under bad weather, the effect of fatigue is amplified and pilots tend to make more mistakes (E.g. ACN 1108392)
- Inappropriate directing of aircrafts (E.g. ACN 1103276)

Revealing Quotes

- ACN 1162404: I was absolutely exhausted since the standard and anticipated rest break was callously changed to accommodate the captain's desires.
- ACN 1158337: The captain and I were very exhausted and we were both positive we were given landing clearnace, but that was obviously not the case.
- ACN 1154201: They say a mishap is generally the result of a chain of circumstances. If so, these are the nineteen linked events that led to our near mid-air collision. None of these are errors; they are circumstances that colluded against us.
- ACN 1145259: Fatigue from an early morning out and back combined with coming off afternoon flying previously was more significant than I thought it would be.
- ACN 1102409: Deadhead flight evening before was delayed due to weather. Hotel air conditioning system broke during middle of night. After late arrival I woke up after only 5 hours of sleep due to excessive heat in the hotel.

C.6 ASRS: Altitude Deviation Incidents

Surface Issues

- Mechanical: ACN 1196194: Crew unable to make a charted crossing restriction during departure, when they were distracted by wake vortex encounter from the preceding B737.

Terminal Issues

- Mechanical: ACN 1196682: First Officer describes an FMS anomaly, that will not allow runway to be changed.
- Cognitive: ACN 1191564: Tower Controller reports of an inbound aircraft and had two low altitude alerts while on final.
- Cognitive: ACN 1188436: Tower Controller reports about an aircraft clearance that is confusing when using the "Climb Via" phraseology.
- Environmental: ACN 1188299: In heavy rain, aircraft crew did not hear a descent clearance.
- Airspace: ACN 1187441: First Officer on final approach ascribed responsibility for a ground conflict with departing traffic. There was a substandard handling by both the Local Controller and to Departure Control for failing to provide altitude separation.
- Airspace: ACN 1187396: During descent, captain cannot control autopilot, aircraft descends below charted altitude.
- Environmental: ACN 1187241: Aircraft encounters icing conditions and requests a climb from ATC but is blocked by another transmission. Aircraft continues to climb and is admonished.

En-Route Issues

- Airpsace: ACN 1198534: Captain reports missing the crossing restriction, due to an excessive amount of altitude to lose.
- Airpsace: ACN 1197953: Captain reports encountering severe icing conditions at FL370 while avoiding a thunderstorm that results in confusing indications and loss of airspeed indication.
- Airspace: ACN 1197025: Altitude deviation due to not noticing the 10,000 foot limit in the routing box.
- Airspace ACN 1196412: Confusion between MUURY and MURRY.
- Airspace ACN 1196111: Crew misunderstands clearance to climb.
- Airspace ACN 1195973: First Officer reported taking evasive action to a TCAS TRAFFIC advisory from a departing jet.
- Airspace: ACN 1195620: Controlled fixed altitude relationship turned chaotic when the Air Carrier in the middle of the altitude sandwich responded to a TCAS RA. resolutions included giving flight crew discretion as to whether to respond to RAs in congested airspace.
- Airspace: ACN 1195614: Three helicopters that encountered icing while working them and two were declared emergencies to be able to descend.
- Airspace: ACN 1195055: When the controller cleared aircraft to proceed, the crew continued their descent and suffered a loss of separation with another aircraft.
- Airspace: ACN : Engine rollback climbing out of 5,000 FT that result in a large yaw angle and a momentary stick shaker. This causes an emergency, fuel is dumped, and flight returns to departure airport.
- Airspace: ACN 1193107: Captain failed to comply with a descent clearance due to distractions.
- Airspace: ACN 1192600: Air Carrier pilot reported taking evasive action, resulting in altitude deviation, without an ATC traffic point out.
- Airspace: ACN 1192162: Pilot took evasive action from an unsighted aircraft, to which he was alerted but not provided Resolution Advisories.
- Mechanical: ACN 1192129: Pilot heat system is not on, and leads to uncontrolled descent and loss of airspeed.
- Airspace: ACN 1191586: Controller reports of an aircraft that needs to descend due to lack of oxygen. Aircraft descends through another Controller's airspace. There is a conflict and loss of separation.

- Airspace: ACN 1191046: Experienced Air Carrier Captain identifies compatibility issues with autopilot and this increases crew work load.
- Airspace: ACN 1189518: Approach flown by a new First Officer that results in a low altitude alert from ATC. The reporter had become distracted when his approach charts fell to the floor.
- Airspace: ACN 1189419: First Officer assumed control of the aircraft in IMC after the elderly pilot flying lost situational awareness during a climbing turn and banked in excess.
- Airspace: ACN 1188189: Captain reports being issued a hard altitude, requiring speedbrakes and high speed to make the crossing.
- Airspace: ACN 1187993: Flight Crew reports being cleared to 11000 feet, but apparently they are not pushing the activate button firmly enough. The aircraft remains at FL220 until queried by ATC.
- Airspace: ACN 1187924: Flight crew was cleared to make a crossing, which they knew they did not have enough time for.
- Airspace: ACN 1187916: First Officer reported the flight crew descended below a crossing restriction on approach when they lost track of the FMS mode.
- Airspace: ACN 1187477: Captain preset the bottom altitude of an anticipated RNAV STAR clearance, but failed to ensure an appropriate VNAV mode. The aircraft began a premature descent. The First Officer intervened.
- Airspace: ACN 1187886: Helicopter that isn't coordinated that descends through the departure corridor of a close proximity airport.
- Airspace: ACN 1187067: Flight cleared direct to its destination through an active jump zone contrary to a revised Letter of Agreement specifying which ATC entity was responsible for the airspace under those conditions. Result of inadequate controller training.

Unsafe Situation Indicators

- Missing crossing restriction
- Loss of airspeed
- Unclear instructions from TCAS (E.g. ACN 1196925)
- Misunderstanding and/or misinterpreting instructions (E.g. ACN 1196102)
- Heading and altitude control difficulties
- Traffic congestion (may lead to increased difficulties and human errors)
- Loss of separation

- Weather-related (thunderstrom, icing, rain) issues complicate other factors
- Usage of unclear, ambiguous phrases for instructions (E.g. ACN 1188436)
- Improper coordination (E.g. ACN 1187886)

Safety Factors - Predictable

- Airspeed
- Poor altitude control
- Incorrect heading
- Congestion in airspace
- Weather-related (icing, turbulence)
- Likelihood of loss of separation
- Mechanical system failures (E.g. ACN: 1188960)
- Altitude separation

Safety Factors - Not Predictable

- Mechanical issues, unnoticed (E.g. ACN 1196178)
- Unclear instructions, misunderstanding/misinterpreting instructions
- Incorrect autopilot
- Poor ATC communication
- Situational awareness
- Incorrect operations/procedures
- Inadequate controller training/experience (E.g. 1187067)

Revealing Quotes

- ACN 1196178: I do know we will all be paying more attention to those door gaskets during future preflight.
- ACN 1196178: In the future, I will not hesitate to obtain confirmation whenever either crew member is even slightly unsure.
- ACN 1195909: Ensure proper readback, no matter how many times it takes. Issue Low Altitude Alert along with cautions, if high terrain. Issue the Brasher phraseology. Talk to the pilot more, ask them what is happening in more detail to try and offer better help or instructions.

- ACN 1195487: I suggest: (1) Always verifying your FMA's before changing altitudes; (2) Practice more RNAV approaches; (3) Do a more thorough brief of the approach to familiarize yourself with the RNAV procedures.
- ACN 1188436: I recommend we stop using the phraseology "Climb via the SID" and use "Climb and maintain" like we have always done.

C.7 Extracting Safety Factors from Fuel Management ASRS Reports

Surface Issues

- Not applicable.

Terminal Issues

- Cognitive/Weather: Technique : 1200309 and 1200081: Controller issued punative holding to flight that would not accept vector into a CB cluster that was approx. 3x8 miles in dimension. Flight had to divert due to delay. Controller workload or attitude considered a factor.
- (Misclassified in ASRS Fuel Management; should be fatigue) Cognitive: Fatigue : 1193833 : Flight arrived one hour late due to ATC re-routing for thunderstorms, lengthy taxi delay due to ground congestion, delays in ground transportation to home did not allow for full 8 hour rest before next flight.
- Environment: Thunderstorms: 1172513: Flight vectored extensively for weather and traffic. Tower called microburst while on approach. Previous flight reported windshear but landed ok. This flight went around and diverted to alternate with very little fuel remaining.
- Cognitive and Environment: Botched approach and runway change: 1167328: Flight botched the first approach. Airport changed configurations.

En-Route Issues

- Environment: Forecast wrong : 1196791: VFR pilot ended up in unforecast IMC.
- Environment: Forecast worse than anticipated: 1182971 : Destination airport closed due to thunderstorm overhead. Flight had been re-routed a couple of times already to avoid en-route weather. Although they had fueled for weather contingencies, the actual weather limited options for further holding. They diverted to an unapproved airport. Dispatcher congestion (they were dealing with 20 diversions and a medical emergency at the time) made them slow.
- Environment: Enroute weather: 1194187: Burned extra fuel deviating for weather. Had to divert due to low fuel.
- Airspace: Structure? : 1193498: Crew refused new clearance because of inadequate fuel onboard. Controller got upset and escalated issue to airline later.

- Environment and Airline procedure: Tailwind : 1153619 : Flight was flying slow to save fuel, taking advantage of 135 kt tailwind, per airline procedure. ATC vectored flight off course to allow faster flights (who had not throttled back because of the tailwind) to get by. Too much vectoring and the airline's minimal fueling (again to save fuel) resulted in minimal fuel.

Unsafe Situation Indicators

- Fuel alert
- Lack of adequate time for crew rest between flights (misclassified fatigue report)
- Clearance refusal
- Diversion to alternate

Features - Predictable

- Conditions significantly worse than forecast
- Unexpected excessive delaying vectors for congested airspace (or for disagreeing with controller)
- Excessive vectoring for weather
- En-route deviation for weather (can lead to low fuel and to interferring with crew rest period)
- Re-routing, especially multiple or distant re-routes (not enough fuel may be on board aircraft to fly new route)
- Re-routing on the wrong side from destination airport of a solid line of thunderstorms
- Delayed lift-off (almost an hour sitting in line)
- Windshear alert (previous flights; +25 kts)
- Microburst alert (tower)
- Thunderstorms enroute (especially if weather radar is inop on the airplane)
- Icing
- Runway change (could lead to 'minimal fuel'; expected to take 15 min)
- Aborted approach (botched approach)
- Tailwind (135kt) plus slower than usual flight to take advantage of it

Features - Not Predictable

- None.

Revealing Quotes

- None.

C.8 ASRS: Wake Turbulence

Surface Issues

- Environmental: Boeing Heavy Jet exiting runway with power above idle: 1196431: A single engine pilot performing touch and go landings at PAE lost control during takeoff after a Boeing heavy jet exited Runway 16R and parked perpendicular to the runway with power apparently above idle. It seems that the large Boeing aircraft, **perpendicular** to the runway and just off the left side, was perhaps doing an engine runup test with his engines aimed at the runway, or was aggressively using power to get the plane moving ... in any event, it is clear that I was a victim of jet blast moving across the runway from a large jet. I called the Tower Controller after my last lap and discussed this with him. He indicated that the Boeing pilots are generally asked to use minimal power on taxi for this very reason.

- Environmental: Wake turbulence encountered in trail of a large aircraft: 1202238: B737-800 flight crew reported encountering possible wake turbulence in trail of a B777 on approach to MIA that resulted in a flap overspeed. On visual approach to Runway 9, 15 flaps were lowered below the flaps 15 limit speed and confirmed in cockpit between pilots. After landing, we pulled up a flap report and printout showed 203 KTS for flaps 15. Flap overspeed was entered in logbook, Maintenance deferred inspection to next 100 hour check.

Terminal Issues

- Environmental: Climbed smaller aircraft through wake of larger aircraft: 1203838: MSY controller climbed a smaller aircraft through the wake of a larger aircraft and did not use the residual wake turbulence rules for proper separation.

- Environmental: Wake turbulence shortly after takeoff: 1201963: CRJ-200 flight crew reported encountering wake turbulence shortly after takeoff in ATL. Flight crew was critical of the new ATL ATC reduced separation procedures. ATC cleared the CRJ-200 for takeoff before the MD-80 was rotated. There was also the fact that CRJ was heavy that day. The new separation minimums between takeoffs in Atlanta needs to be altered. The company needs to present these issues to local ATC to prevent a major accident in the future. One of the threats that occurred in this event, and has been occurring during the past year or two, is Atlanta's ATC clearing aircraft for takeoff while the preceding aircraft is still on its takeoff roll and only half way down the runway.

- Environmental: Wake turbulence just before landing: 1200882: A widebody Captain reported encountering wake turbulence just before landing (50 FT AGL) in trail of another widebody. The controller had said "cleared for the visual to 35R, turn right to heading 320". Had the pilots been allowed to fly a visual approach as is normal, where they choose the track and altitude, they would have gone out another mile or two and would not have had a wake turbulence encounter in the flare. Saying “Cleared for the visual” and then assigning a heading is contradictory, in their opinion. Their approach was stable in all respects until the wake turbulence encounter at about 50 FT. The pilots has requested 290 heading instead but were overruled by the Controller.

- Environmental: Wake vortex encounter in Trail: 1200748: Gulfstream III Corporate Pilot reports several wake vortex encounters in trail of a B737 on approach to STL that led to a go-around decision. B737 was six miles ahead being vectored for the same runway. Two wake turbulences encountered. The second one was due to being too close under the weather conditions. Approach controller did not provide a wake turbulence warning nor was the crew aware of the B737 descent profile. Weather conditions were VFR and wind were 5kts. A greater spacing between the B737 ahead under the weather conditions could have prevented the wake turbulence.

- Environmental: Wake turbulence encounter during approach: 1199034: B737-700 Captain reported encountering wake turbulence on arrival to MDW in trail of a B737 that resulted in a minor flap overspeed and an unstablized approach. The aircraft ahead slowed rather quickly and we closed into about 2.5 to 3 miles behind him. The Captain tried to slow the trailing aircraft as quickly as possible by disconnecting the autopilot and pitching up a bit and calling for more flaps.

- Environmental: Wake turbulence encounter during arrival: 1200266: B737-700 flight crew reported wake turbulence encounter during arrival to LAX in 12-mile trail that resulted in sudden 30-degree roll. Going to LAX with descent of 7000 ft approximately 10 NM west of SMO VOR by SOCAL approach. Wake turbulence encountered 8500 FT. Crew paused their descent and was subsequently criticized by ATC. Even though the Captain advised Approach Control of the level off at 8400 FT due to wake turbulence, the Controller did not acknowledge this transmission as the Controller was saturated with a lot of calls. Later the controller advised the crew that they need to tell him of level off and they need to keep coming down due to other traffic at that altitude. After additional spacing with preceding traffice, aircraft landed without incident. 12 miles perhaps is not enough spacing to avoid wake turbulence. Also, ATC needs to give a higher priority to aircraft that encounter wake turbulence. There was little response from ATC when we advised them of the turbulence.

- Environmental: Wake Turbulence on departure: 1199563: MD-11 flight crew reported encountering wake turbulence on departure from OMDB in trail of a B777 that resulted in a momentary stick shaker. Trail of a B-777 by about 5 miles. The wake turbulence rolled the aircraft right and left about 15 degrees, but was manegeable. After a while, a second wake turbulence was encountered, which was more severe and caused 25 degree rolls. The weight of the MD-11 was heavy, 612k. Possible cause of this could be that Departure Control sequenced the flight too close in trail to previous heavy jet departure.

- Environmental: Wake Turbulence on takeoff/departure: 1193855: Air carrier First Office reported encountering wake turbulence after takeoff in trail of an A320 that resulted in a momentary stick shaker. The flight was about 3.5 miles in trail through most of the climb.

- Environmental: Wake turbulence on arrival: 1199111: CRJ-200 flight crew reported encountering wake turbulence that resulted in rolls to left and right while in trail of a narrow body Boeing during arrival to ATL. ATC provided a turn off course. Rolls of 10, 20, and 30 degrees were experienced. Heading off of the arrival was requested to get out of the wake turbulence. During hand flying in the turbulence, and while in the 20 degrees right turn ATC heading the aircraft got off altitude 100 FT high. This was quickly corrected and automation was re-established. ATC said that the preceding aircraft's turbulence was a threat, and pilot not flying should have been quicker to notify ATC. There was some frequency congestion, but deviating off the assigned altitude by 100 FT was an error both by pilot flying and pilot not flying. Pilot not flying should have been more vigilant, but was distracted making the call to ATC.

- Environmental: Wake turbulence encounter from airplane landing in parallel runway: 1191844: C172 pilot reported wake turbulence encounter on approach to RDU from a B737 landing on the parallel runway which resulted in an uncommanded 50-degree bank. While no one had recently landed on Runway 5R, there was continuous operations into Runway 5L, invluding a B737 which landed approximately 4 minutes ahead of me and a MD-80 series jet which was adjacent to me when the incident occurred. The encounter was at 1000 FT. The whole incident lasted about 10 seconds. It was surprising to encounter such wake from a plane using a parallel runway separated laterally by almost 3500 FT from the approach pilot was using. Had the wake turbulence been more severe, the Pilot may have become inverted and entered an unrecoverable spin. C172 was cleared for visual approach to Runway 5R at RDU and was told to contact the Tower by the Approach Controller.

- Environmental: Wake turbulence in trail: 1189546: CRJ-200 Captain reported loss of control because of wake turbulence from a preceding MD-11 on approach to PHL. Reporter questioned current wake turbulence separation standards. We exited the upset and regained aircraft control and leveled at 11,000 FT. At this time we queried ATC as to what type of aircraft was approximately 8-10 miles ahead and below us. ATC responded that it was a heavy MD-11. At the time of upset, the aircraft was 700 FT below us and around 8 miles ahead of us. We reported to ATC that we had entered an upset possibly due to the MD-11's wake. ATC replied, "Roger, we are complying with published separation standards, but you are the second aircraft to complain about his wake."

- Environmental: Wake turbulence after takeoff: 1189299: B777-200 pilot reported encountering wake turbulence after takeoff from EGLL in trail of a B747. Pilot commented he felt separation standards were not followed by ATC. ([We were] given takeoff clearance approximately 30/35 seconds after a heavy B747. [We] delayed takeoff for approximately 30 more seconds. Wind report was 280/7. Rough ride after takeoff 300 FT to 1,300 FT. [We] reported event to EGLL Tower. I thought EGLL provided a 1 minute minimum delay interval between heavy aircraft. They didn't. [They] should consider longer delays when winds are calm or straight down the runway.)

- Environmental: Wake turbulence on approach: 1186006: A320 Captain reported encountering wake turbulence in trail of an MD-11 on approach to DFW resulting in a 45 degree bank and 8-12 degrees nose down altitude. Captain approximately seven miles from the landing aircraft that was MD-11. As I noticed the rate of closure was increasing - aircraft separation was decreasing. I started slowing down the aircraft and almost at the same time our aircraft experienced an uncommanded 30 degree roll to the left in conjunction with 8-12 degree nose-down immediately after the aircraft rolled through wings level to 45 degree right bank angle. The aircraft also experienced an altitude loss of 300-400 FT in seconds causing high sink rates of up to 4,500 FPM. I immediately disconnected the autopilot and gracefully gained control of the aircraft without allowing the event to exceed any aircraft limitations or causing deviations. During this unexpected event, I tried my best to reduce the loading on the wings.

- Environmental: Wake Turbulence encounter on approach: 1185043: B737-700 Captain reported encountering "heavy wake turbulence" in trail of a heavy on the SEAVU arrival to LAX, resulting in a track deviation. ATC tucked us in about six miles behind a heavy aircraft ahead of us on the arrival. Approximately over SEAVU, we encountered heavy wake turbulence, which kicked off the autopilot. I engaged the autopilot in heading mode, and offset our course momentarily to escape the wake turbulence. I was turning back to LUVYN, when ATC noticed we were off the arrival track, and gave us a clearance to reacquire the arrival at KRAIN. We LNAV'd to KRAIN, and flew the ILS 25L to LAX. I should have immediately advised ATC of our situation to get a proper clearance back to the arrival. It would be very helpful if ATC would be more cognizant of the need to leave more space for arrivals following a heavy aircraft.

- Environmental: Wake turbulence encounter on approach: 1184467 F50 Captain reporter wake vortex encounter at FL350 from a B737 crossing his course at FL360 (left to right) and approximately 5 NM horizontally that resulted in "violent wing rock".

- Environmental: Wake vortex encounter on approach: 1181210: B737-800 flight crew reported difficulty adhering to charted altitudes on arrival into LAX when wake turbulence from preceding B777 distracted them. Turbulence from Heavy 777 ahead [was] now bouncing us around and pilot flying [was] struggling to get aircraft back on profile, altitude, and slightly above wake turbulence. Aircraft was below path significantly and went below crossing restrictions at ENGLI and PECOX. Pilot not flying made verbal alerts that we were below the published descent path. Pilot flying got aircraft back onto proper path (slightly above to avoid wake turbulence) and continued to a normal visual approach to [Runway] 25L. ATC made no mention of deviation. I did mention to ATC during visual approach that we were being affected by preceding aircraft significant wake turbulence.

- Environmental: Wake vortex encounter on takeoff: 1180362: CRJ-200 Captain reported encountering wake turbulence in trail of an A319 on takeoff from ATL that resulted in multiple violent rolls at low altitude. On rotation, the Pilot received momentary stick shaker. At roughly 500 FT AGL encountered wake turbulence that resulted in nose pitching up about five degrees, and then the airplane rolling violently to the left. Corrected the wing levels and continued climbing at V2+15 in an effort to climb above the wake. Encountered the same violent left roll three more times in rapid succession, and finally recovered at about 1,200 FT AGL. By the time control authority was regained, right turn to SNUFY on the RMBLN departure was missed. ATC inquired about our track. First Officer very quickly informed the Controller that we had just recovered from a wake turbulence upset. We were assigned a heading to rejoin the departure. The rest of the flight was uneventful. On checking on with ATL departure Control, a phone number was given to call upon landing to talk to the Tower supervisor. On doing so, the Tower supervisor was gracious and apologetic and wanted to know if the Pilot was familiar with new separation standards and that they were collecting data regarding such incidents. The Pilots confirmed that they indeed were familiar with the new separation standards.

- Environmental: Wake vortex encounter shortly after takeoff: 1179872: CRJ-200 flight crew reported encountering wake turbulence in trail of a B757 after takeoff at ATL from the same Runway 26L that resulted in 30 degree roll and a stick shaker at low altitude. Crew cited new ATL ATC separation procedures as causal. The wake vortex was encountered at approximately 500 FT.

- Environmental: Wake vortex encounter during approach: 1179627: We were on a visual approach to [Runway] 27L Atlanta following another carrier's B757. We were approximately three miles in trail on the TCAS display. At approximately 100 FT, we encountered wake turbulence from the B757. It was the Captain's leg and he initiated a go-around. We coordinated with Atlanta Tower and Atlanta Approach to sequence back in for another approach. I told the Approach Controller the separation between us and the B757 was too tight and he stated, "It is our new separation rules." We landed uneventfully after the second approach.

- Environmental: Wake vortex encounter during approach: 1179462: On arrival to LAX Runway 6R, we were sequenced behind an A380 Super. On initial arrival Approach Control stated that we were 10 miles in trail. I verified it with TCAS. As Approach Control switched us to Tower, he stated that we were 7 1/2 miles in trail of a Super, caution wake turbulence. Due to the 737-800 high approach speed at flaps 30, I elect to use flaps 40 to slow us a little more. As we were approaching 1,000 FT, I heard Tower tell the Super to contact Ground Control clearing Taxiway V. This is the end of the runway. As we were starting the flare, we started to get quite a bit of wing rock, and some airspeed fluctuations. It almost felt like we were "skidding" on the wake. At this point I decided that the best thing was to go-around. I am not sure of the altitude, but it was below 50 FT [AGL]. Tower asked the reason for the go-around as we were handed off to departure control and the First Officer stated that it was due to wake turbulence over the runway. My gut feeling is the A380 landed long since they did not exit the runway until the end. I do not have anyway to verify this, just my gut feeling.

- Environmental: Wake vortex encounter during approach: 1179180: MD-83 Captain reported encountering wake turbulence on approach to LAS that resulted in 30 degree roll both sides. Wake was generated by preceding B737 that crossed his arrival path.

- Environmental: Wake vortex encounter during approach: 1175641: C402C Pilot reported encountering wake turbulence that resulted in a 90 degree bank on approach to STT in trail of a B757. The SJU Approach Controller advised 'caution wake turbulence' and had me switch over to Tower. At this point I am below and a little downwind of the jet, and behind by what I'd estimate to be about 3-4 miles. I decided to go to in-range power at this point to put a little more distance between me and the B757. I would much rather be above the wake than below it, but I knew in order to safely get above it, I'd have to get upwind of it (right and south of localizer course). As I started to make my way to that side of the course, I felt a sharp shake of the airplane and then a quick snap roll to the left, close to 90 degrees of bank. I regained control of the airplane and brought it back to level flight using aileron and rudder. I checked all gauges and looked around the visible surfaces of the airplane and noted everything was working the way it should. I turned around and gave the 6 passengers a questionary "thumbs up" and received thumbs up back. I turned back around and continued to fly.

- Environmental: Wake vortex encounter on approach: 1174373: Widebody First Officer reported encountering wake turbulence in trail of an Airbus at 200 FL AGL on approach to MEM. Close spacing given by ATC and differences in approach speeds by aircraft. On final approach to Runway 36L, we were following an Airbus. [We] were told to slow down final approach speed due to spacing. We did. They were showing about 3-3.5 miles in front of us on TCAS. Tower asked preceding traffic to expedite on touchdown. They said they would. We experienced a wing rock at 200 AGL (possibly due to wake turbulence) and elected to go-around.

- Environmental: Wake vortex encounter on approach: 1173412: ERJ-170 First Officer reported "severe" wake vortex encounter on approach to SEA that rolled the aircraft beyond 30 degrees of bank and resulted in injury to a flight attendant. The flight attendant had hit the aft door and suffered from abrasions, contusions, possible concussion, and lacerations. She had hit her head, shoulder, and hand.

- Environmental: Wake vortex encounter on approach: 1172294 C152 pilot reported encountering wake turbulence at 400 FT AGL from a B787 departing on a parallel runway. Resulted in a roll of about 30 degrees to the left. The pilot realized that the rotation point of the B787 on the longer runway would be very close to his touchdown point. But the pilot did not realize then that the light crosswind of about 3 Knots towards the runway would make a wake turbulence encounter more likely. Yet, the pilot did not consider going around. But once he encountered the wake turbulence, he did do a go around, but eventually landed safely. The pilot was relatively inexperienced, and also was not assertive enough with the ATC to request additional spacing from ATC.

- Environmental: Wake vortex encounter on approach: 1168197: ERJ-170 Captain encountered ”severe” wake turbulence just before touchdown at DFW in trail of an Airbus A320. A somewhat confused and non-SOP go-around was executed. While in the landing flare approximately 10 feet from the runway surface we encountered what I would describe as ”severe wake turbulence”. The aircraft gained between 20 to 30 feet of altitude and experienced a desire to roll. Realizing that the landing must be rejected the pilot called aloud ”go-around”. The pilot had forgotten to push the go-around button though, thereby upsetting the normal flow for a go-around.

En-Route Issues

- Environmental: Wake Turbulence Encounter in Trail: 1204647: EMB-145 First Officer reported encountering wake turbulence in trail of a B757 departing ATL that resulted in a ten-degree roll.
- Environmental: 1204309: Wake Turbulence Encounter in Trail: CRJ-200 Captain reported wake turbulence encounter in trail of an MD80 on approach to DTW that resulted in a 25-degree roll and a “sudden downward push”.
- Environmental: Climbed smaller aircraft through wake of larger aircraft: 1203838: MSY controller climbed a smaller aircraft through the wake of a larger aircraft and did not use the residual wake turbulence rules for proper separation.
- Environmental: Wake turbulence encounter: 1202314: C441 pilot reported a wake turbulence encounter at FL340 that resulted in an excursion from assigned altitude. Pilot was 250 NM away from PUB when the encounter happened.
- Environmental: Wake turbulenve encounter: 1200948: B757-200 flight crew reported encountering wake turbulence shortly after takeoff in trail of another aircraft. Pilot applied almost full right aileron to break out of what I believe to be a wake turbulence encounter from the previously departed aircraft. Corrected back on course with no further turbulence encountered. Wind 180/4 at takeoff. [We] notified Tower and Departure Control of event, Tower as it was occurring and Departure a few moments later. Suspect light tailwind may have created the environment for this to occur. Providing this information as data to evaluate RECAT under these conditions. I have never experienced this type of situation before and consider myself a fan of RECAT.
- Environmental: Wake Vortex Encounter: 1165783: A320 flight crew reported wake vortex encounter at FL350 that resulted in an injury to a flight attendant.
- Environmental: Wake vortex encounter: 1196713: MD-82 Captain reported wake vortex encounter at FL310 five miles in trail of an A319 resulting in a 25 degree roll in both directions. Reporter was surprised at the intensity of the encounter given the relatively small aircraft he was following. The roll was not a ‘snap roll’, but a pronounced gradual right wing down followed by the pronounced left wing down

with no loss of altitude. Cleveland Center told the pilots that they were 7 miles in trail of Airbus A319 in front of them. Suggestions: Inform the aviation community of the flight data results from A319 flight tests showing the severity of wake turbulence generated. Was my encounter today an anomaly or is there a bigger wake generated by the A319? Exactly where does the A319 fall in the spectrum of wake turbulence generated by modern aircraft? A chart that comparatively quantifies and illustrates the wake severity of the most common commercial aircraft flying today would be most useful. Does such a chart exist and if so, where can I obtain the chart?

- Environmental: Wake vortex encounter: 1196194: B737-900 flight crew reported they were unable to make a charted crossing restriction on the LAS SHEAD8 RNAV departure when they were distracted by wake vortex encounter from the preceding B737. The following B737 was surprised at how close it was to the preceding one as the preceding flight was just rotating when the following flight had takeoff power set. This was the pilot's first error. Second mistake was that while the follower pilot encountered wake turbulence, the Pilot instucted the First Officer to go back to VNAV and speed intervention at 230, when the First Officer went to level change/230 on the MCP. **Cause: Trying to follow [the B737] VFR under IFR rules/separation. [We] needed to deviate from NAV path due to wake turbulence. That caused me to not monitor to progress of the MCP and the SID as closely as I should have.**

- Environmental: Wake vortex encounter in trail: 1190692: B737-400 First Officer reported encountering wake vortex after takeoff in trail of a B777 that resulted in a windshear warning. Reporter stated "inadequate separation" was the cause of the event. The pilot waited 2 minutes for roll and passing 600 FT got a windshear warning. There were no speed deviations that warning went away after approximately 3 seconds. ATIS winds were 290/18. The cause of the warning came from B777 jetwash. **Cause: Inadequate separation between B777 takeoff and our takeoff clearance.**

- Environmental: Wake turbulence after takeoff: 1185514: GLF4 Captain reported encountering wake turbulence 20 miles in trail of a DC-10 at FL360 that resulted in a roll to as much as 90 degrees. Both GLF4 and DC-10 were climing through 35000 FT at the same rate. Food service was thrown to the floor. I'm not sure how to correct the separation problem. It would seem 20 miles would be sufficient. If ATC informed us of the aircraft we were following and their position we could have the option of vectors, depending on the winds, to fly off the airway or be able to choose a different altitude.

- Environmental: Wake turbulence during climb: 1183821: B767 First Officer reported encountering wake turbulence in climb at FL375 from a nearby B747 at FL380 that resulted in a 35 degree bank, causing a galley cart to overturn in the cabin. B747 was a little over 10 miles ahead of the B767 at FL380. After discussion with the Captain, since the no load was encountered by the aircraft during the roll or severe turbulence, no logbook entry was made. The remainder of the flight was uneventful.

- Environmental: Wake vortex encounter : 1181406: Support Specialist at A80 reports of aircraft entering wake turbulence and asking for a vector to the left. Controller cannot issue a left heading due to traffic, and issues a right turn. “This may be connected with recat, however without analyzing the data, I am not sure that wake turbulence separation wasn’t even provided under the old standard.”

- Environmental: Wake vortex encounter: 1166380: B737-300 flight reported encountering moderate to severe wake turbulence in climb at FL335 that resulted in a roll right and then left that exceeded the roll authority of the ailerons. ATC was notified of our wake encounter, reporting it as moderate to severe wake turbulence. ATC stated the wake was generated by a Company aircraft. However, the crew was never informed or aware of another aircraft in their flight path.
- Environmental: Wake vortex encounter: 1165944: A-1125 flight crew reported a wake vortex encounter at FL390 with an A380 that passed in front of them. The resulting turbulence caused a 250 FT loss of altitude.
- Environmental: Wake vortex encounter: 1165783: A320 flight crew reported wake vortex encounter at FL350 that resulted in an injury to a flight attendant. Could have been caused by crossing another aircraft’s flight path and wake turbulence.

Unsafe Situation Indicators

- x-degree Roll
- Flaps overspeed
- Stick Shaker activations
- Rejected landing
- Nose pitching up or down
- Go around
- Food cart thrown around in the flight
- Injury to passenger or crew

Safety Factors - Predictable

- Wake Turbulence Separation Standards not adequate
- Wake turbulence separation standards not maintained/followed by ATC - too close spacing
- Wake vortex encounter
- The distance between two planes reduce for some reason. E.g., the plane in front slows down for approach or the plane behind increases speed; difference in approach speeds of two aircrafts

- Primary problem - Environment (non weather related), procedure
- Jet blast from aircrafts parked perpendicular to the runway: 1196431
- Human factors 1196194 (Pilot error/distraction)
- Wake of plane using a parallel runway separated laterally by almost 3500 FT from the approach pilot was using. The encounter was at 1000 FT
- Wake turbulence from parallel runway
- Lack of traffic-alert from other centers

Safety Factors - Not Predictable

- None.

Revealing Quotes

- 1199034: Situational awareness is key here; to anticipate the aircraft in front of you slowing at a specific time and being prepared and configured to do the same.
- 1196431: My point in filing this report is to raise visibility: while we all read and think about wingtip vortices, and get warnings from the Tower about this, I have never in decades of flying read about or thought about the risk that I encountered. If the runway is clear, no vortices, no warning from the Tower, etc. Then I assess my landing risk level as normal. I have never thought to look around at all of the surrounding taxiways, up and down the runway, on parallel taxiways where a plane may be turning, etc., to try and anticipate which large jets might be jet blasting across the runway as they maneuver. Should I have made those checks? Presumably. Should the Tower be issuing ”jet blast” warning, possibly? Should Ground Control not grant taxi permission to the jet if there is a plane landing behind? That would be nice, but perhaps hard to coordinate between Tower and Ground positions. Anyway, scared me, both because of the loss of control/recovery and because I realize I have never thought to guard against this.
- I’m calling into question the FAA’s current published wake turbulence separation standards for heavy aircraft. ATC was complying with published regulations; however, our aircraft still entered a severe upset.
- Better spacing is needed for VNAV descents to high density airports such as lax and VFR aircraft must be kept well away from approach corridors. We could have told ATC we were unable to comply due to late changes and in speed and altitude and wake turbulence made the situation worse. Flying pilot did get ”behind” aircraft and was slow to correct. Eventually caught up to aircraft and proceeded normally.
- Clearly the threat here was wake turbulence and our proximity to the preceding traffic. Hopefully this incident will help ATC assess the effectiveness and safety of the new minima.

- New separation rules apparently do not provide sufficient wake turbulence separation behind larger aircraft. In the future I will not accept immediate departure behind B757 aircraft. The Company needs to seriously review whether the benefits of reduced separation are worth the significant potential risk.

- The new rules for separation used by Atlanta Approach are too tight. If they continue to bring aircraft in with minimal separation, there will be more of these events.

- I take full responsibility for this wake turbulence event. Even though ATC vectored me below and downwind of the B757, it is my responsibility as PIC to avoid wake turbulence. I should have either asked for an avoidance deviation or just deviated and explained later. Visualizing where you think the wake is either drifting or not drifting (based on winds) to is also important.

- Suggestions: Not to accept Tower's clearance even if they say there is room. Not to get rushed by the situation so you can focus on things like wake separation, and inform Tower of your requirement. Find out how much they want us to ”move down” when lining up a second aircraft. Try to accommodate Tower but do not let them fly your plane for you.

- I would suggest that more unanticipated balked landings occur during training. The ”startle factor” of a wake turbulence upset near the runway was intense. I believe this ”startle factor” was what led me to abandon my duty to push the go-around button, thus upsetting the normal flow for a go-around.

- I don't think that there is anything the crew can do to avoid this situation as there are too many variables. However, with the precision of modern aircraft to fly exactly where previous aircraft have flown, separation standards under certain wind conditions might need to be adjusted.

- I believe an earlier traffic-alert from Memphis Center would have provided us with sufficient time to have asked for a turn off-course, thereby enabling us to avoid the wake turbulence.

C.9 Extracting Safety Factors from RNAV ASRS Reports

Surface Issues

- Not applicable.

Terminal Issues

- Environmental: Visibility: 1234808: Two bright lights near terminal looking like PAPI which could cause early descent, especially with restricted visibility.

- Cognitive: Workload: 1229708: Inconsistency between instructed altitude selections during RNAV versus clearances, causing missing a crossing restriction.

- Cognitive: Workload: 1228645: Ill passenger adding to workload. ATC kept changing arrivals (different course vectors, waypoint crossings) and several speed changes. Counldn't keep up and resulted in altitude deviation (nothing from TCAS or ATC about it).
- Congnitive: Communication: 1228204: RNAV waypoint was supposed to be crossed at a certain speed and altitude but controller wanted to keep speed up. Debate erupted.
- Airspace: Procedural: 1227069: Situation in which RNAV departure procedures can result in aircraft turning into each other.
- Airspace: Procedural: 1226480: RNAV STARS into Boise are not safe.
- Cognitive: Workload: 1223570: ATC gave late runway change, which could not be programmed in time (complex procedure, slow FMS) resulting in track deviation.
- Cognitive: Confusion: 1223351: Two RNAV points that are the same in space but with different names causing confusion. Jet continued straight instead of turning toward approach.
- Environmental: Wind: 1222385: Could not maintain decent path to an RNAV arrival with a 40 knot tailwind. Descent gradient is too steep. ATC responded with altitude change to eliminate threat.
- Cognitive: Workload: 1222201: Due to wind unable to comply with ATC crossing altitudes. ATC issued multiple runway changes and crew could not keep up, replied "unable" to last runway change.
- Mechanical: FMS: 1221365: Limitations of FMS made flying complex DFW RNAV arrivals difficult.
- Mechanical: Altimeter: 1219289: Poor lighting of the altimiter plus ringing cellphone made it hard to read altimiter and follow nighttime RNAV approach.
- Cognitive: Workload: 1217807: FMS errors and complex altitude restrictions burnded the pilot flying, nonflying pilot was busy on radio trying to understand what ATC wanted them to do. As a result required a lot of vectoring and missing altitudes (traffic ahead had also been missing altitudes). Issue happened twice and so figure it is bad arrival design.
- Cognitive: Workload: 1216200: Tired at end of 14 hour flight, plus difficulties and distractions of reprogramming FMS to comply with complex descend via clearances.

En-Route Issues

- None.

Unsafe Situation Indicators

- Multiple ATC actions

Features - Predictable

- Visibility

Revealing Quotes

- Descend Via RNAV arrivals in general increase the flight deck workload many times over and exponentially increase the chance of deviations in aircraft without VNAV and auto throttles like the CRJ.
- ATC specialists must not have any idea of the level of disruption the constantly changing speeds impose on the flight crew during arrival into DFW. In my opinion they truly need increased awareness of the destabilizing affect these speed changes have on a safe flight.

C.10 ASRS: Runway Incursion

Surface Issues

- Surface/Mechanical: Runway Incursion due to Controller blind spot: 1188420: Runway Incursion - Pilot refuses instructions: MSP Tower Controller tells an aircraft to cross a runway by using a runway and the pilot refuses instructions. Controller then realizes that an aircraft is just about to touch down on the runway. Controller states Tower view is blocked by Tower cab window pillars and they didn't see the aircraft because of the pillars.
- Mechanical: Construction closing and opening runways and local control did not have that information: 1184518: Two Controllers from ANC Tower describe a shift where they don't know what runways and taxiways are closed or open and land two aircraft on a closed runway.
- Cognition: Lack of use of visual aids leads to forgetting of runway crossing: 1183191: CLT Local Controller reports of an aircraft that he had cleared for takeoff advised him that there was an aicraft crossing the runway down field. Local Controller relizes he had approved the crossing with Ground Control down field, but forgot to use a memory aid to display to him that the crossing was going on.
- Cognition: Lack of use of memory joggers to indicate who owned the runways: 1181349: FRG Ground Controller issues crossing instructions while departure is rolling down the runway. Ground doesn't realize he doesn't own the runway. Memory Joggers were available to show who owned the runways, but not used.
- Mechanical: Aircraft claimed to not have heard tug's announcement that it was on runway: 1179018: PHF controllers describes situation where a tug is reporting its position on the runway, while an aircraft attempts to depart. Aircraft claims not to have heard the announcement of the presence of the tug on the runway. Tower Controller uses radio and tells departing aircraft to stop. Tower is not open when this happens.

- Cognitive: Captain sees jet crossing but does not stop despite ATC instruction of abort as that could have been dangerous: 1174573: A Large Transport flight crew on takeoff roll, approaching V1, detects a small passenger jet incurring ahead and a simultaneous command from the Tower to abort the takeoff. The Captain elects to continue at this point and clears the CRJ by less than 100 feet.

- Cognitive: Cessna did not adhere to instruction of holding short of the runway: 1174540: B737-700 flight crew departing Runway 34L at RNO reports a runway incursion by a Cessna taxiing at high speed on Runway 25 through the intersection.

- Cognitive: Human error - controller judgement: 1174209: IAD Specialist reports of a go-around caused by the Local Controller expediting traffic when not necessary. Controller misjudged how long departures would take on the runway, causing arrival to go-around.

- Cognitive: Human error: 1172856: Aeronca and BE-95 pilots describe the events leading up to the BE-95 pilot landing behind the Aeronca without seeing him. The runway is long and the BE-95 pilot had planned a stop and go but rejects when the Aeronca is sighted at the end of the runway.

- Cognitive: Human error - forgot to get Runway from ground control and also missed the vehicle on visual scanning: 1172047: Controller reports aircraft on final asks if a vehicle is on runway they are cleared to land on. Controller realizes he doesn't own runway currently and sends aircraft around. Controller had the correct runway strips in our strip bay, but failed to do a proper scan of that.

- Cognitive: New Pilot with lack of experience flying in controlled airspace and unclear communication: 1171768: Local Controller describes situation where a new pilot causes problems flying into the airport and then taxiing to the ramp. Controller reported communication difficulties with the new pilot who may not be trained completely or familiar with flying in controlled airspace (the pilot did not provide correct call sign when asked, for example).

- Cognitive: Controller forgets about another aircraft on landing roll while clearing another aircraft for takeoff on the same runway: 1168346: PDX Local Controller doesn't cancel takeoff clearance to departing aircraft while previous arrival is still on runway.

- Cognitive: Fatigue and get-home-itis were cited as possible causes: 1167049: C172 pilot reports an unplanned fuel stop and bathroom break at SUA. On departure a hold line is inadvertently crossed (HS2) and the left crosswind turn on course is made without regard to downwind traffic in the pattern, resulting in a NMAC. Fatigue and get-home-itis were cited as factors.

- Cognitive: Communication breakdown between ground controller and Local Control: 1166840: DFW Local Control attempts coordination for a LAHSO aircraft, when Ground Control advises Local, that he doesn't need this information. Local clears aircraft for takeoff, then observes Ground crossing traffic without approval. Local cancels takeoff clearance of departing aircraft.

- Mechanical: Controller's view blocked by another aircraft: 1165199: Controller working Local position describes incident where he could not see slow moving aircraft exiting runway position because view was blocked by another aircraft, while departing aircraft rejects take-off. "Everyone was at the wrong place at the wrong time."

- Cognitive: Procedural error: 1160105: Reporter describes a runway incursion by a departing aircraft and a vehicle doing inspections on the runway. Vehicle had to take evasive actions to avoid a collision. Narrative: Aircraft X departed Runway 8 while an airport vehicle was conducting a routine runway inspection. The vehicle had to take evasive actions to avoid a collision. I was working the Operational Supervisor in Charge (OSIC) position in the TRACON. The FLM in Tower advised me of the runway incursion. I then notified the OM who had just left the building. Subsequently, I notified the ATM who in turn notified the [Union] REP. I completed the MOR entry in CEDAR and advised the Eastern Region (ROC) Specialist. The ROC advised me that when they received the MOR the Regional QCG Officer would be notified. ALSO, the ASDE-X did issue a runway occupied warning to the Controller and as Facility Operating Procedure the LED ribbon display showing Runway 8 occupied was in use.

- Cognitive: No NOTAM's for snow removal, not sure if snowplow operator was aware of the incursion. No airport personnel utilizing CTAF was observed. 1151260: PC12 pilot reports encountering a snowplow on the takeoff roll entering from a crossing runway. The reporter is at rotation speed when the snowplow enters and is able to fly over the plow. No reports were heard on the CTAF before or after the incident.

- Cognitive: Procedure - one aircraft did not yield to 1144987 $another$: After an air carrier landed at MSP, the Captain stopped abruptly with the aircraft's tail over the runway while another aircraft was taking off on that runway because taxiing traffic [ahead] did not yield. " This was way to close and EXTREMELY lucky; the aircraft taking off/departing was light. Had that been a heavier aircraft with a longer takeoff roll, then the probability of a collision would have been imminent. I sincerely hope the crew of the other flight that did not yield is disciplined. Their actions were willful misconduct and criminally negligent."

- Cognitive: Communication error: 1138890: A low time Private Pilot practicing full stop takeoff and landings in a PA-28 misunderstood the Tower's clearance and taxied onto the departure runway to start his takeoff roll just as an unspecified second aircraft passed closely overhead intending to land on the runway as cleared.

- Cognitive: Communication error: 1125461: C206 pilot reports a vehicle entered the runway ahead as the aircraft nears Vr and rejects the takeoff. The vehicle driver had failed to adhere to Tower instructions.

- Cognitive: Pilot error: 1124300: A pilot taxiing on Runway 4 to Taxiway P, was cleared to cross Runway 30L, but became confused and realized after crossing Runway 30R that he did not have clearance to do so.

- Cognitive: Communication error between Tower and Ground Controller: 1123918: A MDW Ground Controller and two B737 pilots describe the confusion which developed between Tower and Ground when a Cessna Citation was cleared for takeoff while the B737 was cleared to cross that aircraft's runway. The Captain stopped the aircraft barely clear of the runway.

- Mechanical: No signage either painted on the taxiway or vertical, visible for the hold short line for the runway. No signage painted on the ground either. Also baggage door opened requiring rejected takeoff: 1120717: M20 pilot reports confusing Runway 17L for Taxiway F at DWH airport after being cleared to cross Runway 17L, causing an aircraft to go-around. When cleared for takeoff the baggage door opened requiring a rejected takeoff and stopping to latch the door.

- Airspace: Runway exits too far apart : 1118915 : A DEN Tower Controller and an air carrier pilot reported the air carrier failed to make a high speed turn off, so after the go-around command to an aircraft on approach was blocked, that aircraft landed. The Controller commented the DEN airport's general lack of high speed turn offs.

- Mechanical/Cognitive: Communcation breakdown - No radio call from other aircraft, mechanical - curvature of the land made it impossible to see far end of the runway: 1108943 : C172 pilot reports announcing his intentions to cross the active runway on CTAF then noticing a twin turboprop accelerating towards him during the crossing.

- Cognitive: "The Baron had become visible to us as it made a turn on a taxiway. Ultimately, the Captain and I had a conversation after that flight. We believe, due to the on-demand nature of our work, as a crew, we have to operate under immense pressures to get in the air quickly. For the majority of our flying occurs during night hours, we can become complacent about slow traffic at non-towered airports. " 1107908: Turboprop First Officer reports announcing intentions to depart Runway 5 at AND airport then learned that a Baron is rolling out opposite direction.

- Mechanical/Cognitive: Loss of engine power caused pilot to land successfully, but it was a stressful landing, and the pilot exited runway on the wrong side: 1102453: Following a loss of engine power while on short final, the pilot of a C172 landed successfully, but exited the runway to the wrong side, and entered an active runway. ATC subsequently cancelled the takeoff clearance for a departing aircraft.

- Cognitive: Distracted pilot, flights waiting behind him urging him to hurry up: 1101386: C177 pilot, distracted by programming two GPS units and an iPad, and also conscious of traffic waiting behind him, started to taxi onto the active runway causing an aircraft on final to go-around at a non-towered airport. "I was at the runup area when I started programming my panel mount GPS, my portable GPS and my iPad. I also tried to figure out where the ELT was coming from. It must have taken longer than I expected because I didn't realize that the other plane was waiting to takeoff behind me. He came on the radio and said, 'You know, I'm burning 30 gallons an hour sitting here.' I immediately headed toward the runway to takeoff when he yelled over the radio 'STOP! There's an aircraft on short final.' I stopped and immediately saw the aircraft. Fortunately I did not enter the runway, but the plane on final had the good sense to go-around. ”

- Mechanical: Pilot did not recognize thin yellow LAHSO line, and also did not receive any NOTAMs about runways being used as taxiways: 1101156: An air carrier crew missed the CYUL Runway 06 LASHO line on Runway 10/28 because they did not recognize the thin yellow line as a LASHO line and also did not receive the NOTAM indicating Runway 10/28 was being used as a taxiway.
- Cognitive: Fatigue induced complacency and familiarity: 1074183: While taxiing on intersecting runways for takeoff, an MD-83 flight crew experienced a close encounter with a Cirrus on final to a runway they had been cleared to hold short of. Fatigue induced complacency and familiarity were cited as contributing factors.
- Cognitive: Distracted pilot did not scan properly, other aircraft did not have any radio: 1066447: PA44 pilot reports clearing the final approach path with a 360 degree turn before announcing a takeoff on CTAF. An antique aircraft executes a go-around as the reporter enters the runway.
- Cognitive: “blatant disregard of established procedures and safety”: 1066416: An executive jet departed non-tower airport while M20K aircraft was on GPS approach, causing M20K to take evasive action. The executive jet taxied to the hold short line and then, without warning and without any announcement on the UNICOM frequency, pulled into the runway.
- **In the ASRS document: ”primary problems” are listed as ‘Human Factors’, ‘Procedural’, etc.**

Terminal Issues

- Not applicable

En-Route Issues

- Not applicable

Unsafe Situation Indicators

- Runway incursion

Safety Factors - Predictable

- None applicable

Safety Factors - Not Predictable

- Construction work closing and opening taxiways
- Runway closure information was not received by ANC Tower

- Layout of the Tower Cab window pillars blocked view of controller. Controller asked one airplane to cross a runway while another was just about to touch down on the same runway. Blind spots for Controller.
- CLT Local Controller forgets to fill his strip to remind him of runway crossing and asks another pilot to take off from the same runway
- Lack of use of memory joggers to indicate who owned the runways
- Communication errors/breakdown: Aircraft did not hear announcements about a tug being on the runway; Local Control and Ground controller had communication and coordination breakdown
- Pilots not adhering to instructions
- New pilot that may not have experience with flying in controlled airspace and also communicating properly with controllers and ground control
- Fatigue and get-home-itis.
- "Being at the wrong place at the wrong time."
- Random incident such as baggage door open that required a rejected takeoff and stopping to latch the door
- Lack of visible aids on the taxiway or runways indicating where should the pilot stop, e.g., hold short line
- Could not see far end of the runway due to the curvature of the land
- Immense pressure to get in the air quickly
- Mistakes/errors from the ATC
- Distracted pilot, e.g., distraction caused while programming two GPS units and an iPad, and also conscious of traffic waiting behind; potential mechanical issues on mind as pilot was picking up an aircraft from the paint shop
- Not receiving NOTAMs that certain runways are turned into taxiways
- Pilot not recognizing the thin yellow line as a LAHSO line
- Overtaxed ATC may miss other carrier's response/non-response to Tower's instructions
- Vehicles crossing runway at non-towered airports
- lack of instrumentation (e.g., radio) in antique aircrafts
- Pilot fixated on the aircraft called base to final, but did not scan all of final
- Pilots not following established rules and regulations. Same for ATC sometimes

Revealing Quotes

- 1188420: We already have ASDE-X and associated RWSL's at intersections, would it be possible to wire a small red LED light into all the Local Control positions strip bays, and link it to the RWSL's? That way when the RWSL's are activated the LED light would come on and indicate that the runway is unsafe to cross/enter, regardless of any blind spots we might have. It wouldn't even have to be very bright, but I feel something like that would be such a quick and efficient reminder to not cross, or approve any other runway operations.
- 1181349: I would recommend that the SOP be amended to require a positive memory aid, like a strip vertically across the bay. I find the runway ownership strip useless. The absence of the strip at the position is not an attention getter. We worked for decades without them, with no problem. Since they are mandated by national order, we are stuck with them, unless that changes. They don't do any harm, nor do they do any good in my opinion. Other memory aids such as "RUNWAY CLOSED" is a positive flag that is hard to miss.

C.11 Extracting Safety Factors from Controlled Flight Toward Terrain ASRS Reports

Surface Issues

- Not applicable.

Terminal Issues

- Environmental and Cognitive : Terrain : 1206838: Flight climbed too slowly or delayed starting the climb for terrain ahead.
- Cognitive : Missed obstacles depicted on chart: 1199444 : Did not notice obstacle depicted on chart as flight turned toward airport on visual approach.
- Cognitive : Fatigue and Environmental : Conditions worse than forecast : 1198716 : Tired from avoiding convective activity en route, expected to see the runway at decision altitude, conditions worse than forecast so did not see the runway, did not do a missed approach, get-home-itis and brain freeze.
- Environment: Tailwind : 1196310: Unforecast IFR, numerous TS cells near airport, tailwind requiring circle to land, loaded wrong approach into FMC, incorrectly modified to cleared approach, got EGPWS alert, the ESCAPE maneuver led them into a heavy thunderstorm.
- Cognitive : Technique : 1195963 : High sink rate on appraoch, led to terrain warning and a missed approach.
- Cognitive : Communication Congestion : 1195909 : Pilot not following instructions. Pilot missed readback twice. Controller missed the second wrong readback because two other flights were checking in on frequency.

- Airspace : Obstacle : 1195033 : Radio antenna too close to runways (at TEB). Almost ran into it on visual approach. Ignored the EGPWS alerts, thinking they were irrelevant and based on the buildings much lower.
- Environment: Weather - VFR into IMC: 1194685 : Hit a tree top on very low base turn in IMC.
- Airspace : Glideslope OTS : 1180612 : Too low on approach because glideslope was out of service. TRACON not aware of issue so initially approved ILS approach.

En-Route Issues

- None.

Unsafe Situation Indicators

- Too close to nearby terrain or obstacle
- Below the Minimum Altitude (or Minimum Vectoring Altitude) for an area
- Controller issues ”Low Altitude” alert
- Ground Proximity Warning System alert (check parameters under which it issues warning; can use for threshold)
- Unstable approach

Features - Computable

- Climbing too slowly to clear terrain ahead
- Descending too low for obstacles in area (below minimum safe altitude)
- Obstacles near an airport
- Descending below approach minimums
- Descending below decision altitude
- Unstabilized approach – too aggressive a descent, high sink rate
- Night VFR (more difficult to see obstacles or terrain)
- Fatigue caused by avoiding convective activty en route
- Weather worse than predicted
- Moderate rain
- Numerous TS cells near airport, windshear
- Turbulence (low level, near airport)

- Tailwind (15 kts max for one flight)
- Wet runway
- Flight on approach deviating from procedure (puts that flight in jeopardy and could lead to unforeseen actions that bring him too close to another flight)
- Radio congestion (two aircraft checking in while another flight was not reading back clearance correctly)
- Poor radio coverage in area
- Distraction caused by changing runways
- Time of day – landing into the sun at dusk
- Time of day – visual approach at night
- Time of day – very early morning, contributes to fatigue
- Severe turbulence – that causes significant downdrafts
- Glideslope OTS

Features - Not Computable

Revealing Quotes

- Rain, visibility 2 miles, fog. ... Deteriorating weather had closed in behind us ...
- Heavy to extreme precipitation.
- Gains and losses of 20 knots on final with severe turbulence.
- 10 mile gap between two areas of heavy precipitation that could get the aircraft to the [runway] final approach course.
- It was [very early morning] and without any doubt fatigue was a contributing factor. This is probably why I missed when the aircraft caught up with the glidepath and descended below it. My First Officer also felt fatigued. We were both called out on short notice to fly this flight.
- I definitely believe that fatigue played a major role in this case. It was the last leg of a very long day and also visual approach to a night landing.
- My copilot was trying to get a request in for lower, but the frequency was congested.
- Contributing factors was the fact ATC was trying to get us in before visibility conditions at the airport deteriorated.
- A number of distractions before takeoff I believe contributed to my confusion on the direction of turn.

- Frankly, as erratically as the pilot was flying the ILS, I was very surprised that a go-around/missed approach did not occur. This is another vivid reminder to be prepared for anything in ATC, especially during low IMC conditions.

- Based on the early morning hour I thought it would be prudent to utilize a high level of automation. [...] My experience suggests that in this situation I attempted to use too much automation.

- 500+ foot tall radio antenna. [...] obstacle wasn't readily visible – even on a clear day.

- [...] shame on me for disregarding the GPWS advisories when I thought them to be irrelevant.

- The pilot continued to deviate from instructions. [...] Issue the Brasher phraseology.

- Was confused by the unexplained loss of coupling and distracted by trying to get it back. [...] Might have been 2 previous nights of sub-optimal sleep, leading to some degree of degradation of alertness.

- Weather, turbulence, unforecasted IMC conditions and being issued a new approach are really not conducive to a stable, safe approach procedure.

- [...] were fighting to avoid numerous cells, moderate rain and very turbulent conditions.

C.12 Extracting Safety Factors from Pilot / Controller Communications ASRS Reports

Surface Issues

- Airspace : Closed Runway : 1176821 : Pilots report of taxiing to a runway but crossing a closed runway (due to construction) in the process.

Terminal Issues

- Airspace : Structure : 1182016 : Two aircraft – one departing, one arriving – have a near miss due to proximity of arrival and departure routes.

- Human error ; fatigue, complacency, distraction : 1180378 : Flight landed without a clearance. Was not handed off by TRACON.

- Airspace : Structure : 1177420 : Two different reports with confusion of similar sounding intersections (BLUZZ and BLEWS) in the same airspace causing pilots to turn towards the other one.

- Cognitive : Technique : 1174995 : Small aircraft had to do go-around; came in conflict with departure from parallel runway. Contributing factors: controller could not see small aircraft clearly due to size and sun shining from same direction.

- Cognitive : Training : 1172405 : Trainee controller CIC from LVK Tower reports of NMAC that occurred while training was going on and the communication loss of radios with one of the involved aircraft. Pilot reports of close call between his aircraft and another while attempting to land.
- Cognitive : Communication : 1171562 : B747 flight crew reports an altitude deviation descending into ZSPD due to not converting meters to feet before entering the number into the MCP. Also, task saturation due to changing approach close to airport.
- Airspace : Structure : 1166799 : Situation where crossing runways and a packed final leads to a Controller anticipating movement of departure traffic to be faster then actual speed, causing a go-around of arrival on crossing runway.
- Airspace : Structure : 1164636: An A320 on a DEN Runway 35L ILS received a severe DOWN RED arrow TCAS alerted which the crew interpreted as a descend command and also an aural command, MONITOR VERTICAL SPEED. The crew did not descend because the target was also displayed but they incorrectly interpreted the TCAS command.

En-Route Issues

- None.

Unsafe Situation Indicators

- None.

Features - Computable

- Proximity of arrival routes to departure routes
- New style bright LED runway and approach lights – crew distraction
- Infrequent radio transmissions – crew complacency
- Duty time – crew fatigue (5 hrs prior)
- Time of day: night time
- Similar sounding intersections (e.g., BLUZZ and BLEWS)
- Closed runway
- Time of day: Tower Controller looking into the sun
- Training operations: controller
- Approach in use different than approach assumed in flight plan – crew distraction programming FMS
- Communication frequency blind spots in area

- Radar out of service
- Military break-up (going from formation flight to individual flights)
- Crossing runways with one used for arrivals, the other for departures – LOSS if go-around
- Crosswind on parallel approaches (cause traffic to overshoot final approach course)

Features - Not Computable

- None.

Revealing Quotes

- The surface winds were out of the north northeast at approximately 020 degrees at 25 KTS with low overcast ceilings and visibility less than one mile in blowing snow. (also) The current weather was varying between 2,400 to 4,500 RVR, blowing snow, low ceilings, and winds out of the northeast at approximately 25 KTS.

C.13 ASRS: Weather Incidents

Surface Issues

- Mechanical: ACN :90813 : Cleared for landing in wet conditions. Aircraft hydroplaned after landing due to unreported pools of water.
- Weather: ACN:89273: Heavy rain and wind caused run excursion.
- Enviournmental : 575219 : Proper landing but lost control of the aircraft due to icing on the ground.

Terminal Issues

- Mechanical: ACN: 1101304: Multiple devices failed during takeoff. Probable cause was hot temperature. No mention of emergency landing or diversion.
- Mechanical: ACN : 89273 : Heavy rain and wind caused some damage to the aircraft. Precaution to wait for weather to clear or a go around mentioned.
- Mechanical: ACN :90813 : Cleared for landing in wet conditions. Aircraft hydroplaned after landing due to unreported pools of water.

En-Route Issues

- Environmental: ACN 584753: Captain reported sudden turbulence with no warning for 30 secs. One flight attendant knocked unconscious.
- Cognitive: ACN 589996: Pilot took decision to take 230 deg heading instead of the 150 deg mentioned by the controller in a fast moving weather.

- Environmental: ACN 612527 : Turned off the autopilot to avoid thunderstorm but results in a 600 ft. altitude change from assigned position.

- Cognitive: ACN: 758892: Pilot was unable to get clearance to change the route due to the weather. Declares emergency to maintain separation.

- Environmental: ACN: 791021: Experienced wind shear in the final approach did not land did a go around.

- Environmental: ACN: 847439 : Experienced a severe turbulence at FL350. No warning observed on the radar screen. Resulted in short term altitude loss.

- Cognitive: ACN:476100 : Emergency declared when ARTCC would not co-operate request for weather avoidance maneuvering.

- Cognitive: ACN: 838058 : Unexpected tailwind during the final approach. Fatigued air carrier flight crew made a go-around at 1000 FT due to not having attained required stabilized approach criteria.

- Environmental: ACN: 934616 : Dwindling fuel reserves and rapidly accumulating ice, an A319 flight crew declared an emergency in order to get an expedited approach.

- Environmental: ACN: 1141709 : Captain noted thunderstorm activity near destination airport, but elected to continue due to apparent air mass conditions that were not conducive to convective activity. A go-around was initiated at 2,000 FT due to wind-shear encounter.

- Environmental: ACN: 441890 : Aircraft encountered unforecast weather and declared emergency landing at closest airport.

- Environmental/Cognitive: ACN: 80713 : Mis-communication at the landing approach during a severe weather. Missed approach and declared emergency.

- Environmental: ACN:80726 : Descended early to avoid possible thunderstorm ahead. One attendant injured. Flight was normal after the incident.

- Environmental: 80675 : Were kept waiting and rerouted several times due to bad weather at NY. Fuels levels reached the minimum required and critical at the time of landing.

- Environmental: 103750 : Engine damage from icing during takeoff.

- Environmental: 106139 : Due to air drafts lost considerable altitute over 2000 ft. Led to formation of ice and damaged pilot side window.

- Environmental: 580748 : Embarer 120 during climb encountered severe weather with hail storm causing the wings to damage.

Unsafe Situation Indicators

- Missed Approach
- Unclear instructions from ATCC
- Misunderstanding and/or misinterpreting instructions
- Heading and altitude control difficulties
- Loss of separation
- Improper coordination (E.g. ACN 1187886)
- Low Fuel levels for landing
- Passenger Injury
- Passenger/Flight crew knocked unconscious (Eg : 308574)
- Runway excursion

Safety Factors - Predictable

- Airspeed
- Poor altitude control
- Incorrect heading
- Congestion in airspace
- Weather-related (icing, turbulence)
- Likelihood of loss of separation
- Mechanical system failures (E.g. ACN: 1101304)
- Altitude loss

Safety Factors - Not Predictable

- Mechanical issues noticed after inspection (E.g. ACN 89273)
- Unclear instructions, misunderstanding/misinterpreting instructions
- Incorrect autopilot
- Poor ATC communication
- Sudden altitude loss
- Incorrect operations/procedures

Revealing Quotes

- ACN 81196: PREPARE FOR IMPACT

C.14 Extracting Safety Factors from NTSB Aviation Database Reports

Table C1: NTSB Aviation Database Relevant Reports

Date	Event Synopsis
2/15/15	Turbulence, clear air, not forecast.
8/22/14	Wake turbulence.
5/28/14	Bird strike: common loon during descent to land. 10mi from airport, descending through about 3500 to 3000 ft MSL.
2/17/14	Turbulence, clear air, not forecast.
12/23/13	Bird strike; after takeoff from STL.
9/29/13	Turbulence, known moderate-to-severe, RNO.
8/14/13	Crashed short of the runway: Unstabilized approach, descent below minimum approach altitude; expected to break out at 1000 ft AGL due to incomplete weather info; fatigue, distraction, or confusion; fatigue due to acute sleep loss resulting from ineffective off-duty time management and circadian factors.
3/7/13	Tailstrike: incorrect airspeed and pitch attitude.
2/19/13	Turbulence, light to moderate.
12/5/12	Bird strike: snow goose, 1800 EST, descending through 7000 ft on approach to LGA; 30 mi SW LGA, 200 kts, night VMC.
9/18/12	Turbulence, severe on descent into CLT. SIGMET issued for strong winds and embedded TS.
7/31/12	Bird strike: on descent to DEN; damage to pitot tube, resulting in loss of airspeed information.
6/12/12	Turbulence, severe, near Winnie, TX.
5/10/12	Turbulence, 12,400 ft, 45mi W FLL, on descent.
4/27/12	Loss of Separation, simultaneous independent runway operations on runways that do not physically intersect but whose flight paths intersect (LAS, go-around on 25L, departure on 19L; two controllers).
4/15/12	Turbulence, mountain wave, FL320, near Buena Vista, CO; no PIREPS.
3/20/12	Turbulence, moderate; active AIRMET for moderate turbulence, SIGMET for severe turbulence active for area W of accident location; Laverne, OK.
2/23/12	Turbulence, moderate; 2-3 sec after smooth air for more than 30 min; no AIRMETs, no PIREPs.
2/18/12	Turbulence, severe; active SIGMET for occasional severe, 29,000 ft MSL.
12/1/11	Runway incursion; Tower LC cleared aircraft to cross runway immediately after clearing another aircraft to depart.
10/19/11	Turbulence, moderate; climbing through FL220.
9/29/11	Turbulence, clear air moderate, descending through 16,000 ft MSL, more than 20 mi from any significant weather.
9/26/11	Bird strike: red-tailed hawk, on runway at DEN, landing.

9/10/11	Turbulence, continuous moderate, FL270 near TS.
8/8/11	Controller error: NMAC in airport airspace; aircraft departing rwy 32L passed within close proximity to aircraft on approach to rwy 9R; controller distracted by coordination requirements affecting two other airplanes.
7/29/11	Turbulence, convectively induced; on climbout (peak vertical acceleration of over 2G).
6/19/11	Controller error: NMAC in airport airspace; tower LC controller cleared two aircraft for takeoff from runways with intersecting departure flight paths without ensuring the first aircraft had passed the flight path intersection prior to clearing the second aircraft for takeoff (aircraft departing rwy 18 passed with 0 ft vertically and 300 ft laterally from aircraft departing just 16 sec later from rwy 14).
6/5/11	Turbulence, convective, moderate: descending through 15,000 ft, flying around thunderstorms.
5/23/11	Turbulence, convective: FL340, approximately 200 mi NE ATL, maneuvering between two cells, inadvertently entered the edge of a cumulus buildup.
5/16/11	Controller error: NMAC in airport airspace; tower LC failed to adhere to runway separation requirements and issued an improper takeoff clearance. Controller forgot about the arrival inbound to a crossing runway. (At Chicago, aircraft landing on rwy 9R and aircraft departing rwy 32L. Passed within 480 ft horizontally and 275 ft vertically of each other.)
5/9/11	Turbulence, unforecast convective: Flight was passing through or over the extreme top of a rapidly developing area of convective weather at FL320.
4/16/11	Turbulence, moderate to severe, anticipated: Descending out of FL200.
4/11/11	Turbulence, convective, moderate then severe: Entered cumulus cloud due to delay from ATC in approving a deviation. Vertical acceleration forces from 2.2G to 0.6913G within 1 sec, to a minimum of 0.496G about 5 sec after the 2.2G maximum. No SIGMET, no PIREPs, no indication of turbulence on weather radar.
3/26/11	Turbulence, convective: developing TS under the flight path during the airplane's climb to cruise flight.
3/23/11	Controller loss of consciousness: lack of sleep, fatigue resulting from working successive midnight shifts, and ATC scheduling practices. Tower controller was working alone at Reagan Washington National Airport. Investigation revealed that the controller on duty had the necessary preconditions for the development of fatigue at the time of the event, specifically acute sleep loss in the 24 hours before the event and circadian disruption as a result of working the midnight shift.
3/11/11	Controller error and aircraft transponder inoperative: The air traffic controller's failure to adhere to required radar identification procedures, which resulted in loss of separation between the departing Boeing 757 and three other airplanes. Contributing to the incident was the pilot's inadequate preflight checks, which resulted in the airplane departing with an inoperative transponder.
2/27/11	Turbulence: PIREP for light-to-moderate chop between 20,000 ft and 16,000 ft. Aircraft encountered moderate turbulence at 24,000 ft.
2/19/11	Turbulence, severe: On approach at approximately 6,000 ft.

1/31/11	Ice on runway: Controller warned flight crew of ice reported on rwy 6L and possible ice on rwy 6R. Aircraft slid off runway attempting to land on 6R. A special weather observation taken after the incident reported wind from 070 at 8 knots, visibility of 7 miles in light freezing rain, an overcast ceiling at 1,900 feet above ground level, a temperature of -4 degrees Celsius, a dew point of -8 degrees Celsius, with the altimeter indicating 30.10 inches of mercury. Freezing rain began about 3 minutes prior to the incident and an accumulation of .01 inches of snow had fallen in the 14 minutes prior to the start of the freezing rain.
1/20/11	Controller error, New York Center (ZNY): B777-200 and flight of two C-17s came within approximately 0 ft vertically and 0.38 mi laterally from each other. TCAS RA issued. Probable cause from NTSB: Incomplete and incorrect coordination between air traffic controllers that resulted in the 777 and the two C17s being cleared to maintain the same altitude (FL220). Contributing to the incident was the controller's non-adherence to established communications phraseology and incorrect data entry into the radar data blocks for each aircraft.
12/31/10	Runway incursion, operations vehicle: The driver of the operation vehicle's misidentification of the runway for an adjacent taxiway, resulting in a runway incursion with an aircraft in position for takeoff.
12/9/10	Controller error: potential NMAC, averted by pilot attention: B737 LUAW, held for helicopter on departure path 4 mi from rwy, B737 issued takeoff clearance. E-145 on approach to same runway, 1/2 nm short final, pilot queried about go-around. Controller issued go-around. Airport Movement Area Safety System alerted at about the same time. No loss of separation.
12/3/10	Turbulence, clear air but convective activity in the region, moderate. On departure. Although no convective activity was noted at the accident location at the accident time, satellite imagery identified convective activity in the region. The airplane was ascending near a boundary defined by a significant decrease in atmospheric moisture. This type of boundary is conducive to the propagation of gravity waves and most likely contributed to the convectively-induced turbulence that the airplane encountered.
11/30/10	Turbulence, forecast. Active SIGMET for occasional severe turbulence between 14,000 ft and 24,000 ft, backed up by PIREPs. Aircraft encountered light then moderate turbulence at 15,000 ft.
11/15/10	Bird strike. During climb through 5,000 ft MSL. Large flock. Minneapolis, MN.
11/11/10	Controller error: Loss of separation in ARTCC airspace. B737 and A319. Operating in same sector but under control of two different controllers due to early handoff to next sector controller for the A319. Both controllers had dropped the data tags for the flights they handed off to the other controller. Aircraft came within 1800 ft vertically and 2.81 mi laterally. (FAA requires 2000 ft vertically or 5 mi lateraly.)
11/8/10	Bird strike, Common Loon (avg weight 10.9 lbs), approach to land at LAX.
9/16/10	Controller and pilot error: NMAC in airport airspace. A320 departed rwy 30R, Beech 99 departed rwy 30L. Two aircraft converged 1/2mi NW of rwy 30L, coming within 0 ft laterally and 50 ft vertically. Beech did not turn to assigned heading early enough, controller distracted with ground operation to notice deviation.

9/4/10	Controller error: NMAC in airport airspace, class B. B737-700 passed within 700 ft laterally and 200 ft vertically of a helicopter operating under VFR. NTSB: Failure of the air traffic controller to exercise positive control of the situation by issuing clear and timely control instructions to the helicopter pilot. Contributing to the incident was delay by the helicopter pilot in responding to instructions issued by the controller.
8/10/10	Bird strike, white pelican: On downwind leg of traffic pattern during visual approach. Large flock of birds. SLC.
8/9/10	Pilot deviation, NMAC. In cruise at FL290, TCAS RA to climb issued to Embraer 170. Radar data indicates that a U.S. Air Force Northrop Corporation T-38 Talon, call sign FAST 13, was on a cross country instrument training flight at 28,000 feet and deviated to 28,600 feet for approximately 30 seconds as it was converging on Shuttle America flight 7630.
7/20/10	Turbulence, convective, forecast: B777 at FL340. Airplane flew through an isolated cell of convective weather with a large area of storms about 40 miles to the north of the flight path.
7/15/10	Turbulence, clear air. Navigating around scattered cloud build-ups. Nothing was showing on radar. According to the operator, no turbulence was forecast for the area in which the airplane was flying at the time of the turbulence encounter. In addition, satellite imagery revealed that the airplane was in an area not conducive to turbulence when the event occurred. According to the flight data recorder, the vertical acceleration during the turbulence encounter varied between +1.5 g and -0.3 g. The encounter lasted about 5 seconds.
6/28/10	Turbulence, convective. Crew noticed a very small red return (thunderstorm cell)on the radar about 5 miles in front of them. The crew did not have enough time to take evasive action and they penetrated the cell, encountering moderate rain with a strong updraft followed by one instance of a severe downdraft. NTSB: The inadvertent encounter with convective weather during cruise flight. Contributing to the accident was the flight crew's failure to detect and avoid the thunderstorm cell earlier in the flight, and the failure of air traffic controllers to provide the convective weather information to the flight crew.
5/25/10	Turbulence, clear air, unforecast. Downdraft of about 13 ft/sec, followed sharply by an updraft of about 24 ft/sec. Analysis of the surrounding atmosphere and GOES-3 satellite photographs indicated the presence of icecap wave instability along the airplane's route of flight that was capable of producing rapidly changing vertical winds on the order of 20 feet per second, which resulted in conditions conducive to severe turbulence.
5/21/10	Controller error: NMAC in airport airspace. A319 executed a missed approach for rwy 14, converging with B747 departed from rwy 25R. Aircraft came wtihin 100 ft vertically and 0.33 mi laterally. NTSB probable cause: The approach controller's delayed transfer of communications on the A319 to the tower controller and failure to account for the aircraft's speed when he directed the crew to turn north. Contributing to the incident was the 747 crew's transfer of radio communications to departure control prior to being directed to do so by the tower controller.
4/29/10	Turbulence, convective: The flight crew's inadequate separation from convective activity. Vertical acceleration from 0.5 to 2 Gs and an altitude change of 100 ft in each direction.
4/29/10	Controller error: NMAC in airport airspace; controller did not issue control instructions necessary to ensure positive control/standard separation of traffic operating within the Class C airspace. CRJ-200 was on base at 1500 ft and AStar 350 was maneuvering nearby at 1400 ft. Helicopter was operating under VFR. Conditions: dusk, VMC.

4/28/10	Controller error: NMAC in airport airspace; controller did not issue control instructions necessary to ensure positive control/standard separation of traffic operating within the Class B airspace. B737 and Bell 207 came within 125 ft vertically and 100 ft laterally as a result.
4/21/10	Controller error: NMAC in airport airspace: Departing Embraer regional jet conflicted with Raytheon-Beech King Air conducting navigational flight check. Training controller issued improper takoff clearance. Controller instructor did not notice error and failed to intervene.
4/19/10	Controller error: Cessna 172 in departure of touch and go flew in front of B737 which was on landing rollout. Controller distracted by another departing aircraft, attention focused on radar display, not out the tower window.
4/5/10	Turbulence, convective. Airplane entered a cumulus or convective cloud system and encountered moderate to severe turbulence as it approached its destination.
4/3/10	Turbulence, clear air. Embraer in cruise at 31,000 ft. Captain noted a change in wind direction and speed. Maximum and minimum vertical accelerations during the turbulence event were 1.902 g and -0.199 g, respectively.
3/27/10	Controller error: NMAC in terminal airspace: Boeing 777 and a Cessna 182 transiting the Class B surface area passed within approximately 480 feet laterally and 300 feet vertically of each other. Local controller issued a takeoff clearance to the Boeing 777 without ensuring that approved separation would exist with the Cessna 182. Contributing to the incident were tower procedures that permitted transitioning aircraft to cross the runway 28 departure corridor at low altitude while runways 28L/R were in use.
3/25/10	Controller error: LOSS/NMAC: B737 and Gulfstream II passed within 1.04 miles laterally and 300 feet vertically. Required minimum separation was 5 miles and 1000 feet. R10/12 controller issued an improper vector and descent clearance to the GII to avoid restricted airspace that put the airplane on a coverging flight path with the B737. Contributing to the incident was the failure of the FAA's training program to correct ongoing controller performance deficiencies before certifying the D10/12 controller to work without immediate supervision.
3/19/10	Pilot error: sun angle: Cessna 208 overflew B737 (by 50 feet) holding in position to takeoff on runway 25R. Cessna was given clearance to land on 25L. Pilot reported difficulty seeing runway because of setting sun.
3/12/10	Lightning strike: Embraer received damage to tailcone bulkhead that inhibited full travel of elevator during approach.
3/11/10	Turbulence: FL240 Airbus A319 experienced unexpected severe turbulence for 1 to 2 seconds. The maximum g recorded was 1.773 and the minimum g recorded was 0.391.

Notes:

- Airbus weather radar system includes a Turbulence detection function to detect ”wet” (convective) turbulence.
- Reduced airspeed prescribed for turbulence penetration.
- Chicago airport is not equipped with automated assistance for detecting conflicts between departures and arrivals on crossing runways.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704–0188

1. REPORT DATE *(DD-MM-YYYY)*
01-12-2015

2. REPORT TYPE
Technical Memorandum

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Real-Time Monitoring and Prediction of Airspace Safety

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Indranil Roychoudhury, Lilly Spirkovska, Matthew Daigle,
Edward Balaban, Shankar Sankararaman, Chetan Kulkarni,
Scott Poll, and Kai Goebel.

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
NASA Ames Research Center
Moffett Field, California 94035

8. PERFORMING ORGANIZATION REPORT NUMBER
NASA/TM–2015–218928

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSOR/MONITOR'S ACRONYM(S)
NASA

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
NASA/TM–2015–218928

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified-Unlimited
Subject Category Distribution: Standard
Availability: NASA CASI (301) 621-0390

13. SUPPLEMENTARY NOTES
An electronic version can be found at http://ntrs.nasa.gov.

14. ABSTRACT

The U.S. National Airspace System (NAS) has reached an extremely high level of safety in recent years. However, it will become more difficult to maintain the current level of safety with the forecasted increase in operations. Consequently, the Federal Aviation Administration (FAA) has been making revolutionary changes to the NAS to both expand capacity and ensure safety. Our work complements these efforts by developing a novel model-based framework for real-time monitoring and prediction of the safety of the NAS. Our framework is divided into two parts: (offline) safety analysis and modeling, and real-time (online) monitoring and prediction of safety. The goal of the safety analysis task is to identify hazards to flight (distilled from several national databases) and to codify these hazards within our framework such that we can monitor and predict them. From these we define safety metrics that can be monitored and predicted using dynamic models of airspace operations, aircraft, and weather, along with a rigorous, mathematical treatment of uncertainty. We demonstrate our overall approach and highlight the advantages of this approach over the current state-of-the-art through simulated scenarios.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			STI Help Desk (email: `help@sti.nasa.gov`)
U	U	U	UU	163	**19b. TELEPHONE NUMBER** ***(Include area code)*** (301) 621-0390

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18