Identification of Safety Metrics for Airport Surface Operations

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Abstract

A large fraction of safety incidents occurs on the ground during airport surface operations. Although these incidents are mostly non-fatal with a few exceptions, they are high profile incidents that remain a source of concern for the National Transportation Safety Board (NTSB), the Federal Aviation Administration (FAA), major airlines, and other stakeholders of the National Airspace System (NAS). These incidents have historically been mitigated by implementing changes to regulations, policies, and procedures over time. This approach has minimized but not eliminated the risk of occurrence of safety incidents. It is thus important to develop integrated techniques to assess, model, and prevent these incidents by analyzing the risk and likelihood of occurrence and communicating results of the analysis to decision-making personnel who can mitigate and prevent incidents in real time. The work presented in this paper builds on a previously developed architecture for safety, Real-Time Safety Monitoring (RTSM), to enable monitoring and prediction of the safety of the NAS. In the RTSM framework, hazards to flight are translated to safety metrics such as *wake vortex encounters* or *loss of separation*, that can be modeled and analyzed offline and also predicted and monitored in real time (online). The intent of this paper is to integrate predictable incidents that occur during surface and ground operations into the safety portfolio of the RTSM project by (i) identifying suitable information sources from which ground incidents can be studied, (ii) developing safety metrics correlated with surface operations, and (iii) recommending suitable data sources that can be quantified and used for the computation of pertinent safety metrics.

I. Introduction

The U.S. National Airspace System (NAS) is a complex aviation system composed of facilities, airports, and airspace. Ensuring the safety of all persons, aircraft, and stakeholders involved in the operations of such a complex system is a critical role of the NAS. To mitigate risk and maintain safety, rules, regulations, policies, and procedures are implemented to cover personnel, equipment, and aircraft at different phases of flight. As a result of these efforts to ensure that operators, aircraft, and necessary technology work cohesively and safely, the NAS is safe with significantly low accident rates and a minimal number of fatalities.

Although the safety of the NAS is currently at acceptable levels, the volume of air traffic in the national airspace, which has increased significantly within the past few decades, is projected to increase even more as demand increases.[1] The integration of unmanned aerial systems into the airspace will increase NAS usage and further stretch the capabilities of the NAS. As a result, to ensure the continued safety of all persons, aircraft, vehicles, and infrastructure in the airspace, a proactive approach must be taken to prevent and mitigate possible safety violations and incidents. Furthermore, more emphasis has historically been placed on ensuring safety during the take-off, climb, cruise, descent, and

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landing phases of flight as opposed to the push-back, standing, and taxiing operations.[2] It is imperative that all phases of aircraft operations, in air and on the ground, are included in the holistic NAS safety endeavor.

A few tools have been developed to increase airport ground safety through aircraft tracking within and outside the U.S. NAS. The European air traffic management agency, EUROCONTROL, utilizes the Advanced-Surface Movement Guidance and Control System (A-SMGCS) - a surveillance, airport safety support, routing and guidance service - to maintain ground safety and throughput in European airports in all weather conditions.[3] However, current ground surveillance technology has some limitations. Surface Movement Radars (SMR) are susceptible to shadows, reflections, or obstruction by airport buildings. Automatic Dependent Surveillance-Broadcast (ADS-B) systems only provide information relative to other ADS-B-equipped systems, and ground receivers that utilize ADS-B can derive location information only if aircraft transponders are switched on and functional. To fill gaps in A-SMGCS surveillance, several projects have worked on surface tracking methods. One of these is a cost-effective video tracking system developed by Bloisi et al.[4] In addition, the European Commission's INTERVUSE project developed artificial intelligence systems that fill in A-SMGCS blind spots using a network of intelligent digital cameras.[5] These include the TRAVIS system, which used a network of calibrated cameras to detect motion, and the ISMAEL project, which tracked magnetic signatures of ferromagnetic objects. These have all been tested in European airports with promising results.[6]

In addition to the plans and procedures outlined in the SMGCS,[7] the United States also uses two newer variants of the A-SMGCS: the Airport Surface Surveillance Capability (ASSC) and the Airport Surface Detection Equipment, Model X (ASDE-X). Deployed across 44 airports (9 ASSC, 35 ASDE-X), both use similar technologies to the A-SMGCS, combining multiple sensor layers from SMRs using Multilateration (MLAT), Airport Surveillance Radar (ASR), and ADS-B information. A Multi-Sensor Data Processor (MDSP) uses safety logic to alert controllers to potential conflicts. While very accurate, these systems require updates and replacements and also have high operating and maintenance costs.[8–10]

Although these improved tracking systems increase ground safety, they typically provide short look-ahead safety nets without predictive capabilities and do not handle the uncertainty inherent in measurements. It is therefore important to consider ground operations as part of a comprehensive NAS safety effort to predict and mitigate unsafe incidents early enough, while considering the uncertainty in forecasts and predictive models. Roychoudhury et al[11] developed one such comprehensive approach to monitoring NAS safety by creating a framework for real-time safety monitoring (RTSM) and prediction of pre-defined safety metrics in the NAS. This framework is configurable and allows for the incorporation of any safety hazard that can be quantified and modeled. To develop the RTSM system, environmental, airspace, and human workload hazards were extracted offline from databases of the National Transportation Safety Board (NTSB), the NASA Aviation Safety Reporting System (ASRS), and the Federal Aviation Administration (FAA). These hazards were then converted to safety metrics - quantities of interest that can be evaluated based on available data and are predictive of an unsafe incident. The safety metrics, such as risk of collision with aircraft/vehicle/structure, can then be modeled offline, monitored online, and predicted online to determine the likelihood of the metrics crossing pre-defined safety thresholds and leading to unsafe events, such as a loss of separation.

To that effect, this paper focuses on the expansion of the predictive RTSM framework to ground safety hazards, as the current safety metrics for the RTSM framework do not account for hazards to ground operations that occur during standing, pushback, and taxi phases of flight. Although a variety of safety incidents are investigated, this paper focuses only on those safety incidents which can be quantified, modeled, and predicted, such as aircraft collisions during taxi. Unpredictable incidents, such as a passenger trips and falls, are outside the scope of this paper and are only briefly discussed.

This paper is structured as follows: first an overview of the RTSM framework, previously developed, is presented. The literature review methods to identify ground operation hazards, incidents, and accidents are then discussed. After which the safety metrics are developed for the pervasive prevailing predictable incidents observed in the literature study. A conclusion and guide to future work, based on the safety metrics and inclusion into the RTSM framework, is finally presented.

II. Real-Time Safety Monitoring Framework Overview

The Real-Time Safety Monitoring (RTSM) framework is a novel architecture developed to monitor and predict the safety of the NAS in real time. The authors of this paper and other RTSM publications consider the term *real time* or *in time* to mean as "required by the user or necessitated by the process under consideration".[12] The framework can (i) be used to model, monitor, and predict hazards to flight as long as the hazard can be modeled quantitatively, (ii) rigorously handle the inherent uncertainties associated with the defined hazards, and (iii) give an overall safety assessment of not just individual flight hazards in the NAS but also an aggregate safety assessment of the NAS or a region of the NAS. This section describes the process of identifying hazards to safety in the NAS and the development of the safety metrics for integration in the RTSM framework. Brief overviews of the modeling, monitoring, and prediction facets are also presented, along with a demonstration of how the framework is utilized to monitor and predict unsafe events in the NAS.

A. Hazard Identification and Development of Safety Metrics

The NASA ASRS[13] and NTSB[14] databases were studied to identify hazards to NAS operations that were frequently occurring or particularly important to safety. These hazards were characterized into four different categories: (i) airspace-related hazards such as congestion or a loss of separation between aircraft, (ii) environmental hazards such as convective weather or bird/animal strikes, (iii) human performance hazards such as pilot or controller error/fatigue, and (iv) aircraft malfunction hazards such as engine or landing gear failure.[11] For the hazards identified, the focus was on those which could be modeled and predicted based on available data sources. Hazards that could not be predicted or modeled are outside the scope of the RTSM framework and include mechanical hazards such as undiscovered mechanical issues, operational hazards such as disgruntled pilots/ controllers and inadequate corporate procedures/policies, and human-related hazards such as lack of situational awareness or confusion by pilots and controllers.[11]

After the individual predictable hazards for the different categories are extracted from the literature, a set of safety metrics and associated thresholds are then developed. These safety metrics, $\boldsymbol{\phi}$, are represented as algebraic functions of NAS states that can be propagated in time. They are quantities of interest that can be monitored and predicted in order to predict unsafe events. In this paper, an unsafe event is defined as a transition event from an acceptable to unacceptable region of $\boldsymbol{\phi}$. The boundaries between the acceptable and unacceptable regions are defined through threshold equations, $\mathbf{T}_E(\boldsymbol{\phi}(k))$[11] which can be obtained from subject matter experts, FAA and ICAO (International Civil Aviation Organization) regulations, airline Safety Management Systems (SMS), aviation best practices, etc. Although these safety metrics and associated threshold equations/values can be non-trivial to determine, the customizable RTSM framework allows individual users/operators to modify the safety metrics and thresholds so long as there are appropriate data sources for modeling and prediction.

As an example, a *loss of separation* between two aircraft, considered an *unsafe event*, can be predicted by monitoring the *aircraft separation* distance between the two aircraft. In this case, the safety metric is the *aircraft separation* with a safety metric function of parameters that may utilize the aircraft identifiers, aircraft velocities, intended flight path, coordinates, etc., to output the distance and altitude difference between the two aircraft as well as their relative headings with respect to one another.[11] The threshold in this case can be obtained from aviation separation standards for en-route flight: 5 miles for lateral separation and 1000 feet for vertical separation. In the following sections, an overview is given of how the safety metrics are monitored with respect to their thresholds by keeping track of a *safety margin*, the distance between the current value of a safety metric and its pre-defined threshold.

B. Monitoring and Prediction

Once the safety metrics are defined and hazards identified, a model-based approach is utilized to develop models of the different components of the NAS in order to monitor and predict their evolution with time. At any discrete time k the NAS is in some state

$$\mathbf{x}(k) = [x_1(k), x_2(k), ..., x_n(k)]^T, \tag{1}$$

where x_i(k) can be aircraft positions and velocities, weather positions, etc., for $i = 1 : n$ where n is the number of states under consideration in the NAS. From these states, a vector of safety metrics, $\boldsymbol{\phi}$ can be computed from algebraic functions, **F**, of the states. Thus, if we know the state of the NAS, **x**, at any discrete point in time, k, we can compute the associated safety vector, $\boldsymbol{\phi}$.

Within the space of $\boldsymbol{\phi}$, unsafe regions exist that are unacceptable to NAS operators and stakeholders. These regions correspond to unsafe events $e \in E$ such as an aircraft encountering a convective weather region, another aircraft's wake vortex, or a loss of separation.

$$E = \{e_1, e_2, \ldots, e_p\}. \tag{2}$$

The boundary between a safe/acceptable and unsafe/unacceptable region of $\boldsymbol{\phi}$ is defined through a threshold function, $\mathbf{o}_E(k)$, which utilizes the thresholds that come from aviation standards and best practices. Each element of $\mathbf{o}_E(k)$ is a Boolean variable, $\mathbf{o}_{e_i}(k)$, that indicates whether its corresponding event, e_i, has occurred ($\mathbf{o}_{e_i}(k) = true$) or not ($\mathbf{o}_{e_i}(k) = false$). If no unsafe event has occurred, the NAS is in an acceptable state and vice versa.

When the NAS crosses into an unsafe/unacceptable region, the time of occurrence, k_e, for that unsafe event, e, is defined as the first time at which its threshold function, $\mathbf{o}_{e_i}(k)$, evaluates to true. Thus, for all possible combination of unsafe events under consideration in the NAS, a vector of unsafe event times can be represented as

$$\mathbf{k}_E = \begin{bmatrix} k_{e_1} \\ k_{e_2} \\ \vdots \\ k_{e_p} \end{bmatrix}. \tag{3}$$

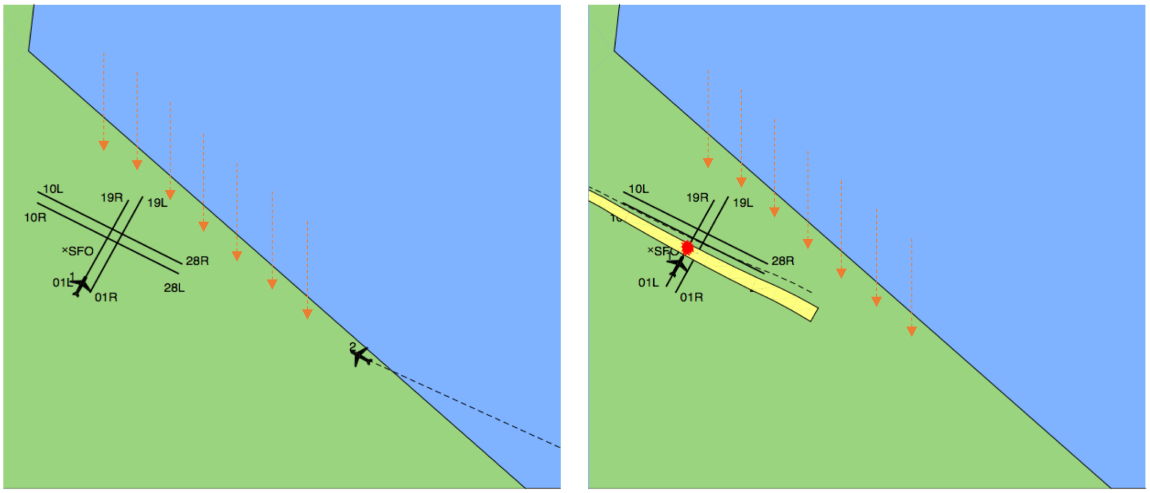
All of these quantities, including the state of the NAS are inherently uncertain. The RTSM framework is developed to handle these uncertainties by representing the states and safety metrics as probability distributions as opposed to point estimates. Furthermore, future states and inputs to the NAS, such as wind magnitudes and directions, weather forecasts, and aircraft intended flight paths are also uncertain, necessitating representations in terms of probability density functions.[11,15]

The RTSM architecture can be viewed as a two-part problem involving (i) *monitoring* the safety metrics and their evolution in time and (ii) *predicting* the likelihood of an unsafe event occurring within a specified look-ahead time frame. The monitoring facet involves computing the probability distribution of the safety metrics, $p(\boldsymbol{\phi}(k))$, at a current time k from NAS state estimates obtained using nonlinear estimation techniques such as unscented Kalman filters or particle filters.[15] The prediction problem focuses on using uncertainty propagation techniques such as Monte Carlo sampling to compute the probability distribution of future NAS states, safety metrics $p(\boldsymbol{\Phi}_k^{k_H})$, and safety-related events occurring within a prediction horizon $k_H > k$.[15,17] For detailed information on the development, modeling, monitoring, and prediction aspects of the RTSM framework, References [11, 15–17] should be consulted.

C. Demonstration

In this section, we present a scenario showing how the RTSM framework can be used to monitor and predict a wake turbulence encounter in the terminal airspace[15] of the San Francisco International Airport (SFO). Aircraft wake vortices, created by lift-generating aircraft in flight,[18–20] can be detrimental to smaller trailing aircraft without the control authority to trim the large induced moments experienced in the wake.[21,22] In this scenario, we consider two aircraft depicted in Fig. 1: a light aircraft A1 waiting to take off from runway 01L, and a large aircraft A2, coming in for a landing on crossing runway 28L. As the scenario unfolds, strong crosswinds, depicted with the dashed arrows in Fig. 1, prevent the pilot of A2 from maintaining directional control, necessitating a go-around. As he accelerates the A2 aircraft and begins to generate lift for the go-around, a region of turbulent wake vortex is formed behind. Interactions between residual wake vortices and trailing aircraft are rare in the terminal airspace, thus a controller may not be cognizant of the wake turbulence generated by A2 as he clears A1 for departure. In this case, the wake vortex from A1 is present and detrimental to the lighter A1 aircraft preparing to depart from the crossing runway.

To model, monitor, and predict the encounter between aircraft A1 and the wake, the elements for the RTSM framework are first extracted from the scenario. The unsafe event, e, is the encounter of a wake turbulence region by an aircraft. This unsafe event can be predicted by monitoring the safety metric $\boldsymbol{\phi}$, the distance between aircraft A1 and the wake turbulence region of A2. To model this distance, a simple vortex model is created to define the wake



(a) $t = 100$ s. (b) $t = 220$ s.

Figure 1. RTSM Demonstration: Wake Turbulence Encounter (Aircraft not drawn to scale)[15]

turbulence region as a function of the wake-generating aircraft position, wind direction, and time.[17] The safety metric is constantly monitored and predictions are made every 10 s with up to a five-minute look-ahead time. Thus, we can compute the probability of a wake turbulence encounter as well as the time and location of the encounter. This is also depicted in Fig. 1 which shows the yellow wake turbulence region generated by aircraft A2 after its missed approach, the predicted time of a wake vortex encounter ($t = 220s$) and the predicted location of wake turbulence encounter, the red region.

III. Surface Operations Hazard Analysis

Similar to the hazard identification during the RTSM framework development, two primary sources for accident and incident reporting were utilized in this paper: the NTSB database[14] and the NASA ASRS database.[13] Over 600 reports were queried for the NTSB study, spanning multiple decades of incidents during the standing, taxi, takeoff, and landing phases of flight for Part 121 Air Carriers. Additionally, 50 reports from the ASRS database were characterized by incidents on the ramp, runway, and taxiway. Finally, an assessment of runway incursions and their contributing factors was done using Skybrary,[23] a wiki of aviation safety information created by the European Organization for the Safety of Air Navigation, ICAO, and the Flight Safety Foundation (FSF). This literature review shows that human errors and non-compliance with operating policies and procedures are pervasive and dominant factors that lead to surface incidents. A histogram of the most frequent ASRS categories associated with these incidents is shown in Fig. 2. Fig. 2, which depicts the number of ACN (ASRS Record Number) records broken down by cause, shows that ”human factors” causes greatly exceed all other causes. Weather conditions, faulty communication tools, and malfunctioning ground service equipment, though present, emerged as lesser causes.

IV. Ground Incident Classification

The three databases, NTSB, ASRS, and Skybrary, were utilized to identify potential hazards to ground operations and classify them as either predictable hazards, which can be measured, modeled, and predicted using real-time data, or unpredictable hazards, which cannot. The underlying difference between the two lies in the quantification of a safety precursor that will indicate a certain hazard or incident. For instance, the failure of a taxiing aircraft to maintain clearance from another aircraft waiting on the ramp is considered to be an incident which can potentially be predicted

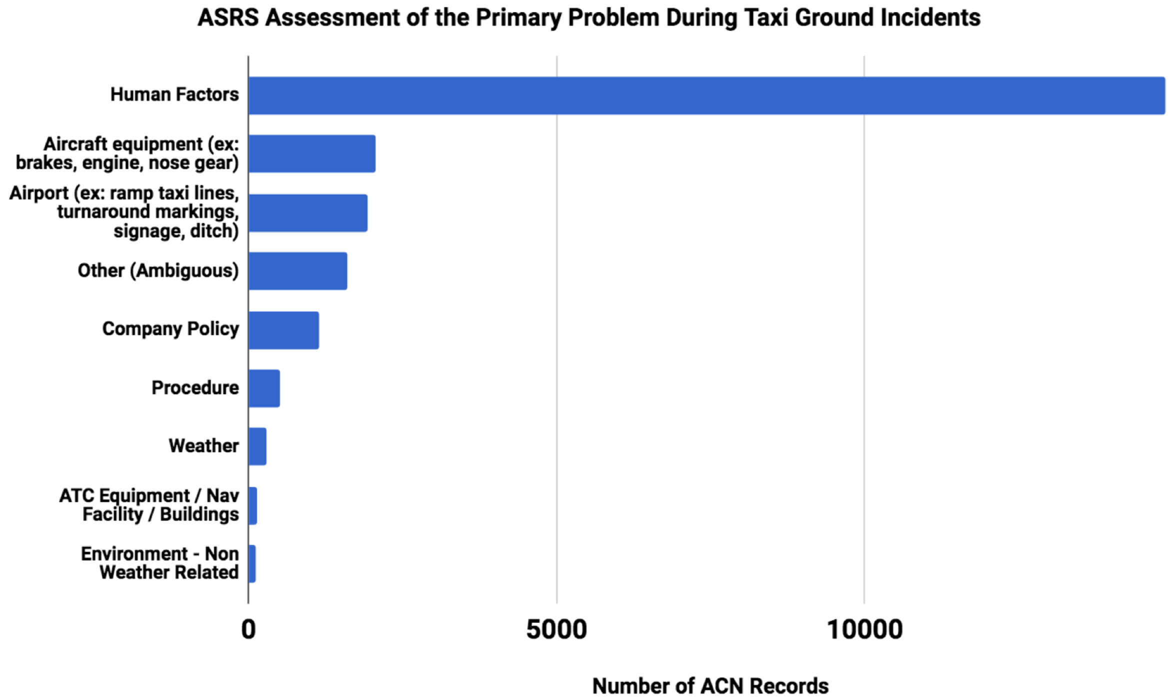


Figure 2. Breakdown of ASRS Incidents During Taxi

with a short look-ahead and avoided with relevant data precursors. On the other hand, there are no data precursors that allow prediction of a flight attendant tripping over his foot, falling, and fracturing his wrist.

In Section A, we provide an overview of the unpredictable ground incidents with a list of examples. We then discuss the predictable incidents in Section B and classify them into three categories: aircraft to aircraft collisions that occur during taxi, collisions between aircraft and other vehicle (tractors, tugs, and aircraft) that occur during pushback, and predictable weather-related incidents.

A. Unpredictable Ground Incidents

Most accidents and incidents (collectively referred to as ”incidents” in this paper) that occur during airport surface operations arise from causes which cannot be measured, modeled, or predicted using the RTSM framework. These incidents include:

- Runway incursions, the ”incorrect presence of an aircraft, vehicle, or person on the protected area of a surface designated for the landing and takeoff of an aircraft,”[23] can be unpredictable particularly if the incursion is a pedestrian or foreign object debris (FOD).
- Passenger or flight attendant loss of balance, trips, and falls.[14]
- Inadvertent throttle movement by flight crew member and captain’s inadequate supervision during engine start sequence.[14]
- Lack of situational awareness by catering or deicing truck drivers causing impact to parked airplane.[14]
- Ramp service clerk, station manager, baggage handler, or other ground crew member inadvertently walking into a spinning propeller and sustaining injuries.[14]

- Equipment failure such as nose landing gear separation, fractured tow bar, fatigue failure of the wheel assembly, cabin door jamming and becoming inoperative, etc.[14]
- Airport's improper decision to ignore current standards. For instance, deactivating a jet braking system resulting in collision between jet bridge and aircraft during a wind gust.[14]

The list above is by no means exhaustive of the unpredictable incidents discovered during the hazard analysis and literature review. To mitigate this category of incidents, the authors recommend adherence to current standards, operating procedures, and regulatory practices established by airlines, the FAA, and other stakeholders.

B. Predictable Ground Incidents

Three classes of pervasive predictable incidents are identified in the databases: wingtip to tail/wingtip collision between a taxiing aircraft and a standing aircraft, collisions during pushback either between a tug and an aircraft or between two aircraft, and lastly, weather-related incidents due to icing, snow, etc. Fig. 3 shows the relative frequency of occurrence of the three categories in the NTSB database. Predictable incidents that do not fall in any of the three categories are also depicted and classified as "other" in Fig. 3. Examples of these include jet blast incidents on congested taxiways or a loss of separation between aircraft departing from intersecting runways.[14] Aircraft collisions during taxi are the most pervasive ground incidents, occurring 45% of the time as seen in Fig. 3 while weather-related incidents occur less frequently. These NTSB results, showing the non-pervasive nature of weather-related incidents and the high number of aircraft-aircraft collisions during taxi that result primarily from human factors, are in agreement with the ASRS assessment depicted in Fig. 2. The next few sections give detailed explanations of the three classes of predictable incidents.

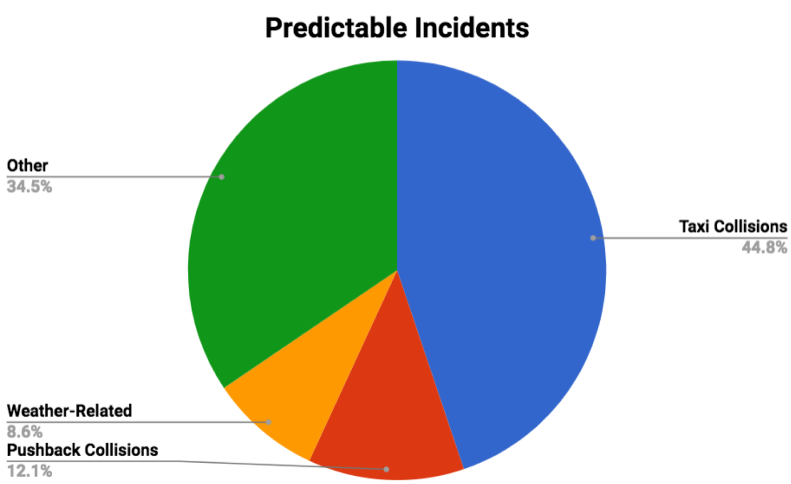


Figure 3. Categories and Frequencies of Predictable Incident Types

1. Aircraft-Aircraft Ground Collisions During Taxi

During the taxi phase of flight, there are numerous incidents of the wingtip/winglet of the taxiing aircraft impacting the horizontal/vertical tail of an adjacent aircraft. In these cases, the pilot of the taxiing aircraft underestimates the proximity of the standing aircraft and makes a judgement call to pass, resulting in a collision. In some cases, the co-pilot or support crew, who provide feedback to the pilot taxiing on the availability of clearance, also misjudge the distance between the two aircraft. One pervasive contributing factor to these collisions is that the wingtips of certain transport aircraft, such as the B767, are not visible from the cockpit unless the windows are open. Thus, when there are multiple aircraft in close proximity, the pilots of a taxiing aircraft make decisions about maneuvering around the stationary aircraft using incomplete and inaccurate distance information.

2. Collisions During Pushback

Pushback operations lead to another category of incidents that occur when an aircraft is being pushed away from the gate using a pushback tractor or tug operated by a driver. With these incidents, the tug driver fails to maintain clearance from a nearby aircraft as he/she pushes the aircraft from the gate. A lack of situational awareness of nearby aircraft, inadequate visual look-out, or an underestimation of the proximity of the adjacent aircraft leads to collisions which can be prevented by current operating procedures. The tug operators work with wing walkers to ensure safe operations, but occasionally, there is a failure of the tug operator to monitor the wing walker and obtain position information of the tug, the aircraft being pushed back, and other aircraft in the vicinity. During pushback, there are also multiple incidents of the tug operator losing control of the vehicle, resulting in the tug striking the aircraft and causing damage. The collisions that occur during tug operations where vehicle control is maintained by the tug operator, may be predictable with accurate dimensions and precise position information of the tug/tractor, aircraft being towed, and nearby aircraft which may be impacted.

3. Weather-Related Incidents

Weather-related ground incidents appear as recurring sources of aircraft damage in both NTSB and ASRS reports.[14,23] In the ASRS database, the five most common causes of weather-related taxiing incidents (and number of incidents of each) were rain (489), snow (326), ice (228), fog (220), and thunderstorms (153). However, weather conditions may contribute to the incidents indirectly, as only 108 total incidents listed weather as the primary problem.[14] NTSB reports for standing and taxiing incidents cite causes for weather-related incidents as ground contamination, the presence of deicers on taxiways and ramps, decreased visibility, unexpected hazards, and loss of aircraft control (exacerbated by inadequate pilot training for crosswind conditions and a lack of dissemination of wind information by ATC[14]). Existing hazards can lead to incidents through failure to follow existing policies and procedures regarding speed, ground communication, surveillance of aircraft, flight attendant safety, or tugs and belt loaders. Recurring issues for weather-related incidents as described in the NTSB and ASRS database reports searched can be categorized as follows:

- Tugs slip and collide with aircraft from ramp or taxiway contamination due to snow/ice, rain, or slush.[14]
- Icy conditions cause the presence of deicers and snow plows, which can cause incidents through human error and collision with aircraft in low visibility conditions.[14]
- Wind causes unexpected hazards for airline or ground crew, in the form of blowing doors, windows, baby strollers, and deicing fluid.[14]
- Flight attendants can be injured due to not following safety procedures in gusty wind conditions.[14]
- Wind causes loss of aircraft control by pilot and debris collision with windshield.[14]
- Fog/mist causes lack of visibility, which contributes to aircraft collision or runway excursions.[14]
- Snow negatively impacts braking quality.[13]

In addition to weather-related causes, lighting conditions can also become hazards, with sun glare affecting visibility and night conditions obscuring the edges of ramps or taxiways (particularly if combined with snow), sometimes causing taxiway excursions. While many of these incidents themselves cannot be predicted, we can predict the adverse conditions given appropriate weather forecasts and alert personnel of the increased risk to upcoming ground operations.

V. Safety Metrics for Predictable Surface Incidents

The predictable hazards to safety, as defined in the previous section, can be transformed to safety metrics, for which models can be developed to monitor and predict the hazards to ground operations. The goal is to monitor and predict these safety metrics in real time so as to determine if and when an unsafe event may occur. Defining an unsafe event, such as a collision between a taxiing and standing aircraft, requires an explicit safety threshold which delineates the boundary between safe and unsafe for each safety metric. These safety thresholds are obtained from regulations stipulated by the FAA and other regulatory bodies, aviation best practices, and company policies and procedures.[11]

Table 1 shows the safety metrics developed for ground/surface operations, function arguments, and outputs of the safety metric functions. These function arguments may simply be parameters of interest such as aircraft position, heading, and velocity, or they may be helper functions (defined in curly brackets) that are also safety metrics. An example helper function is weather at coordinate, a safety metric in its own right, and a helper function for other safety metrics such as the probability of runway excursion, risk of drifting foreign object debris (FOD-G), and taxi complexity. Table 1 also shows example threshold equations that define the margins of safety and some of the data required for the safety metric monitoring and prediction.

Table 1: Safety Metrics for Surface Operations

Safety Metric (SM)	SM Function Arguments	SM Function Outputs	Threshold Equation Example	Required Data Examples
Weather at coordinate	Point of interest, time	Matrix of all weather categories (e.g. precipitation, wind, temperature, etc) and their relevant properties (e.g., type, direction, severity, persistence, etc.)	A threshold is needed for each element of the matrix. Examples: thunderstorm began = :08, precipitation.type = ice.pellets	Current weather, forecast weather
Surface visual range (SVR) aka visibility	Point of interest, time, {weather at coordinate}	Distance in feet	SVR $>$ 50 ft	As required by "Weather at coordinate" SM
Ground services operating status	Volume of interest, time	Matrix of all service categories (e.g., lights, tracking coverage, runways, etc.) and operational status (e.g., Inoperative, nominal)	servicesOperatingStatus.asde.x = NOMINAL	NOTAMs (Notice to Airmen)
Degree of taxi route normalcy	{Airport configuration at time t}, {airport configuration at time t+5}, {probability of ramp/taxiway/runway congestion}, {surface facilities operating status}, off-nominal ops (e.g., priority aircraft, etc.)			NOTAMs regarding closed taxiways, standard taxi routes, expected airport reconfiguration
Taxi complexity	Taxi clearance, time, {weather at coordinate}, {degree of taxi route normalcy}	Complexity category, e.g., low, medium, high	taxiComplexity $<$ MEDIUM	Airport layout, location of hot spots, taxi clearance
Airport configuration at a given time	Time, {weather at coordinate}	Runways in use, taxi routes in use		Current and forecast weather, especially wind magnitude and direction, airport layout, standard operating procedures, traffic forecasts
Risk of aircraft collision with aircraft/vehicle/structure	Position, heading and speed of ownship, position, heading, and speed of other aircraft/vehicle/structure, {probability of ramp/taxiway/runway congestion}	Nearest distance (ft), risk category. e.g., none, low, medium, high	ProximityViolation = NONE	Position and heading of aircraft, aircraft type and dimensions, winglet type, weather, airport infrastructure information e.g., locations and dimensions
Probability of ramp/taxiway/runway contamination	Point of interest, time, {weather at coordinate}	Probability of all contamination categories such as ice e.g., black ice, slush, water; {FOD debris}; dead wildlife	rwyContamination.blackIce = 0	Current and forecast weather, PIREPs (Pilot Reports), runway condition reports;

Table 1: Safety Metrics for Surface Operations

Safety Metric (SM)	SM Function Arguments	SM Function Outputs	Threshold Equation Example	Required Data Examples
Probability of vehicle loss of control on the ground (LOC-G)	Point of interest, time, {probability of taxiway contamination}, {weather at coordinate}	Risk category, e.g., none, low, medium, high	VehicleLOCG $\leq$ LOW	Current and forecast weather providing information about surface icing
Risk of drifting Foreign Object Debris (FOD-G)	Point of interest, time, {weather at coordinate}, FOD at nearby coordinates	risk category, e.g., none, low, medium, high	FODGRisk $\leq$ LOW	FOD existence (e.g., camera-fed image recognition)
Risk of jet blast	Point of interest, time	Risk category, e.g., none, low, medium, high	jetblastRisk $\leq$ LOW	Precise position and heading of all operating aircraft
Probability of ramp/taxiway/runway congestion	{Airport configuration at a given time}, {weather at coordinate}, {aircraft at coordinate}	Comparison to expected congestion, i.e. low, normal, high	probCongestion $\leq$ NORMAL	Data required for the helper functions
Probability of pilot error during ground ops	Pilot id, time, {taxi complexity}, {visibility conditions}	Probability in percentages	pilotErrorProb $< 10\%$	Position and heading of aircraft, plus all the data required for the helper functions
Probability of controller error on ground ops	Controller id, time, {Ground service operating status}, {taxi complexity}, {Controller workload}	Probability in percentages	controllerErrorProb $< 1\%$	Data required for the helper functions

VI. Conclusion

Although commercial aviation has made significant progress in terms of safety, surface operations during aircraft taxiing, pushback, and standing, remain risky and accident-prone. This paper builds on prior efforts in monitoring NAS safety in real time using a novel approach, the Real-Time Safety Monitoring (RTSM) framework. The goal of this paper is to create a holistic NAS safety effort that includes both air and ground operations by laying the groundwork for extension of the RTSM architecture to airport surface operations.

In this paper, we develop a set of safety metrics that can be monitored and predicted in real time to provide safety assessments of NAS surface operations. Hazards to the safety of persons, aircraft, facilities, and NAS infrastructure are investigated and categorized into ”unpredictable” and ”predictable incidents.” Unpredictable incidents, caused primarily by disregard of existing FAA rules, regulations, and company procedures, may be prevented by personnel compliance with policies and procedures. For the predictable surface incidents, safety metrics, data sources required, and safety thresholds, are developed for integration into the RTSM framework to enable real time monitoring and prediction of ground incidents.

This work can also be integrated into other safety management systems such as the the FAA's System Safety Management (SSM) portfolio that utilizes tools such as the Integrated Safety Assessment Model (ISAM) to identify safety incident precursors and model various system safety scenarios. One novelty of the RTSM framework in comparison to other approaches is in its systematic handling of uncertainty inherent in data sources, modeling, and prediction. With continued development and integration of data from safety net tracking systems such as ASDE-X, uncertainty in the data can be reduced to improve results for other architectures without the capability to manage uncertainty.

VII. Acknowledgments

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References

[1] Administration, F. A., “NextGen – Safety,” 2017, Accessed: 05-Oct-2017.

[2] Administration, F. A., “Pilot’s Handbook of Aeronautical Knowledge (FAA-H-8083-25B),” PDF, 2016.

[3] EUROCONTROL, “Advanced-Surface Movement Guidance and Control System (A-SMGCS),” Online, 2017.

[4] Bloisi, D., Locchi, L., Nardi, D., Fiorini, M., and Graziano, G., “Ground traffic surveillance system for Air Traffic control,” *12th International Conference on ITS Telecommunications*, 2012.

[5] Pavlidou, N., Grammalidis, N., Dimitropoulos, K., Simitopoulos, D., Strintzis, M., Gilbert, A., Piazza, E., Herrlich, C., and Heidger, R., “Using intelligent digital cameras to monitor aerodrome surface traffic,” *IEEE Intelligent Systems*, Vol. 20, 2005, pp. 76–81.

[6] Dimitropoulos, K., Semertzidis, T., and Grammalidis, N., “Video and Signal Based Surveillance for Airport Applications,” *6th IEEE International Conference on Advanced Video and Signal based Surveillance*, IEEE, 2009, pp. 170–175.

[7] Administration, F. A., “Surface Movement Guidance and Control System,” 1996.

[8] Young, R., “Multi-sensor fusion for UAS ground-based detect and avoid capability,” *IEEE Integrated Communications, Navigation and Surveillance Conference (ICNS)*, 2017.

[9] Administration, F. A., “Airport Surface Detection Equipment, Model X (ASDE-X),” 2014.

[10] Administration, F. A., “Airport Surface Surveillance Capability (ASSC),” 2016.

[11] Roychoudhury, I., Spirkovska, L., Daigle, M., Balaban, E., Sankararaman, S., Kulkarni, C., Poll, S., and Goebel, K., “Real-Time Monitoring and Prediction of Airspace Safety,” Tech. Rep. NASA/TM-2015-218928, NASA Ames Research Center, December 2015.

[12] Spirkovska, L., Roychoudhury, I., Daigle, M., and Goebel, K., “Real-Time Safety Monitoring: Concept for Supporting Safe Flight Operations,” *Proceedings of the AIAA Aviation Forum*, San Diego, CA, June 2017, AIAA Paper 2017-4494.

[13] NASA, “ASRS Online Database,” 2017.

[14] Transportation, N. and Board, S., “Aviation Accident Database & Synopses,” 2017.

[15] Roychoudhury, I., Spirkovska, L., Daigle, M., Balaban, E., Sankararaman, S., Kulkarni, C., Poll, S., and Goebel, K., “Predicting Real-Time Safety of the National Airspace System,” *Proceedings of the AIAA InfoTech Conference*, San Diego, CA, January 2016, AIAA Paper 2016-2131.

[16] Roychoudhury, I., Daigle, M., Goebel, K., Spirkovska, L., Sankararaman, S., Ossenfort, J., Kulkarni, C., McDermott, W., and Poll, S., “Initial Demonstration of the Real-Time Safety Monitoring Framework for the National Airspace System Using Flight Data,” *Proceedings of the AIAA Aviation Forum*, Washington, DC, June 2016, AIAA Paper 2016-4216.

[17] Daigle, M., Roychoudhury, I., Spirkovska, L., Goebel, K., Sankararaman, S., Ossenfort, J., and Kulkarni, C., “Real-Time Prediction of Safety Margins in the National Airspace,” *Proceedings of the AIAA InfoTech Conference*, San Diego, CA, January 2017, AIAA Paper 2017-4388.

[18] Okolo, W., Dogan, A., and Blake, W., “Effect of Trail Aircraft Trim on Optimum Location in Formation Flight,” *AIAA Journal of Aircraft*, Vol. 52, No. 4, 2015, pp. 1201–1213.
doi: 10.2514/1.C032865.

[19] Okolo, W. A., Dogan, A., and Blake, W., “Ride Quality Within Conventional and Delta-Wing Trail Aircraft in Formation Flight,” *AIAA Journal of Aircraft*, Vol. 0, No. 0, 2018, pp. 0–0
doi: 10.2514/1.C034754.

[20] Okolo, W., Dogan, A., and Blake, W., “Ride Quality within Trail Aircraft in Formation Flight,” *Proceedings of the AIAA Atmospheric and Space Environments Conference*, Dallas, TX, June 2015, AIAA Paper 2015-3325.

[21] Okolo, W., Dogan, A., and Blake, W., “Formation Flight Analysis of Two KC-135R Aircraft,” Tech. rep., Air Force Research Laboratory, Wright Patterson AFB OH, 2011.

[22] Okolo, W., Dogan, A., and Blake, W., “Alternate Trimming Methods for Trailing Aircraft in Formation Flight,” *AIAA Journal of Guidance, Control, and Dynamics*, Vol. 38, No. 10, 2015, pp. 2018–2025.
doi: 10.2514/1.G000574.

[23] SKYbrary, “Runway Incursion,” 2017.