NASA/TM–2015-218705

Development and Execution of the RUNSAFE Runway Safety Bayesian Belief Network Model

Lawrence L. Green
Langley Research Center, Hampton, Virginia

May 2015

NASA STI Program . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA scientific and technical information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NTRS Registered and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA Programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counter-part of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include organizing and publishing research results, distributing specialized research announcements and feeds, providing information desk and personal search support, and enabling data exchange services.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at http://www.sti.nasa.gov

- E-mail your question to help@sti.nasa.gov

- Phone the NASA STI Information Desk at 757-864-9658

- Write to:
  NASA STI Information Desk
  Mail Stop 148
  NASA Langley Research Center
  Hampton, VA 23681-2199

NASA/TM–2015-218705

Development and Execution of the RUNSAFE Runway Safety Bayesian Belief Network Model

Lawrence L. Green
Langley Research Center, Hampton, Virginia

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

May 2015

Available from:

NASA STI Program / Mail Stop 148
NASA Langley Research Center
Hampton, VA 23681-2199
Fax: 757-864-6500

Table of Contents

1.0 List of Figures

2.0 List of Tables

3.0 Nomenclature

AC	Aircraft
ANOVA	Analysis of Variance
AOSP	Aviation Operations and Safety Program
App	Approach
ARMD	Aeronautics Research Mission Directorate
ASIAS	FAA Safety Information Analysis and Sharing
ATADS	FAA Air Traffic Activity Data System
ATC	Air Traffic Control
Avg	Average Value
AvSP	Aviation Safety Program
BBN	Bayesian Belief Network
Cat	RI Event Severity Category
Cert	Certification
Comm	Communication
Cont	Contamination Control
Cntrb	Contribution
CPT	Conditional Probability Table

Curr	Current
Dep	Departure
DX8	Design-Expert version 8
DX9	Design-Expert version 9
FAA	Federal Aviation Administration
HFACS	Human Factors Analysis and Classification System
Hi	high bound for SME values
LaRC	Langley Research Center
Lo	low bound for SME values
Max	Maximum value
Mech	Mechanical
Mfac	Multiplicative Factor
Min	Minimum value
NASA	National Aeronautics and Space Administration
NextGEN	Next Generation Air Transportation System
OJT	On-the-Job-Training
PED	Pedestrian
RE	Runway Excursion
RI	Runway Incursion
RUNSAFE	Combined RI and RE event model
RW	Runway
SME	Subject Matter Expert
StDev	Standard Deviation
TC	Technical Challenge

TW	Taxiway
Unstab	Unstabilized
VEH	Vehicle

4.0 Abstract

One focus area of the National Aeronautics and Space Administration (NASA) is to improve aviation safety. Runway safety is one such thrust of investigation and research. The two primary components of this runway safety research are in runway incursion (RI) and runway excursion (RE) events. These are adverse ground-based aviation incidents that endanger crew, passengers, aircraft and perhaps other nearby people or property. A runway incursion is the incorrect presence of an aircraft, vehicle or person on the protected area of a surface designated for the landing and take-off of aircraft; one class of RI events simultaneously involves two aircraft, such as one aircraft incorrectly landing on a runway while another aircraft is taking off from the same runway. A runway excursion is an incident involving only a single aircraft defined as a veer-off or overrun off the runway surface.

Within the scope of this effort at NASA Langley Research Center (LaRC), generic RI, RE and combined (RI plus RE, or RUNSAFE) event models have each been developed and implemented as a Bayesian Belief Network (BBN). Descriptions of runway safety issues from the literature searches have been used to develop the BBN models. Numerous considerations surrounding the process of developing the event models have been documented in this report. The event models were then thoroughly reviewed by a Subject Matter Expert (SME) panel through multiple knowledge elicitation sessions. Numerous improvements to the model structure (definitions, node names, node states and the connecting link topology) were made by the SME panel. Sample executions of the final RUNSAFE model have been presented herein for baseline and worst-case scenarios. Finally, a parameter sensitivity analysis for a given scenario was performed to show the risk drivers.

The NASA and LaRC research in runway safety event modeling through the use of BBN technology is important for several reasons. These include: 1) providing a means to clearly understand the cause and effect patterns leading to safety issues, incidents and accidents, 2) enabling the prioritization of specialty areas needing more attention to improve aviation safety, and 3) enabling the identification of gaps within NASA's Aviation Safety funding portfolio.

5.0 Introduction

One focus area of the National Aeronautics and Space Administration (NASA), enabled through the former Aviation Safety Program (AvSP), now the Airspace Operations and Safety Program (AOSP)[1], of the NASA Aeronautics Research Mission Directorate (ARMD), and in cooperation with the Federal Aviation Administration (FAA), is to improve aviation safety. Specifically, this Program seeks to provide increasing capabilities to:

- predict and prevent safety issues;
- monitor for safety issues in-flight and lessen their impact should they occur;
- analyze and design safety issues out of complex system behaviors;
- analyze designs and operational data for potential hazards.

The AvSP / AOSP explores hardware and software systems (technologies or products) that will operate in the Next Generation Air Transportation System (NextGEN)[2]. Runway safety is one thrust of investigation and research. The two primary components of runway safety are runway incursion (RI) and runway excursion (RE) events.

A ***runway incursion*** is the incorrect presence of an aircraft, vehicle or person on the protected area of a surface designated for the landing and take-off of aircraft (as defined by the FAA Office of Runway Safety)[3-4]. A ***runway excursion*** is an incident involving only a single aircraft defined as a veer-off or overrun off the runway surface[4]. In short, RI and RE events are adverse ground-based aviation incidents that endanger crew, passengers, aircraft and perhaps other nearby people or property. Additional detail about RI and RE events is provided in subsequent sections of this document.

Within the scope of this effort, statistical RI framework[5], and generic RI, RE and combined (RI plus RE, or RUNSAFE) event models[6-7] have each been developed and implemented as a ***Bayesian Belief Network (BBN)***[8-10]. Data from the FAA and descriptions of issues from the literature searches, described subsequently, have been used to develop the BBN models. The development of the RUNSAFE (combined RI and RE) BBN model[7], and some sample executions, are documented later in this report. Other similar BBN modeling efforts have been recently documented within a group working at NASA Langley Research Center (LaRC)[8, 11-13]. More discussion about BBN models also follows subsequently.

The NASA Aviation Safety Program conducts cutting-edge research to produce innovative concepts, tools, and technologies that can improve the intrinsic safety attributes of current and future aircraft. The AvSP research centers have defined a set of Technical Challenge (TC)[1] issues that are aligned with program goals and project objectives. These TC issues serve to focus research toward solving aviation safety problems and provide a consistent framework to focus, direct, plan, execute, manage, and communicate Center-distributed research. Among the TC issues relevant to this work are:

- Assurance of Flight Critical Systems (air traffic control operations)
- Discovery of Precursors to Safety Issues
- Assuring Safe Human-Systems Integration
- Improve Crew Decision-Making and Response in Complex Situations

The NASA and LaRC research in event modeling through the use of BBN technology is important for several reasons. These reasons include: 1) a means to provide a clear understanding of the cause and effect patterns leading to safety issues, incidents and accidents, 2) to enable the prioritization of specialty areas needing more attention to improve aviation safety, and 3) to enable the identification of gaps within NASA's Aviation Safety funding portfolio.

5.1 Runway Incursion Events

Again, a runway incursion is the ***incorrect presence*** of an ***aircraft (AC)***, ***vehicle (VEH)*** or ***person (pedestrian or PED)*** on the protected area of a surface designated for the landing and take-off of aircraft (as defined by the FAA Office of Runway Safety[3-4]). Generally, RI events are reported by ***air traffic control (ATC) personnel*** (this phrase is intended to include those personnel that may be controlling only ground traffic at airports) in one category (Cat) among several severity categories, originally defined as:

- Cat A = an accident or near miss occurred
- Cat B = significant potential for collision existed
- Cat C = ample time and/or distance existed to avoid a collision
- Cat D = an RI event with no immediate safety consequences
- Other = RI events that have not yet been properly classified

The FAA has recently revised these severity categories to be: Accident, Cat A (Near Miss), Cat B, Cat C, Cat D and Cat E (Other) as noted above[3-4]. Once initiated, RI events are short in duration and timing is critical; typical landing and takeoff times are 20 to 30 seconds and the event severity can easily escalate with just slightly different timing.

As shown in the timeline of Figure 1, an RI event consists of a development phase (blue box) and a mitigation phase (red). During the development phase, various circumstances (bad weather, poor airport layout, confusing communication with the ATC, etc.) contribute to the occurrence and possible severity of a future RI event; the development phase may take place over minutes or hours. During the mitigation phase, various actions may take place that can reduce the severity of the RI event; this phase may only be a few seconds. Three intermediate instances in time as marked in Fig. 1 are also relevant: 1) at some point in time, one or more of the people involved may realize that an RI is imminent but has not actually occurred yet, 2) at some point in time, due to the physics of the situation, the RI event becomes unavoidable, and 3) at some point in time, the RI event is actually initiated. Under some circumstances, the three instances in time (indicated as 1, 2 and 3 in Figure 1) coalesce and there is no overlap between the development and mitigation phases.

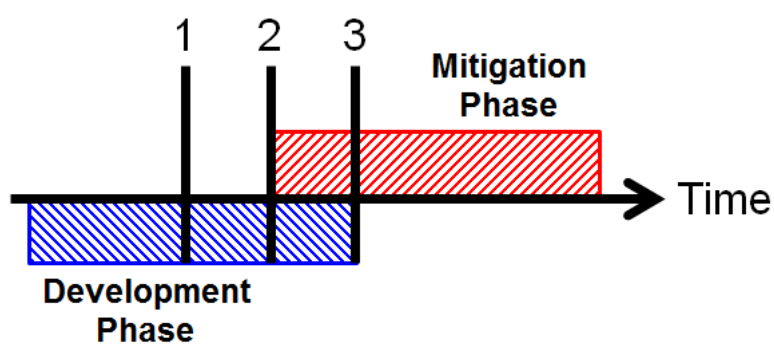

Figure 1. Runway Incursion timeline sketch.

One can imagine a situation where a pilot, on final approach for a landing, observes a VEH being driven at high speed toward the runway on which their aircraft has been cleared to land. An RI event has not yet been initiated but the pilot suspects that an RI event will occur. At this point (instance 1 in Figure 1), the pilot has ample time to initiate a go-around (whether self-initiated or directed by the ATC); the VEH may stop before entering the runway, and the RI event may never technically occur. Under slightly different circumstances, the pilot may only realize that an RI event will occur after it is too late to be avoided (i.e., the VEH will enter the runway without authorization, instance 2 in Figure 1) and begin to initiate a go-around that results in a near miss with the VEH; without the go-around attempted, this event may have resulted an AC / VEH collision. Again, under slightly different circumstances, the pilot may only realize that an RI event has occurred after the VEH enters the runway without authorization (RI event initiated, instance 3 in Figure 1); any attempted mitigation at this point could still result in an AC / VEH collision, a near miss, or the AC may have an accident on its own attempting to avoid the VEH. There are many complex situations to consider in this context.

In reviewing the literature on this topic, a recent NASA study on non-towered airports[14] indicated that the number of RI events is increasing with time, with about half of the events being of low severity and the remainder being split among moderate, high, and severe RI events; among these events, intersecting runaways are noted as the highest contributing factor. A 2013 presentation by the Boeing Company[15] shows that flight hours, departures, and the size of the worldwide fleet have generally increased, while accident rates have remained essentially flat (but at a very low level) over the last 20 years; the same presentation points to about 61% of all fatal accidents and about 50% of onboard fatalities worldwide being associated with final approach, landing, takeoff and initial climb during the period 2004 through 2013. A recent U.S. Department of Transportation, Volpe Center[16] report shows that the spacing of parallel runways has just a small effect (if any) on the number of RI events across all severity categories; the same reports illustrates that crossing the hold short line, entering the runway and crossing a runway as the most likely types of RI events. A recent journal article[17] illustrates a dramatic increase in the number of RI reported in 2008 compared to previous years, with pilot deviations always being the largest source of these events. A recent FAA report[18] described the strong correlation among airport geometry, complexity and various communication tools (including signage and runway markings) with RI events. A Pilots Association report[19] illustrates an increase in RI events with air traffic, but with overall the RI event rate being less than 6 per million operations; this reports also points to major domestic airports (Chicago, Atlanta, Dallas/Fort Worth, Los Angeles, St. Louis and Philadelphia) as having the greatest number of RI events.

With the goal of improving runway safety, a statistical analysis[5] of the Runway Incursion (RI) Database[20] from the FAA Safety Information Analysis and Sharing (ASIAS) website[21] and the FAA Air Traffic Activity Data System (ATADS)[22], also from the FAA, was conducted to ascertain its relevance to the top ten challenges of AvSP. The information contained in the RI database was found to contain data that may be relevant to several of the AvSP top ten challenges[1] including: 1) the assurance of flight critical systems [i.e., airport operations], (2) the discovery of precursors to safety issues, and 3) improve crew decision-making and response in complex situations. Prior conference papers by this author fully documented the statistical analysis of RI data[5] and the initial development of a BBN model for RI events[6]. A subsequent conference paper[7] extended this BBN model to also include RE events; these three reports together serve as the basis for much of what is reported in this NASA TM.

Some of the important findings of the statistical analysis[5] were that:

- while the number of RI events was found to be increasing over time, there has been essentially no change in the number of higher severity RI events over the time period examined (2001-2011)
- the assumed risk level was found to be increasing over time
- part of the observed increase in the number of RI Events and the assumed risk level can be attributed to an RI definition change by the FAA between 2007 and 2008, described in a 2010 paper by Chapman[23]
- Chapman also notes that pilots consistently rated RI events at higher severity than the FAA controllers that typically report the RI events[23]
- while a few airports, such as Winston / Salem, NC and Fort Wayne, IN had a number of RI events well above the mean value for all the airports considered, those airports with large traffic volume, such as O'Hare, Chicago, IL and Atlanta, GA clearly stand out with statistically significant high average risk sums
- when the average risk sum is normalized by the air traffic volume associated with each airport, other smaller airports stand out with statistically significant high risk levels, meaning that a flyer's actual risk of being involved in a RI event at high traffic volume airports may actually be significantly lower than the risk at other smaller volume airports
- by far the most prevalent cause of RI events is pilot error (about 72% of all RI events)
- an unauthorized person or vehicle account for about 19% of the RI events
- among the pilot errors, two contributing factors were readily identified as major contributors: accidental use of the wrong runway or taxiway (about 25% of pilot errors),

and confusion about the extent of authority granted to the pilot at a specific time by the air / ground / local traffic control personnel (about 20% of the pilot errors)

- among weather factors, adverse lighting conditions may have the greatest overall and the most consistent contribution to severe runway events
- snow (and other freezing conditions) are less of a potential contributor to runway events (only 2% to 9% of RI events cite these conditions) than wind, rain, visibility and lighting
- surprisingly, only about 16% of the RI events examined included some form of intervention, where a corrective or mitigative action was taken
- when an intervention or mitigation occurred, these actions were successful in reducing the RI event severity about 70% of the time
- a "go-around" issued to incoming planes was the most common form of intervention

5.2 Runway Excursion Events

The RE event rate is quoted in several references: about 1 to 2 per million flights for the period 1990 through 2006[24], up to 16 accidents and incidents per year during the period 1978 to 2008, and 30 runway excursion accidents per year[25]. The approach and landing phases of flight have shown little improvement in safety over the last decade (up to 2008) and RE events are the third greatest source of aircraft crashes behind in flight loss of control and controlled flight into terrain[26]; according to this source, the frequency of runway incursions is about half that of runway excursions, which may amount to 10 to 20 overruns and veer-offs each year[26]; the data used in this report suggests that severe RI (Category A / B) are together about as common as RE. If the reader is concerned that the references cited here are out of date, prior versions of the 2013 Boeing report[15], dating back to 2010 (and considering data back to 2004) show almost identical numbers for RI end RE events over a broad number of years.

According to one source[24], landing RE events are the most common, representing about 77% of all RE events. Some contributing factors are shared across the various types of RE events. The most common contributing factor associated with landing overruns is wet/contaminated runways, with long landings being the second most common contributor. Several other contributing factors are also noted (incorrect decision to land, speed to high, late/incorrect use of brakes, late/incorrect use of thrust reversers, aquaplaning, tailwind and being too high on approach). For landing veer-offs, the most common contributing factors include crosswind, nose wheel steering problems, collapsed landing gear, hard landing, tire failures and asymmetric power. The most common contributing factors to takeoff overruns include late abort/reject and an inaccurate estimation for takeoff mass. The most common contributing factors for takeoff veer-offs include inadequate supervision of the flight[24].

Other additional causal and contributing factors for RE events exist, which are summarized here and noted again later in this report where they are particularly relevant. While the direct role of air traffic control (ATC) personnel in runway excursions was relatively small[24], the ATC personnel may contribute to RE events by providing poor, complex or incomplete instructions. Several other contributing factors, including communication/coordination/planning, poor decision making processes about landing or takeoff under adverse circumstances and approach/takeoff procedures are important[27]. One contributing factor not previously mentioned is the inconsistent reporting of runway conditions and braking action at airports across the world[26]. Numerous challenges exist for improving runway safety for existing airports[28] because, due to fixed runway layouts and surrounding populated areas, these facilities may lack the flexibility to implement recommended runway safety mitigation strategies. While contaminated runways (ice, snow, slush, wet or flooded) are a significant contributor to RE events, almost 47% of RE events occurred on dry runways[29]. Takeoff runway excursions were likewise predisposed by a number of factors[30].

Some other reports discuss other model development and application efforts, also aimed at improving runway safety. For instance, one reference describes an analysis tool to quantify risk, support planning, and engineering decisions when determining runway safety area requirements for various types and sizes of airports[27]. The FAA is developing integrated risk models to forecast the risk and assess the impact of additional control measures at specific airports based on traffic volumes, complexity, and environmental factors[31]. Another study is taking a more novel and holistic approach to make sure that resources spent by airports to improve runway safety are actually used to address the most common types of RE events[32]. Yet another study employed human-in-the-loop simulations to evaluate traffic capacity at the Los Angeles International Airport[33]. An automated risk rating model for RI events was presented in another report[34]. Another document by the same author explores what is known about the human errors and other factors that have been identified as contributing to runway incursions, and offers some error mitigation strategies[16]. An example of a BBN devoted to RI events is given in another source[35].

5.3 Bayesian Belief Network Models

The modeling philosophy includes the use of a generic, high-level, system-integrated modeling with a systems level risk-based causal model. It should capture the multi-dependencies (interactions) of causal and contributing factors from various problem domains. However, the modeling should not be a representation of a specific accident/incident case, nor a detailed simulation analysis.

In general, the modeling steps undertaken include: 1) determining the causalities and cause-to-effect relations based on the historical risks and anticipated future risks from safety data/database and literature reviews, 2) constructing a baseline risk-based causal model as a BBN, 3) conducting Subject Matter Experts (SME) Knowledge Elicitation sessions to review the baseline model structure and to elicit the Conditional Probability Table (CPT) values for the baseline model without product insertions, and 4) inserting the NASA safety technologies/products into the model and eliciting CPT values with products included. The expected modeling results include 1) a quantification of the relative likelihood of concerned aviation risks, with technology products inserted and without, 2) an assessment of the direct risk mitigation effectiveness of the NASA safety technologies/products, 3) a portfolio gap analysis and 4) a sensitivity analysis for risk drivers.

Several recent BBN modeling efforts[6-7,9-13] have been undertaken to support the AvSP portfolio assessments and to determine if the AvSP technologies are addressing/mitigating aviation safety problems. The characteristics of issues selected for modeling are:

- A significant accident category based on the historical data and/or future trend
- Alignment with the focus and research areas of AvSP
- Broad coverage on AvSP safety technology products
- Many underlying causal/contributing factors that lead to aviation accidents
- Suitability for a high-level system analysis and modeling

A typical BBN consists of the model structure and the model content. The model structure consists of a set of relevant definitions, as well as the node names, the node states, the ordering of the defined states for each node to facilitate SME comment, the connecting link topology and the connecting link priority as they enter specific nodes (again, to facilitate SME comment). The model content consists of the sets of marginal and Conditional Probability Table values. During the first phase of a typical BBN development cycle, NASA researchers develop (based upon database and literature search) and propose a model structure to an SME panel; the development step may take months to complete. Then, the various elements of the proposed structure are reviewed, modified and validated by the SME panel. Once the model structure has been agreed upon and validated by the SME panel, a CPT elicitation process (model population) is conducted by a facilitator on behalf of NASA to determine the appropriate model content. Some portions of the model review, modification, validation and population can be conducted in parallel. Once the model has been populated, it is executed to obtain a set of baseline results and a baseline sensitivity analysis.

Although both RI and RE events may involve numerous contributing factors (e.g., airport layout, airport operations, weather, training and mechanical failures), RI events are more complex than RE events. RI events are “people intensive”, possibly involving multiple pilots, controllers, airport employees or contractors and perhaps other participants. There are also organizations (FAA, Airport Management, Aircraft Operators, etc.) that support each of the people directly involved in the runway safety events. RI events are also “communication (Comm) intensive”; several instances of two-party communications must simultaneously function properly in order to avoid problems. Two-party communications involve both the content and hardware transmission of information. Instances of two-party communications exist between all the people involved in the event (e.g., pilot to pilot, pilot to controller, controller to controller, controller to airport personnel). All runway safety events are short in duration and timing is critical; typical landing or takeoff reaction times are about 20 seconds (or less) and the event severity can easily escalate with just slightly different timing. The RI and RE models could be joined together through a set of common definitions for accident and incidents, based upon the level of aircraft damage and passenger injuries[36] but this was deemed out of scope for the current models.

An SME panel consisting of four consultants was assembled to review the model structure and to populate its content. The SME panel included two pilots and two other aviation expert consultants. The preliminary BBN RI event model discussed in the prior conference paper[7] (describing the SME session of November 2013) was substantially modified and simplified during the second SME panel review (April 2014), as shown in Figure 2. The nodes in Figure 2 are color coded to indicate associations among the various groups. Generally, the flow of specific contributing factors through causal paths is from left to right in the figure. The SME panel validated many of the proposed definitions and most of the proposed model structure. However, the SME panel also provided significant clarification of several essential definitions within the RI event model. It is intended that the node names are suggestive of the states of each node; hence, limited clarifying information is presented about each of the nodes. Most of the nodes in the RI event model are binary, meaning they have only two possible states: the issue is present, or not, in the RI event under consideration. Where more than two states are present in a node, this will be made clear from the explanation of the node given subsequently. The goal of the SME elicitation is to provide probabilities for each of the possible states; for example, for the node "Airport Layout", the SME goal is to determine the probability that the Airport Layout is an issue or not in the RI event.

The SME panel unanimously agreed that developing a model for runway safety was much more difficult than developing one for in-flight operations. Two members of this SME panel have also participated in prior similar model reviews hosted by this NASA team for different applications. However, in this case, it was quite challenging to even achieve agreement on the basic structure of the BBN model among the NASA team and the SME panel. Numerous alternative models have been developed, discussed and discarded by the NASA team, either because they did not provide a satisfactory causal path, or because they were deemed to be too complex for use within the SME elicitation process for the purpose of portfolio assessment. The model proposed and discussed during the November 2013 session was significantly changed by the SME panel at that time and then significantly changed again by the same SME panel (April 2014). Yet another SME review by the same panel (July 2104) altered the model structure further. However, through all the discussions and modifications, the runway safety model has been steadily improved and clarified.

5.4 Methodology and Software

The scope of the work detailed in this document employed three commercially–distributed software products: Microsoft Excel[37] and Design-Expert (versions 8 and 9, referred to herein as DX8 and DX9, respectively) from Stat-Ease, Inc[38] and the Hugin Explorer software (version 8.1) from Hugin Expert A/S[39]. The first two pieces of software (Microsoft Excel[37] and Design-Expert[38]) were generally used during the data collection and analysis phase of the work[5], while the Hugin Explorer software was generally used during the BBN modeling phase of the work[6, 7]. The general workflow that was employed in this study was first to download the RI data set from the

ASIAS web site. Then, the air traffic volume data set[20] was downloaded from the FAA ATADS web site[22]. These datasets were downloaded in Microsoft Excel[37] format and this software was used to sort and extract the information of interest in addition to some statistical processing. The intent of this data pre-processing was to develop representative marginal and conditional probabilities for use in the BBN modeling of specific events, causes, combinations of contributing factors, and the participant types (aircraft classes, and if vehicles or pedestrians were involved) of RI events that occurred. In this context, it is not necessary that these searches and sorts be 100% accurate, but merely that they provide reasonable guidance about the relative percentages. Having prepared the data set into suitable formats, the data was then imported into DX8 for the development of response surface (RS) models via the analysis of variance (ANOVA) technique, and for additional statistical processing with the software[40-44]. Having identified primary and secondary causes and contributing factors, a series of increasingly more detailed BBN models were developed with the Hugin software and discussed among the team to determine which represented the best way to model the RI and RE event structures. These RI and RE event models were then present to, and discussed at length with, the SME panel; the SME panel made many additional clarifications, simplifications and structural changes to the BBN models.

The software choices noted above simply represent software currently available to the author, and software packages to which the author is quite familiar, but in no way represent an official federal government or NASA endorsement of these software packages. However, these software packages are known to include the desired capabilities for accomplishing the objectives of this study.

The original RI database that was used consists of 10459 records for RI events from October 1, 2001 through September 30, 2011. The structure and use of this data set has been previously documented in detail[5,20].

The primary Federal Air Regulations (FAR) aircraft categories of interest within this modeling effort are 121 (commercial), 135 (air taxi) and 91 (general aviation), but other categories of aircraft were included in the data set. In order to compare RI incident rates at various airports, the event data was combined with a data set of aircraft traffic volume. The air traffic volume data set provided quantitative measures of how many landings and takeoff (grouped together) occurred by year at each of over 400 domestic airports in several categories of aircraft. The total air traffic volume for each airport is also provided. These datasets were used together to investigate issues such as the percentage of the air traffic volume (total, or at a specific airport) that resulted in runway incursions over a given period of time, and the true, traffic–normalized risk level that is associated with those RI events. Again, the intent of the various data analysis operations was to develop representative marginal and conditional probabilities of specific events, causes, combinations of contributing factors, and participant the types of RI events that occurred. The data operations need only provide reasonable guidance about the relative percentages. All the quantitative data was then used as the basis for developing the BBN models.

6.0 Model Development

6.1 Runway Incursion Model

Not all possible combinations of these objects (AC, VEH and PED) are of interest to NASA, e.g., VEH in combination with VEH / PED is not a subject of this study. To avoid ambiguity for the most important Cat A events, the RI event severity rankings used henceforth in this report are: Accident, Near Miss, Cat B, Cat C and Other (including Cat D and Other from above, mentioned for completeness but this categorization will not be a subject of modeling or expert elicitation). For the purposes of this modeling effort, the scope of attention is restricted to aircraft involved, Cat C and above RI events, with movement restrictions to be defined subsequently. For the purposes of this study, only two types of RI events are considered: 1) AC and AC and 2) AC and VEH. RI events include at least two objects [aircraft (AC), vehicle (VEH) and/or person/pedestrian (PED)] with one of the objects being the aircraft.

As mentioned previously, the initial referenced RI data base includes 10459 RI events (with no narratives). Among these, seven were accidents, 110 were near misses, 114 were Cat B, 2014 were Cat C. Note that some RE events started as RI events and these were categorized as "not applicable" within the RI database; one such event occurred on August 27, 2006 where an aircraft crashed at the Lexington, KY airport resulting in 49 deaths[45]. The event was ultimately classified as an RE event, aircraft takeoff on wrong runway, but actually started as an RI event wherein the aircraft entered the takeoff runway (incorrect and too short) without authorization. This initial data set is useful for establishing overall probabilities related to the type of RI events that occur. The final data set consisted of 1596 RI events (Cat C and above, with brief narratives). Of these, there was just one accident (the others among the 10459 were excluded because no narrative was provided by the FAA), 30 were near misses, 20 were Cat B and 1545 were Cat C events. Of the 1596 RI events, 1299 were caused by AC, 260 were caused by VEH and 37 were caused by PED. The complete data time frame ranges from 2001 through 2011, however, the narrative data time frame ranges from 2007 through 2011. The modeling time frame ranges from 2007 through 2014, or possibly 2015, at the latest.

It is important to realize that RI events are "people intensive", involving possibly two pilots and possibly two controllers (when some form of split control such as air / ground is in effect). A VEH driver or PED could replace one of the pilots. There are also organizations (FAA, Airport Management, private air transport companies, etc.) behind each of the people directly involved in the RI event. The Human Factors Analysis and Classification System (HFACS) by Wiegmann and Shappell[146] are frequently used to describe the organizational, supervisory and personal factors states that establish preconditions for human errors and violations. Unfortunately, the narratives provided for the RI events do not provide sufficient detail for a standard HFACS assessment. Hence, simplified HFACS models are used within this model, discussed subsequently.

Furthermore, RI events are also "communication (Comm) intensive"; several instances of two-party communications (e.g., communications between pilot and ATC) must simultaneously function properly in order to avoid problems. Two-party communications involve both the content and transmission of information. The content must be correct and complete, timely and not too complex for the situation. The transmission must be accomplished without garbled or blocked information exchanges. Instances of two party communications exist between all the involved people in the RI event. Many times, communication frequencies are shared by numerous simultaneous two-party instances and confusion among all the parties can result when incorrect or incomplete information is transmitted correctly, or when correct information is not transmitted correctly. Taking this to the next level, split controllers are expected (by cockpit crews) to act as a unified controller and cockpit crews involving a pilot and co-pilot are expected (by control) to operate as a unified AC operator. Hence, any spilt entity needs adequate internal two party communications and adequate external two party communications must exist between the various entities. Failure of any part of this complex communication network results in deficient two party communications that can lead to confusion, a shared attribute among some or all of the participants.

The RI event severity rating is based strictly on the time / distance. The severity rating does not consider the object FAR vehicle classes, the potential for loss of life or damage to property, the causal path or error types, nor does it consider the HFACS states of the participants. In short, the existing FAA RI event definitions provide a very narrow way to examine runway safety, especially if the ultimate goal is to study the impact of technology injections. Many interesting questions can be posed and answered in the context of runway safety events that do not directly support RI event modeling by the strict FAA definitions; answers to these additional questions would provide significant insight into various aspects of possible technology injections and their effectiveness. During this work numerous alternative models have been developed, discussed and discarded either because they did not provide a satisfactory causal path, or because they were deemed to be too complex for use within the SME elicitation process.

As noted previously, an attempt has been made to restrict the RI event scenarios of interest within this study. Part of this reduced scope involves movement restrictions for the objects involved. Object 1 (AC, VEH or PED) initiates the RI event and must be on the runway (RW) at the start of the RI event, or as an AC on final approach to the runway, having crossed the runway threshold. As an AC, Object 1 arrived (or will shortly arrive) on the RW either by incorrectly landing on it, taxiing onto it, or (in the case of crossing runways) the AC may be landing or taking off on one RW, while a second AC (Object 2) is using the second RW. If Object 1 is VEH or PED, it is assumed to be an authorized agent of airport (an airport affiliated contractor or employee) that has moved onto the wrong runway or onto the correct runway but at the wrong time. Cases in which the VEH / PED arrived on the RW by uncontrolled, inappropriate runway access either directly via the airport perimeter, or indirectly through the airport terminal have been excluded from consideration.

An RI event perspective versus an aviation perspective has been adopted. This means that every situation considered herein is assumed to result in an aircraft involved, Cat C or above RI event. Only controlled US airports are considered. The RI event time frame is assumed in the range from seconds to minutes. The FAR aircraft types of interest are Part 121 (Commercial) and Part 135 (Air Taxi). These are considered together due to presumed similar equipment levels; this assumption was validated by the SME panel. Another aircraft type of interest, and a major contributor to RI events, is Part 91 (General Aviation). Discussion with the SME panel revealed that virtually any type of aircraft may be operated as a Part 91 vehicle; thus, the Part 91 distinction is not very useful in this context. Other categories of AC (e.g., military, maintenance taxi) are included in the original data set, but these are not explicitly of interest in this study. The study considers pilot(s), controller(s), and relevant objects (vehicles and pedestrians) on the ground. The study also indirectly considers various airport geometries, various weather and visibility conditions, and various operating conditions. These factors are considered to be fixed during an RI event, whereas the participant HFACS states and two party communications are considered to be active during an RI event. Likewise, airport signs and markings are considered to be fixed mitigations during the RI event, whereas go-arounds, aborted takeoffs or other evasive maneuvers are considered to be active mitigating actions performed by the object operators.

At this point, a preliminary BBN RI event model has been developed. An SME panel consisting of four consultants was assembled to review the model structure and to populate its content. The SME panel met over two days for about 14 hours of discussion about the complex RI event problem. A preliminary baseline RI model was agreed upon, as shown in Figure 2 and model population with SME likelihood belief values was also accomplished, discussed in a later section of this report. The nodes in Figure 2 are color coded to indicate associations among the various nodes. Generally, the flow of specific contributing factors through causal paths is from left to right in the figure. Many items funnel together through the two nodes identified as Fixed and Active Contributing Factors. The node identified as "RI Event Initiation" can be thought of as the start of the active mitigation phase of the RI event, which also ties back to the contributing factors.

Figure 2. The Runway Incursion Bayesian Belief Network.

The SME panel validated many of the proposed definitions and most of the proposed model structure. However, the SME panel also provided significant clarification of several essential definitions within the RI event model. Moreover, the SME panel suggested several structural changes to the model, especially as related to the best way to model the active mitigation phase of the RI events. The overall complexity of the proposed RI event model was reduced from 39 nodes and a combined conditional probability table (CPT) size of 1041 elements to one of 37 nodes and combined CPT size of 735 elements. The remainder of this section describes the current preliminary RI event model. The node name for each is presented along with some clarifying comments. Most of the nodes are binary, meaning they have only two possible states: yes or no; where more states are present in a node, this will be made clear from the explanation. The goal of the SME elicitation is to provide probabilities for each of the possible states; for example, for the node "Airport Layout", the SME goal is to determine the probability that the Airport Layout is an issue or not in the RI event.

The reader should first observe the numbers in Figure 2, representing the three possible primary participants in an RI event: 1 is the pilot or pilots (orange node), 2 is the air traffic controller (ATC) or controllers (cyan node) and 3 is an airport or contractor vehicle driver (pink node). Each of these nodes has a number of other color-coded nodes with links pointing into these three primary nodes. Likewise, each of these three primary nodes have links pointing into the black node (Primary Error State). Starting with the green nodes (middle top), and moving counter-clockwise, the node descriptions of the RI event model follow:

Airport Issues

Airport Layout. The airport layout is an issue[16,18]. This may include potentially confusing elements such as parallel runways (with spacing of less than 1000 feet), intersecting runways, and taxiways parallel to and near runways, numerous taxiways crossing runways instead of perimeter taxiways.

Signs, Markings and Lighting. The signs, markings and/or fixed equipment (e.g., lights) at the airport are deficient. This problem may be exacerbated under severe weather conditions when signs, etc. may be obscured from view[20].

Airport Construction or RW/TW Closure. Airport construction or runway/taxiway closure is an issue.

Contamination Control. Contamination control, generally related to rain, snow or ice, is an issue[18, 47].

Airport Issues. One or more of the issues within this grouping are present.

ATC HFACS Issues

Next are the purple nodes (upper left) which represent some of the most (as determined by the SME panel) Human Factors Analysis and Classification System[46] issues**.** The reader will note that a similar purple HFACS group accompanies both the pilot and the vehicle driver, though in the latter case, the HFACS group only includes training.

ATC Cert Training Issues. Certification training for the ATC involved is an issue.

ATC OTJ Training Issues. On the job training for the ATC involved is an issue as a distraction[13].

ATC Mental or Physical State. The current physical or mental state of the ATC involved is an issue.

ATC HFACS Issues. One or more of the HFACS issues within this grouping is an issue for the ATC involved[46].

ATC Operational Issues

The cyan nodes (middle left) are other contributing factors that may influence the performance of the ATC.

Automation Interaction Issues (ATC). Automation interaction is an issue for the ATC involved[48].

Abnormal Air Traffic Volume or Complexity. The traffic volume or complexity at this airport, at this time is an issue. For example, if the average traffic volume is high, it may cause a significantly increased work load for controllers and/or pilots; if low, it may result in extended periods of inactivity for controllers[16].

Staffing or Procedures Issues. The staffing level and/or work load management not appropriate for the situation is an issue, or the use of ambiguous or non-standardized ATC procedures is an issue[16].

ATC Operational Issues. One or more of the issues within this grouping are present.

Two Party Communications

The next group (blue nodes) describe the state of the system-wide two-party communications.

Communication Content Issues. The completeness, correctness timeliness or complexity of communicated information is an issue. This may include the lack of a required usage for a call sign. Information may not have been transmitted at the appropriate time, i.e., it was not delayed[17].

Comm Hardware Error. Comm transmission is an issue. This may occur when the Comm system fails to operate as expected and may include blocked (“stepped on” communications where one party cuts off the communications of another), partially blocked (garbled or inaudible Comm transmission), hardware limitations / malfunctions and/or faulty headset jacks or connections[17].

Two Party Communication Issues. Comm Content Issues or a Communications Hardware Error has resulted in a Two Party Communications Error and is an issue.

Pilot HFACS Issues

Another group of HFACS contributing factors is present for the pilot. The grouping is the same as before, although the relevant probabilities of these factors being an issue in an RI event may be different than for the ATC.

Pilot Cert Training Issues. Certification training for the pilot(s) involved is an issue.

Pilot OTJ Training Issues. On the job training for the pilot(s) involved is an issue as a distraction[13].

Pilot Mental or Physical State. The current physical or mental state of the pilot(s) involved is an issue.

Pilot HFACS Issues. One or more of the HFACS issues within this grouping is an issue for the pilot(s) involved[46].

Other Pilot Operational Issues

Other contributing factors that may influence the performance of the pilot(s) involved are show in the orange nodes.

Inappropriate Aircraft Operations: Pilot operations of the aircraft, outside of the flight operational manual guidelines, is an issue causing the RI event.

Automation Interaction Issues (Pilot): Automation interaction is an issue for the pilot(s) involved[48].

Pilot Operational Issues: One or more of the issues within this grouping are present.

Driver Operational Issues

These issues include the two nodes below. (purple and pink nodes, top right)

Driver Training: The training of airport vehicle drivers is an issue[13].

Driver Operational Issues: One or more of the HFACS issues within this grouping is an issue for the vehicle driver(s) involved[46].

The preceding discussion covers all the nodes on the periphery of the left hand side of Figure 2. These are all the issues potentially present that enable the RI event to occur. The nodes and states on the far right hand side of the figure generically define a specific RI event, of which numerous types and combinations may occur. NASA would hope to be in a position to broadly address many, if not all, of these specific RI event types with technology injections. Starting with the black node of Figure 2 (middle right), the node descriptions follow.

Primary Error State: The primary error source is either Controller Error (typically, loss of oversight), Pilot Error (typically, failure to hold short of a runway without authorization), or Other (includes mechanical failure and Driver Error, i.e., a failure to hold short of a runway without authorization). The SME panel excluded from consideration in this model non-airport authorized vehicles and all pedestrians on the runway.

Collision Scenarios. The SME panel identified the most common collision scenarios: crossing in front of an aircraft on departure, crossing in front of an aircraft on arrival, or intersection events (crossing active runways) and other (everything else that leads to an RI event)[13].

Reaction time. This node has two states defined by the SME panel, short (eight seconds or less) and long (nine seconds or more)

Final RI Event Severity. The RI event severity as would be reported by the FAA, including the impact of Contributing Factors and Mitigating Actions is established here. The states enumerated by the SME panel are accident / near miss, or other. Although less severe RI event categories have been defined by the FAA, these were deemed out of scope for this BBN model because the SME panel could not provide sufficient discrimination among these less severe RI events.

This concludes the presentation of the RI event model. Likewise, the SME panel vetted many of the proposed definitions and most of the proposed model structure of the RE event model, shown in Figure 3. The SME panel again provided significant clarification of several essential definitions within the RE event model. Moreover, the SME panel suggested several simplifying structural changes to the model. The remainder of this section describes the current preliminary RE event model. The node name for each is presented along with some clarifying comments. Again, most of the nodes are binary with only two possible states (present as in issue in RE Events or not); where more states are present in a node, this will be made clear from the explanation of the node given subsequently.

6.2 Runway Excursion Model

An overrun is an RE event in which the aircraft departs the end of a runway; a veer-off is an RE event in which an aircraft departs the side of a runway. As an RE event may occur on landing or takeoff, four types of RE events are possible: landing overrun, landing veer-off, takeoff overrun and takeoff veer-off. Some sources also include within RE events an aircraft attempting a landing that touches down in the undershoot area of the designated landing runway within the aerodrome perimeter[49].

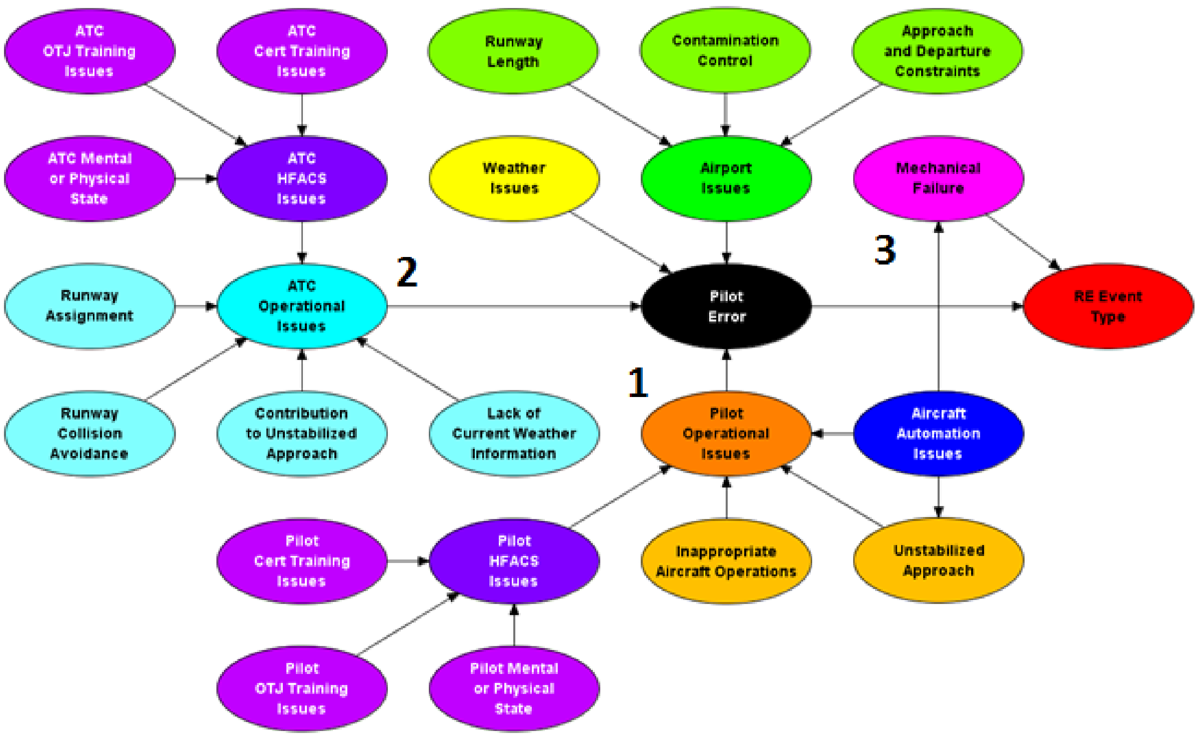

Figure 3. The Runway Excursion Bayesian Belief Network.

Airport Issues

Beginning with green nodes in the upper right corner of Figure 3, and moving counter-clockwise, the nodes and states are below.

Approach and Departure Constraints. The physical or regulatory constraints on approach or departure trajectories for the airport in question are an issue.

Contamination Control. Contamination control (e.g., rain, snow or ice) for the airport in question is an issue.

Runway Length. The runway length is an issue. This may be due to prevailing wind conditions, runway maintenance, or an aircraft landing on a runway that is too short for safe operations.

Airport Issues: One or more of the issues within this grouping are present.

ATC HFACS Issues

As in the RI event network, the ATC HFACS Issues group (purple nodes) is repeated in the RE event network. The SME panel rated the relative importance of these contributing factors for the ATC as being of much less consequence for RE events than for RI events. Next, the cyan nodes are described:

ATC Operational Issues

Runway Assignment. The runway assignment provided by ATC is an issue. This may be due to prevailing wind conditions, runway maintenance, or unusual airport operations.

Runway Collision Avoidance. An RI event (typically failure to hold short of an active runway) has precipitated an RE event. This was noted by the SME panel as being an extremely rare occurrence.

Contribution to Unstabilized Approach. The ATC has provided instructions that contribute to an unstabilized approach.

Lack of Current Weather Information. The ATC involved have provided non-current weather information that contributes to an RE event.

ATC Operational Issues. One or more of the issues within this grouping are present.

Pilot HFACS Issues

As in the RI event network, the Pilot HFACS Issues is repeated in the RE event network. The SME panel rated the relative importance of these contributing factors for the pilot as being about equal for RE and RI events.

Pilot Operational Issues and Remainder Nodes

Inappropriate Aircraft Operations. Pilot operations of the aircraft, outside of the flight operational manual guidelines, is an issue causing the RE event.

Unstabilized Approach. The pilot(s) involved have failed to perform a stabilized approach.

Pilot Operational Issues. One or more of the issues within this grouping are present.

Aircraft Automation Issues (blue node). Automation interaction is an issue for the pilot(s) involved[49].

Pilot Error. A pilot error has initiated an RE event.

Weather Issues (yellow node). Weather issues have contributed to, or caused, an RE event.

Mechanical Failure (pink node). Mechanical failure has contributed to, or caused, an RE event.

RE Event Initiated: This node simply states whether an RE event has been initiated or not.

7.0 Model Population

7.1 Runway Incursion Model

The subject matter expert (SME) model elicitation for the node Airport Layout is summarized in Table 1. Four SMEs, identified as SME1, SME2, SME3 and SME4, were used for the probability elicitation.

Table 1. SME Probabilities and Confidence Bounds for the Node Airport Layout.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	SME1	SME2	SME3	SME4	Min	Max	Avg	StDev	99% Lo	95% Lo	90% Lo	90% Hi	95% Hi	99% Hi
issue	0.30	0.40	0.30	0.25	0.25	0.40	0.31	0.06	0.15	0.19	0.21	0.41	0.43	0.47
not	0.70	0.60	0.70	0.75	0.75	0.60	0.69	0.94	0.85	0.81	0.79	0.59	0.57	0.53

The first column identifies the state of the node as being an issue for RI events or not. Columns two through five provide the SME probabilities for each state. In column six, the minimum (Min) of the four SME responses is computed. In column seven, the maximum (Max) of the four SME responses is computed. In column eight, the average (Avg) of the four SME responses is computed. In column nine, the standard deviation (StDev) of the four SME responses is computed. Columns 10 through 15 provide enclosed confidence bounds of the SME responses defined as:

- Column 10: 99% Lo = Avg – 2.58*StDev
- Column 11: 95% Lo = Avg – 1.96*StDev
- Column 12: 90% Lo = Avg – 1.64*StDev
- Column 13: 90% Hi = Avg + 1.64*StDev
- Column 14: 95% Hi = Avg + 1.96*StDev
- Column 15: 99% Hi = Avg + 2.58*StDev

The multiplicative factors above were derived for the confidence intervals were based upon the Microsoft Excel function NORMINV(Prob,0,1), where Prob = 0.950, 0.975 and 0.995 for the 90%, 95% and 99% confidence bounds above, respectively. These provide some meaningful ranges of the SME inputs to desired levels of confidence that can be used in sensitivity analysis studies.

The SME model elicitation for the node Signs, Markings and Equipment is summarized in Table 2.

Table 2. SME Probabilities and Confidence Bounds for the Node Signs, Markings and Equipment.

	SME1	SME2	SME3	SME4	Min	Max	Avg	StDev	99% Lo	95% Lo	90% Lo	90% Hi	95% Hi	99% Hi
issue	0.15	0.2	0.15	0.15	0.15	0.2	0.16	0.02	0.1	0.11	0.12	0.2	0.21	0.22
not	0.85	0.8	0.85	0.85	0.85	0.8	0.84	0.98	0.9	0.89	0.88	0.8	0.79	0.78

The SME model elicitation for the node Airport Construction or runway (RW) or taxiway (TW) Closure is summarized in Table 3.

Table 3. SME Probabilities and Confidence Bounds for the Node Airport Construction or RW/TW Closure.

	SME1	SME2	SME3	SME4	Min	Max	Avg	StDev	99% Lo	95% Lo	90% Lo	90% Hi	95% Hi	99% Hi
issue	0.10	0.10	0.10	0.15	0.10	0.15	0.11	0.02	0.05	0.06	0.07	0.15	0.16	0.17
not	0.90	0.90	0.90	0.85	0.90	0.85	0.89	0.98	0.95	0.94	0.93	0.85	0.84	0.83

The SME model elicitation for the node Contamination Control is summarized in Table 4. In this case, the 99%, 95% and 90% Lo confidence bounds would be less than zero. However, the computed values have been constrained to be greater than or equal to zero and less than or equal to unity.

Table 4. SME Probabilities and Confidence Bounds for the Node Contamination Control.

	SME1	SME2	SME3	SME4	Min	Max	Avg	StDev	99% Lo	95% Lo	90% Lo	90% Hi	95% Hi	99% Hi
issue	0.00	0.05	0.01	0.01	0.00	0.05	0.02	0.02	0.00	0.00	0.00	0.06	0.07	0.08
not	1.00	0.95	0.99	0.99	1.00	0.95	0.98	0.98	1.00	1.00	1.00	0.94	0.93	0.92

The probabilities for the node Airport Issues are conditioned upon the presence or absence of the contributing factors in the leaf nodes which link into this node. That is to say the conditional probability table (CPT) in the node Airport Issues is conditioned upon the probabilities in the nodes 1) Airport Layout, 2) Signs, Marking and Equipment, 3) Airport Construction or RW/TW Closure and 4) Contamination Control. Strictly speaking, the Airport Issues is an "or" node: if any one of the contributing factors is present, then the result should be that airport issues are present. Such a CPT for a binary node (two output states, issues are present or issues are not present, highlighted in yellow) with two binary input factors is shown in Table 5. The reader should notice that all the probabilities are set to either zero or unity (highlighted in green).

Table 5. Conditional Probability Table for a Two-Factor Binary "or" Node.

Factor 1	Present	Present	Not Present	Not Present
Factor 2	Present	Not Present	Present	Not Present
Present	1	1	1	0
Not Present	0	0	0	1

However, "or" nodes pose some difficulties for sensitivity analysis; hence a variety of other methods to populate the CPT for nodes like Airport Issues have been explored. In the current instance, the average SME probability for each of the four leaf nodes as being an issue that input to Airport Issues were summed, and then the probabilities were renormalized so as to sum to unity. That is, 0.31, 0.16, 0.11 and 0.02, for each of Airport Layout, Signs, Marking and Equipment, Airport Construction or RW/TW Closure and Contamination Control, respectively were summed (0.60) and then the probabilities were renormalized (0.52, 0.27, 0.18 and 0.03, respectively), so as to sum to unity. These renormalized probabilities were then summed to reflect the presence of the contributing factors. The resulting CPT for the Airport Issues node is shown in Table 6. A "yes" state indicates the factor is an issue, whereas a "no" state indicates that the factor is not an issue.

Table 6. Conditional Probability Table for the Node Airport Issues.

Factor																
1	yes	yes	yes	yes	yes	yes	yes	yes	no	no	no	no	no	no	no	no
2	yes	yes	yes	yes	no	no	no	no	yes	yes	yes	yes	no	no	no	no
3	yes	yes	no	no	yes	yes	no	no	yes	yes	no	no	yes	yes	no	no
4	yes	no	yes	no	yes	no	yes	no	yes	no	yes	no	yes	no	yes	no
State																
yes	1.00	0.97	0.82	0.78	0.73	0.70	0.55	0.52	0.48	0.45	0.30	0.27	0.22	0.18	0.03	0.00
no	0.00	0.03	0.18	0.22	0.27	0.30	0.45	0.48	0.52	0.55	0.70	0.73	0.78	0.82	0.97	1.00

Other techniques for populating a CPT such as shown in Table 6 include: direct SME elicitation to determine combinatorial probabilities of the individual contributing factors, rank ordering, and weighting of the individual contributing factors. Direct elicitation of the SME to determine combinatorial probabilities (CPT values) of the individual contributing factors for a node like Airport Issues proved to be very difficult and time consuming for the RI model shown in Figure 2. If the node under consideration has more than two states (such as the Primary Error State node, black, in Figure 2 with three states), this process became exponentially more tedious. What is desired is to get some measure of the relative importance of the individual contributing factors when considered in combination. The simplest approach is just to assume equal weighting for the contributing factors. Thus, for a node like Airport Issues, with four input nodes, the only possible values for the CPT are 0.00, 0.25, 0.50, 0.75 or 1.00, depending on how many of the four contributing factors are present. The next simplest approach may be just to have the SME panel rank order the contributing factors. For example the SME panel might (on average) rank the four contributing factors in this order:

1. Sign, Marking and Equipment (most influential)
2. Layout
3. Construction or RW/TW Closure
4. Contamination Control (least influential)

The sum of the rank orderings is 10 (1 + 2 + 3 + 4 = 10). The probabilities can then be renormalized and allocated in reverse order (0.4, 0.3, 0.2 and 0.1, respectively), so that the most influential contributing factor (Sign, Marking and Equipment) gets the greatest relative probability contribution (0.4). These relative importance probabilities can then be summed as described previously. This would lead to CPT values in the Airport Issues node having all the possible combinations of these values, as shown in Table 7.

Table 7. Conditional Probability Table based on rank ordering of contributing factors.

Factor																
1	yes	yes	yes	yes	yes	yes	yes	yes	no	no	no	no	no	No	no	no
2	yes	yes	yes	yes	no	no	no	no	yes	yes	yes	yes	no	No	no	no
3	yes	yes	no	no	yes	yes	no	no	yes	yes	no	no	yes	Yes	no	no
4	yes	no	yes	no	yes	no	yes	no	yes	no	yes	no	yes	No	yes	no
State																
yes	1.00	0.90	0.80	0.70	0.60	0.50	0.40	0.30	0.70	0.60	0.50	0.40	0.30	0.20	0.10	0.00
no	0.00	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00

Finally, the SME panel can be asked to provide specific weightings for each of the contributing factors. If these weightings sum to unity, then no renormalization is necessary.

The SME model elicitation for the node Air Traffic Control (ATC) Certification (Cert) Training Issues is summarized in Table 8.

Table 8. SME Probabilities and Confidence Bounds for the Node ATC Cert Training Issues.

	SME1	SME2	SME3	SME4	Min	Max	Avg	StDev	99% Lo	95% Lo	90% Lo	90% Hi	95% Hi	99% Hi
issue	0.01	0.02	0.01	0.01	0.01	0.02	0.01	0.01	0.00	0.00	0.00	0.02	0.02	0.02
not	0.99	0.98	0.99	0.99	0.99	0.98	0.99	1.00	1.00	1.00	1.00	0.98	0.98	0.98

The SME model elicitation for the node ATC On-The-Job Training (OJT) Issues is summarized in Table 9.

Table 9. SME Probabilities and Confidence Bounds for the Node ATC OJT Issues.

	SME1	SME2	SME3	SME4	Min	Max	Avg	StDev	99% Lo	95% Lo	90% Lo	90% Hi	95% Hi	99% Hi
issue	0.05	0.05	0.08	0.08	0.05	0.08	0.06	0.02	0.02	0.03	0.03	0.09	0.09	0.10
not	0.95	0.95	0.92	0.93	0.95	0.92	0.94	0.98	0.98	0.97	0.97	0.91	0.91	0.90

The SME model elicitation for the node ATC Mental or Physical State Issues is summarized in Table 10.

Table 10. SME Probabilities and Confidence Bounds for the Node ATC Mental or Physical State Issues.

	SME1	SME2	SME3	SME4	Min	Max	Avg	StDev	99% Lo	95% Lo	90% Lo	90% Hi	95% Hi	99% Hi
issue	0.05	0.10	0.02	0.10	0.02	0.10	0.07	0.04	0.00	0.00	0.01	0.13	0.15	0.17
not	0.95	0.90	0.98	0.90	0.98	0.90	0.93	0.96	1.00	1.00	0.99	0.87	0.85	0.83

The same method, described above, used for the node Airport Issues was also used to construct the CPT for the node ATC Human Factors Analysis and Classification System (HFACS) Issues. That is, the average probabilities for the three input nodes were summed and renormalized; the resulting normalized probabilities were then summed again to reflect the presence of the three contributing factors, as shown in Table 11.

Table 11. Conditional Probability Table for the Node ATC HFACS Issues.

state	yes	yes	yes	yes	no	no	no	no
ojt	yes	yes	no	no	yes	yes	no	no
cert	yes	no	yes	no	yes	no	yes	no
ATC HFACS Issues	1.00	0.93	0.57	0.50	0.50	0.43	0.07	0.00
No ATC HFACS Issues	0.00	0.07	0.43	0.50	0.50	0.57	0.93	1.00

The SME model elicitation for the node Communication (Comm) Content Issues is summarized in Table 12.

Table 12. SME Probabilities and Confidence Bounds for the Node Comm Content Issues.

	SME1	SME2	SME3	SME4	Min	Max	Avg	StDev	99% Lo	95% Lo	90% Lo	90% Hi	95% Hi	99% Hi
issue	0.25	0.35	0.30	0.40	0.25	0.40	0.33	0.06	0.16	0.20	0.22	0.44	0.46	0.50
not	0.75	0.65	0.70	0.60	0.75	0.60	0.67	0.94	0.84	0.80	0.78	0.56	0.54	0.50

The SME model elicitation for the node Comm Hardware Issues is summarized in Table 13.

Table 13. SME Probabilities and Confidence Bounds for the Node Comm Hardware Issues.

	SME1	SME2	SME3	SME4	Min	Max	Avg	StDev	99% Lo	95% Lo	90% Lo	90% Hi	95% Hi	99% Hi
issue	0.01	0.01	0.00	0.01	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.02	0.02	0.02
not	0.99	0.99	1.00	1.00	1.00	0.99	0.99	1.00	1.00	1.00	1.00	0.98	0.98	0.98

The same method, described above, used for the node Airport Issues was also used to construct the CPT for the node Two-Party Comm Issues. That is, the average probabilities for the two input nodes were summed and renormalized; the resulting normalized probabilities were then summed again to reflect the presence of the two contributing factors, as shown in Table 14.

Table 14. Conditional Probability Table for the Node Two-Party Comm Issues.

content	yes	yes	no	no
hardware	yes	no	yes	no
Two-Party Comm Issues	1.00	0.97	0.03	0.00
No Issues	0.00	0.03	0.97	1.00

The SME model elicitation for the node Pilot Cert Training Issues is summarized in Table 15.

Table 15. SME Probabilities and Confidence Bounds for the Node Pilot Cert Training Issues.

	SME1	SME2	SME3	SME4	Min	Max	Avg	StDev	99% Lo	95% Lo	90% Lo	90% Hi	95% Hi	99% Hi
issue	0.01	0.02	0.02	0.01	0.01	0.02	0.02	0.01	0.01	0.01	0.01	0.03	0.03	0.03
not	0.99	0.98	0.98	0.99	0.99	0.98	0.98	0.99	0.99	0.99	0.99	0.97	0.97	0.97

The SME model elicitation for the node Pilot OJT Issues is summarized in Table 16.

Table 16. SME Probabilities and Confidence Bounds for the Node Pilot OJT Issues.

	SME1	SME2	SME3	SME4	Min	Max	Avg	StDev	99% Lo	95% Lo	90% Lo	90% Hi	95% Hi	99% Hi
issue	0.05	0.01	0.01	0.03	0.01	0.05	0.03	0.02	0.00	0.00	0.00	0.06	0.07	0.08
not	0.95	0.99	0.99	0.97	0.99	0.95	0.97	0.98	1.00	1.00	1.00	0.94	0.93	0.92

The SME model elicitation for the node Pilot Mental or Physical State Issues is summarized in Table 17.

Table 17. SME Probabilities and Confidence Bounds for the Node Pilot Mental or Physical State Issues.

	SME1	SME2	SME3	SME4	Min	Max	Avg	StDev	99% Lo	95% Lo	90% Lo	90% Hi	95% Hi	99% Hi
issue	0.05	0.05	0.02	0.02	0.02	0.05	0.04	0.02	0.00	0.01	0.01	0.07	0.07	0.08
not	0.95	0.95	0.98	0.98	0.98	0.95	0.96	0.98	1.00	0.99	0.99	0.93	0.93	0.92

The same method, described above, used for the node Airport Issues was also used to construct the CPT for the node Pilot HFACS Issues. That is, the average probabilities for the three input nodes were summed and renormalized; the resulting normalized probabilities were then summed again to reflect the presence of the three contributing factors, as shown in Table 18.

Table 18. Conditional Probability Table for the Node Pilot HFACS Issues.

state	yes	yes	yes	yes	no	no	no	no
ojt	yes	yes	no	no	yes	yes	no	no
cert	yes	no	yes	no	yes	no	yes	no
Pilot HFACS Issues	1.00	0.78	0.67	0.44	0.56	0.33	0.22	0.00
No Pilot HFACS Issues	0.00	0.22	0.33	0.56	0.44	0.67	0.78	1.00

The SME model elicitation for the node Automation Interaction Issues (Pilot) is summarized in Table 19.

Table 19. SME Probabilities and Confidence Bounds for the Node Automation Interaction Issues (Pilot).

	SME1	SME2	SME3	SME4	Min	Max	Avg	StDev	99% Lo	95% Lo	90% Lo	90% Hi	95% Hi	99% Hi
issue	0.03	0.01	0.05	0.01	0.01	0.05	0.02	0.02	0.00	0.00	0.00	0.05	0.06	0.07
not	0.97	0.99	0.95	1.00	1.00	0.95	0.98	0.98	1.00	1.00	1.00	0.95	0.94	0.93

The SME model elicitation for the node Inappropriate Aircraft Operations is summarized in Table 20.

Table 20. SME Probabilities and Confidence Bounds for the Node Inappropriate Aircraft Operations.

	SME1	SME2	SME3	SME4	Min	Max	Avg	StDev	99% Lo	95% Lo	90% Lo	90% Hi	95% Hi	99% Hi
issue	0.10	0.10	0.01	0.10	0.01	0.10	0.08	0.05	0.00	0.00	0.01	0.15	0.17	0.20
not	0.90	0.90	0.99	0.90	0.99	0.90	0.92	0.96	1.00	1.00	0.99	0.85	0.83	0.80

The SME model elicitation for the node Automation Interaction Issues (ATC) is summarized in Table 21.

Table 21. SME Probabilities and Confidence Bounds for the Node Automation Interaction Issues (ATC).

	SME1	SME2	SME3	SME4	Min	Max	Avg	StDev	99% Lo	95% Lo	90% Lo	90% Hi	95% Hi	99% Hi
issue	0.00	0.05	0.05	0.10	0.00	0.10	0.05	0.04	0.00	0.00	0.00	0.12	0.13	0.15
not	1.00	0.95	0.95	0.90	1.00	0.90	0.95	0.96	1.00	1.00	1.00	0.88	0.87	0.85

The SME model elicitation for the node Abnormal Air Traffic Volume or Complexity is summarized in Table 22.

Table 22. SME Probabilities and Confidence Bounds for the Node Abnormal Air Traffic Volume or Complexity.

	SME1	SME2	SME3	SME4	Min	Max	Avg	StDev	99% Lo	95% Lo	90% Lo	90% Hi	95% Hi	99% Hi
issue	0.20	0.20	0.05	0.25	0.05	0.25	0.18	0.09	0.00	0.01	0.04	0.32	0.35	0.40
not	0.80	0.80	0.95	0.75	0.95	0.75	0.82	0.91	1.00	0.99	0.96	0.68	0.65	0.60

The SME model elicitation for the node Staffing or Procedural Issues is summarized in Table 23.

Table 23. SME Probabilities and Confidence Bounds for the Node Staffing or Procedural Issues.

	SME1	SME2	SME3	SME4	Min	Max	Avg	StDev	99% Lo	95% Lo	90% Lo	90% Hi	95% Hi	99% Hi
issue	0.05	0.15	0.20	0.25	0.05	0.25	0.16	0.09	0.00	0.00	0.02	0.30	0.33	0.38
not	0.95	0.85	0.80	0.75	0.95	0.75	0.84	0.91	1.00	1.00	0.98	0.70	0.67	0.62

For the node ATC Operational Issues, a rank ordering of the relative effects of the six input nodes (Airport Issues, ATC HFACS Issues, Automation Interaction Issues (ATC), Abnormal Air Traffic Volume or Complexity, Staffing or Procedural Issues and Two-Party Comm Issues) was used. The average SME ranking of the six inputs was as follows:

1. ATC HFACS Issues (most influential)
2. Abnormal Air Traffic Volume or Complexity
3. Staffing or Procedural Issues and Two-Party Comm Issues (tied)
4. Airport Issues
5. Automation Interaction Issues (ATC) (least influential)

This Excel ranking (6, 5, 3.5, 3.5, 2 and 1, respectively) summed to 21, providing renormalized values of 0.29, 0.24, 0.17, 0.17, 0.10 and 0.05, respectively, highlighted in green in Table 24. The resulting 64 column CPT is too large to be legibly shown horizontally in this report. Hence, a transposed version of the CPT is shown in Table 24. The cells shown in green are the renormalized relative probabilities for the six input nodes that were summed in the column labeled “ATC Ops Issues” when a “yes” appeared in a row under the six input factors.

Table 24. Transposed Conditional Probability Table for the Node ATC Operational Issues.

0.10	0.17	0.29	0.17	0.24	0.05		
airport	comm	hfacs	staffing	volume	auto	ATC Ops Issues	No ATC Ops Issues
yes	yes	yes	yes	yes	yes	1.00	0.00
yes	yes	yes	yes	yes	no	0.95	0.05
yes	yes	yes	yes	no	yes	0.76	0.24
yes	yes	yes	yes	no	no	0.71	0.29
yes	yes	yes	no	yes	yes	0.83	0.17
yes	yes	yes	no	yes	no	0.79	0.21
yes	yes	yes	no	no	yes	0.60	0.40
yes	yes	yes	no	no	no	0.55	0.45
yes	yes	no	yes	yes	yes	0.71	0.29
yes	yes	no	yes	yes	no	0.67	0.33
yes	yes	no	yes	no	yes	0.48	0.52
yes	yes	no	yes	no	no	0.43	0.57
yes	yes	no	no	yes	yes	0.55	0.45
yes	yes	no	no	yes	no	0.50	0.50
yes	yes	no	no	no	yes	0.31	0.69
yes	yes	no	no	no	no	0.26	0.74
yes	no	yes	yes	yes	yes	0.83	0.17
yes	no	yes	yes	yes	no	0.79	0.21
yes	no	yes	yes	no	yes	0.60	0.40
yes	no	yes	yes	no	no	0.55	0.45
yes	no	yes	no	yes	yes	0.67	0.33
yes	no	yes	no	yes	no	0.62	0.38
yes	no	yes	no	no	yes	0.43	0.57
yes	no	yes	no	no	no	0.38	0.62
yes	no	no	yes	yes	yes	0.55	0.45
yes	no	no	yes	yes	no	0.50	0.50
yes	no	no	yes	no	yes	0.31	0.69
yes	no	no	yes	no	no	0.26	0.74
yes	no	no	no	yes	yes	0.38	0.62
yes	no	no	no	yes	no	0.33	0.67
yes	no	no	no	no	yes	0.14	0.86
yes	no	no	no	no	no	0.10	0.90
no	yes	yes	yes	yes	yes	0.90	0.10
no	yes	yes	yes	yes	no	0.86	0.14
no	yes	yes	yes	no	yes	0.67	0.33
no	yes	yes	yes	no	no	0.62	0.38

no	yes	yes	no	yes	yes	0.74	0.26
no	yes	yes	no	yes	no	0.69	0.31
no	yes	yes	no	no	yes	0.50	0.50
no	yes	yes	no	no	no	0.45	0.55
no	yes	no	yes	yes	yes	0.62	0.38
no	yes	no	yes	yes	no	0.57	0.43
no	yes	no	yes	no	yes	0.38	0.62
no	yes	no	yes	no	no	0.33	0.67
no	yes	no	no	yes	yes	0.45	0.55
no	yes	no	no	yes	no	0.40	0.60
no	yes	no	no	no	yes	0.21	0.79
no	yes	no	no	no	no	0.17	0.83
no	no	yes	yes	yes	yes	0.74	0.26
no	no	yes	yes	yes	no	0.69	0.31
no	no	yes	yes	no	yes	0.50	0.50
no	no	yes	yes	no	no	0.45	0.55
no	no	yes	no	yes	yes	0.57	0.43
no	no	yes	no	yes	no	0.52	0.48
no	no	yes	no	no	yes	0.33	0.67
no	no	yes	no	no	no	0.29	0.71
no	no	no	yes	yes	yes	0.45	0.55
no	no	no	yes	yes	no	0.40	0.60
no	no	no	yes	no	yes	0.21	0.79
no	no	no	yes	no	no	0.17	0.83
no	no	no	no	yes	yes	0.29	0.71
no	no	no	no	yes	no	0.24	0.76
no	no	no	no	no	yes	0.05	0.95
no	no	no	no	no	no	0.00	1.00

For the node Pilot Operational Issues, a hybrid approach was used to populate the CPT. The average SME input for the Inappropriate Aircraft Operations (0.08) and Automation Interaction Issues (Pilot) (0.02) were used. The remaining three input nodes to Pilot Operational Issues (e.g., Airport Issues, Two-Party Comm Issues and Pilot HFACS Issues) were already conditional nodes and no ranking ordering of these was performed. Hence, the average CPT value (0.5) was used as the weighting value for each of these three inputs to the Pilot Operational Issues node. The resulting renormalization of the weighting values (0.5, 0.5, 0.5 0.08 and 0.02 renormalized to 0.31, 0.31, 0.31, 0.05 and 0.01, highlighted in green in Table 25) gives a disproportionate weight to the five inputs. The resulting CPT is shown (transposed) in Table 25. In retrospect, eliciting a rank ordering, or even using equal weighting, of the five inputs would have been a preferred method.

Table 25. Transposed Conditional Probability Table for the Node Pilot Operational Issues.

0.31	0.31	0.31	0.05	0.01	Pilot Ops Issues	No Pilot Ops Issues
airport	comm	hfacs	in ops	auto		
yes	yes	yes	yes	yes	1.00	0.00
yes	yes	yes	yes	no	0.99	0.01
yes	yes	yes	no	yes	0.95	0.05
yes	yes	yes	no	no	0.94	0.06
yes	yes	no	yes	yes	0.69	0.31
yes	yes	no	yes	no	0.68	0.33
yes	yes	no	no	yes	0.64	0.36
yes	yes	no	no	no	0.63	0.38
yes	no	yes	yes	yes	0.69	0.31
yes	no	yes	yes	no	0.68	0.33
yes	no	yes	no	yes	0.64	0.36
yes	no	yes	no	no	0.63	0.38
yes	no	no	yes	yes	0.38	0.63
yes	no	no	yes	no	0.36	0.64
yes	no	no	no	yes	0.33	0.68
yes	no	no	no	no	0.31	0.69
no	yes	yes	yes	yes	0.69	0.31
no	yes	yes	yes	no	0.68	0.33
no	yes	yes	no	yes	0.64	0.36
no	yes	yes	no	no	0.63	0.38
no	yes	no	yes	yes	0.38	0.63
no	yes	no	yes	no	0.36	0.64
no	yes	no	no	yes	0.33	0.68
no	yes	no	no	no	0.31	0.69
no	no	yes	yes	yes	0.38	0.63
no	no	yes	yes	no	0.36	0.64
no	no	yes	no	yes	0.33	0.68
no	no	yes	no	no	0.31	0.69
no	no	no	yes	yes	0.06	0.94
no	no	no	yes	no	0.05	0.95
no	no	no	no	yes	0.01	0.99
no	no	no	no	no	0.00	1.00

The SME model elicitation for the node Driver Training is summarized in Table 26.

Table 26. SME Probabilities and Confidence Bounds for the Node Driver Training.

	SME1	SME2	SME3	SME4	Min	Max	Avg	StDev	99% Lo	95% Lo	90% Lo	90% Hi	95% Hi	99% Hi
issue	0.03	0.01	0.04	0.03	0.01	0.04	0.03	0.01	0.00	0.01	0.01	0.05	0.05	0.06
not	0.97	0.99	0.96	0.97	0.99	0.96	0.97	0.99	1.00	0.99	0.99	0.95	0.95	0.94

For the node Driver Operational Issues, the hybrid approach (described above) was again used to populate the CPT. The average SME input (0.03) for the node Driver Training was used along with the average CPT value (0.5) for the nodes Airport Issues and Two-Party Comm Issues. The resulting renormalization of the weighting values (0.5, 0.5, and 0.03 renormalized to 0.49, 0.49 and 0.03) gives a disproportionate weight to the three inputs. The resulting CPT is shown in Table 27. In retrospect, eliciting a rank ordering, or even using equal weighting, of the five inputs would have been a preferred method.

Table 27. Conditional Probability Table for the Node Driver Operational Issues.

training	yes	yes	yes	yes	no	no	no	no
comm	yes	yes	no	no	yes	yes	no	no
airport	yes	no	yes	no	yes	no	yes	no
driver ops issues	1.00	0.51	0.51	0.03	0.97	0.49	0.49	0.00
no driver ops issues	0.00	0.49	0.49	0.97	0.03	0.51	0.51	1.00

The node Primary Error State has three input links (Driver Operational Issues, ATC Operational Issues and Pilot Operational Issues) and three output states: Pilot Error, Controller Error and Other. Unfortunately, the SME panel provided probabilities for a different version of this table in which four output states were possible: Pilot Error, Controller Error, Driver Error and Other (mechanical failure); subsequent discussions removed the “Other” state from this node and removed from consideration any RI caused by mechanical failure. However, since the elicitation results did not align with the final version of table, a decision was made to combine the elicitation results for the Driver Error state with those for the Other state, and to rename the third output state as Other (includes Driver Error and mechanical failure). The resulting CPT has 3 rows and 8 columns. Each column describes the probabilities for a combination of Driver Operational Issues, Pilot Operational Issues and ATC Operational Issues; these combinations are highlighted in orange, yellow and green as shown in Table 28.

Table 28. SME Probabilities and Confidence Bounds for the Node Primary Error State.

	driver issues		yes	pilot issues		yes	controller issues		yes
	Min	Max	Avg	99% Lo	95% Lo	90% Lo	90% Hi	95% Hi	99% Hi
pilot error	0.30	0.49	0.44	0.19	0.25	0.28	0.60	0.63	0.69
controller error	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
other	0.31	0.50	0.36	0.11	0.17	0.20	0.52	0.55	0.61
	driver issues		yes	pilot issues		yes	controller issues		no
	Min	Max	Avg	99% Lo	95% Lo	90% Lo	90% Hi	95% Hi	99% Hi
pilot error	0.45	0.70	0.59	0.32	0.39	0.42	0.76	0.79	0.86
controller error	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
other	0.30	0.55	0.42	0.13	0.20	0.23	0.61	0.64	0.71
	driver issues		yes	pilot issues		no	controller issues		yes
	Min	Max	Avg	99% Lo	95% Lo	90% Lo	90% Hi	95% Hi	99% Hi
pilot error	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
controller error	0.35	0.40	0.38	0.31	0.32	0.33	0.43	0.44	0.45
other	0.59	0.66	0.63	0.54	0.56	0.57	0.69	0.70	0.72
	driver issues		yes	pilot issues		no	controller issues		no
	Min	Max	Avg	99% Lo	95% Lo	90% Lo	90% Hi	95% Hi	99% Hi
pilot error	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
controller error	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
other	0.99	1.00	1.00	0.99	0.99	0.99	1.00	1.00	1.00
	driver issues		no	pilot issues		yes	controller issues		yes
	Min	Max	Avg	99% Lo	95% Lo	90% Lo	90% Hi	95% Hi	99% Hi
pilot error	0.60	0.70	0.65	0.50	0.54	0.56	0.74	0.76	0.80
controller error	0.25	0.39	0.32	0.16	0.20	0.22	0.42	0.44	0.48
other	0.01	0.05	0.03	0.00	0.00	0.00	0.07	0.08	0.09
	driver issues		no	pilot issues		yes	controller issues		no
	Min	Max	Avg	99% Lo	95% Lo	90% Lo	90% Hi	95% Hi	99% Hi
pilot error	0.99	1.00	0.99	0.98	0.98	0.98	1.00	1.00	1.00
controller error	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

other	0.00	0.01	0.01	0.00	0.00	0.00	0.02	0.02	0.02
	driver issues		no	pilot issues		no	controller issues		yes
	Min	Max	Avg	99% Lo	95% Lo	90% Lo	90% Hi	95% Hi	99% Hi
pilot error	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
controller error	0.99	1.00	0.99	0.98	0.98	0.98	1.00	1.00	1.00
other	0.00	0.01	0.01	0.00	0.00	0.00	0.02	0.02	0.02
	driver issues		no	pilot issues		no	controller issues		no
	Min	Max	Avg	99% Lo	95% Lo	90% Lo	90% Hi	95% Hi	99% Hi
pilot error	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
controller error	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
other	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

The SME model elicitation for the node Collision Scenarios is summarized in Table 29.

Table 29. SME Probabilities and Confidence Bounds for the Node Collision Scenarios.

Collision Scenarios	SME1	SME2	SME3	SME4	Min	Max	Avg	StDev	99% Lo	95% Lo	90% Lo	90% Hi	95% Hi	99% Hi
crossing / departure	0.10	0.15	0.20	0.15	0.10	0.20	0.15	0.04	0.04	0.07	0.08	0.22	0.23	0.26
crossing / arrival	0.10	0.15	0.10	0.20	0.10	0.20	0.14	0.05	0.02	0.05	0.06	0.22	0.23	0.26
intersecting runways	0.05	0.05	0.05	0.10	0.05	0.10	0.06	0.03	0.00	0.01	0.02	0.10	0.11	0.12
other	0.75	0.65	0.65	0.55	0.55	0.75	0.65	0.08	0.44	0.49	0.52	0.78	0.81	0.86

The SME model elicitation for the node Reaction Time is summarized in Table 30.

Table 30. SME Probabilities and Confidence Bounds for the Node Reaction Time.

reaction time	SME1	SME2	SME3	SME4	Min	Max	Avg	StDev	99% Lo	95% Lo	90% Lo	90% Hi	95% Hi	99% Hi
short (8 sec or less)	0.30	0.40	0.03	0.05	0.03	0.40	0.20	0.18	0.00	0.00	0.00	0.50	0.56	0.67

long (9 sec or more)	0.70	0.60	0.97	0.95	0.97	0.60	0.80	0.18	0.33	0.44	0.50	1.00	1.00	1.00

The node Potential RI Event Severity is conditioned upon the nodes Primary Error State, Collision Scenario and Reaction Time. A direct CPT elicitation was used and the average probabilities for the node are presented in Table 31. In Table 31, the following abbreviations are used: "cont" refers to controller error and "xrw" means crossing runways.

Table 31. Transposed Conditional Probability Table for the Node Potential RI Event Severity.

reaction time	collision scenario	error state	accident / near miss	other
short	depart	cont	0.05	0.95
short	depart	pilot	0.08	0.92
short	depart	other	0.09	0.91
short	arrive	cont	0.05	0.95
short	arrive	pilot	0.07	0.93
short	arrive	other	0.03	0.97
short	xrw	cont	0.03	0.97
short	xrw	pilot	0.06	0.94
short	xrw	other	0.08	0.92
short	other	cont	0.01	0.99
short	other	pilot	0.02	0.98
short	other	other	0.02	0.98
long	depart	cont	0.038	0.962
long	depart	pilot	0.0608	0.9392
long	depart	other	0.0684	0.9316
long	arrive	cont	0.038	0.962
long	arrive	pilot	0.0532	0.9468
long	arrive	other	0.0228	0.9772
long	xrw	cont	0.0228	0.9772
long	xrw	pilot	0.0456	0.9544
long	xrw	other	0.0608	0.9392
long	other	cont	0.0076	0.9924
long	other	pilot	0.0152	0.9848
long	other	other	0.0152	0.9848

7.2 Runway Excursion Model

The SME model elicitation for the node Approach and Departure Constraints is summarized in Table 32.

Table 32. SME Probabilities and Confidence Bounds for the Node Approach and Departure Constraints.

	SME1	SME2	SME2	SME4	Min	Max	Avg	StDev	99% Lo	95% Lo	90% Lo	90% Hi	95% Hi	99% Hi
issue	0.05	0.10	0.05	0.03	0.03	0.10	0.06	0.03	0.00	0.00	0.00	0.11	0.12	0.14
not	0.95	0.90	0.95	0.98	0.98	0.90	0.94	0.97	1.00	1.00	1.00	0.89	0.88	0.86

The SME model elicitation for the node Contamination Control is summarized in Table 33.

Table 33. SME Probabilities and Confidence Bounds for the Node Contamination Control.

	SME1	SME2	SME3	SME4	Min	Max	Avg	StDev	99% Lo	95% Lo	90% Lo	90% Hi	95% Hi	99% Hi
issue	0.05	0.05	0.00	0.01	0.00	0.05	0.03	0.03	0.00	0.00	0.00	0.07	0.08	0.09
not	0.95	0.95	1.00	0.99	1.00	0.95	0.97	0.97	1.00	1.00	1.00	0.93	0.92	0.91

The SME model elicitation for the node Runway Length is summarized in Table 34.

Table 34. SME Probabilities and Confidence Bounds for the Node Runway Length.

	SME1	SME2	SME3	SME4	Min	Max	Avg	StDev	99% Lo	95% Lo	90% Lo	90% Hi	95% Hi	99% Hi
issue	0.10	0.15	0.10	0.15	0.10	0.15	0.13	0.03	0.05	0.07	0.08	0.17	0.18	0.20
not	0.90	0.85	0.90	0.85	0.90	0.85	0.87	0.97	0.95	0.93	0.92	0.83	0.82	0.80

The average SME input for node Airport Issues is shown in Table 34. The following abbreviations are used in Table 35: app =approach, dep = departure, cont = contamination control and rw = runway.

Table 35. Conditional Probability Table for the node Airport Issues.

app/dep	yes	yes	yes	yes	no	no	no	no
cont	yes	yes	no	no	yes	yes	no	no
rw length	yes	no	yes	no	yes	no	yes	no
issue	0.99	0.61	0.71	0.28	0.82	0.19	0.59	0.01
not	0.01	0.39	0.29	0.72	0.18	0.81	0.41	0.99

The SME model elicitation for the node Runway Assignment is summarized in Table 36.

Table 36. SME Probabilities and Confidence Bounds for the Node Runway Assignment.

	SME1	SME2	SME3	SME4	Min	Max	Avg	StDev	99% Lo	95% Lo	90% Lo	90% Hi	95% Hi	99% Hi
issue	0.05	0.05	0.01	0.05	0.01	0.05	0.04	0.02	0.00	0.00	0.01	0.07	0.08	0.09
not	0.95	0.95	0.99	0.95	0.99	0.95	0.96	0.98	1.00	1.00	0.99	0.93	0.92	0.91

The SME model elicitation for the node Runway Collision Avoidance is summarized in Table 37.

Table 37. SME Probabilities and Confidence Bounds for the Node Runway Collision Avoidance.

	SME1	SME2	SME3	SME4	Min	Max	Avg	StDev	99% Lo	95% Lo	90% Lo	90% Hi	95% Hi	99% Hi
issue	0.00	0.01	0.01	0.01	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.01	0.02	0.02
not	1.00	0.99	1.00	0.99	1.00	0.99	0.99	1.00	1.00	1.00	1.00	0.99	0.98	0.98

The SME model elicitation for the node Contribution to Unstabilized Approach is summarized in Table 38.

Table 38. SME Probabilities and Confidence Bounds for the Node Contribution to Unstabilized Approach.

	SME1	SME2	SME3	SME4	Min	Max	Avg	StDev	99% Lo	95% Lo	90% Lo	90% Hi	95% Hi	99% Hi
issue	0.10	0.10	0.20	0.25	0.10	0.25	0.16	0.08	0.00	0.02	0.04	0.29	0.31	0.36
not	0.90	0.90	0.80	0.75	0.90	0.75	0.84	0.93	1.00	0.98	0.96	0.71	0.69	0.64

The SME model elicitation for the node Lack of Current Weather Information is summarized in Table 39.

Table 39. SME Probabilities and Confidence Bounds for the Node Lack of Current Weather Info.

	SME1	SME2	SME3	SME4	Min	Max	Avg	StDev	99% Lo	95% Lo	90% Lo	90% Hi	95% Hi	99% Hi
issue	0.10	0.01	0.01	0.10	0.01	0.10	0.06	0.05	0.00	0.00	0.00	0.14	0.16	0.19
not	0.90	0.99	0.99	0.90	0.99	0.90	0.94	0.95	1.00	1.00	1.00	0.86	0.84	0.81

The average SME model elicitation for the node ATC Operational Issues is summarized in Table 40. The HFACS contribution to the CPT are considered separately. The following abbreviations are used in Table 40: hfacs = human factors assessment and classification system, rw = runway, cntrb = contribution, unstab = unstabilized, app = approach, and curr = current.

Table 40. Transposed Conditional Probability Table for the node ATC Operational Issues.

hfacs	rw assign	coll avoid	cntrb to unstab app	lack of curr weather	ATC Ops Issues	No ATC Ops Issues
yes	yes	yes	yes	yes	1.0000	0.0000
yes	yes	yes	yes	no	0.8705	0.1295
yes	yes	yes	no	yes	0.5702	0.4298

yes	yes	yes	no	no	0.4311	0.5689
yes	yes	no	yes	yes	0.9039	0.0961
yes	yes	no	yes	no	0.7370	0.2630
yes	yes	no	no	yes	0.5006	0.4994
yes	yes	no	no	no	0.1530	0.8470
yes	no	yes	yes	yes	0.8761	0.1239
yes	no	yes	yes	no	0.6536	0.3464
yes	no	yes	no	yes	0.4172	0.5828
yes	no	yes	no	no	0.2086	0.7914
yes	no	no	yes	yes	0.8066	0.1934
yes	no	no	yes	no	0.6258	0.3742
yes	no	no	no	yes	0.1418	0.8582
yes	no	no	no	no	0.0147	0.9853
no	yes	yes	yes	yes	0.9925	0.0075
no	yes	yes	yes	no	0.7825	0.2175
no	yes	yes	no	yes	0.5125	0.4875
no	yes	yes	no	no	0.3875	0.6125
no	yes	no	yes	yes	0.8125	0.1875
no	yes	no	yes	no	0.6625	0.3375
no	yes	no	no	yes	0.4500	0.5500
no	yes	no	no	no	0.1375	0.8625
no	no	yes	yes	yes	0.7875	0.2125
no	no	yes	yes	no	0.5875	0.4125
no	no	yes	no	yes	0.3750	0.6250
no	no	yes	no	no	0.1875	0.8125
no	no	no	yes	yes	0.7250	0.2750
no	no	no	yes	no	0.5625	0.4375
no	no	no	no	yes	0.1275	0.8725
no	no	no	no	no	0.0133	0.9868

The SME model elicitation for the node Unstabilized Approach is summarized in Table 41.

Table 41. SME Probabilities and Confidence Bounds for the Node Unstabilized Approach.

with automation issue														
	SME1	**SME2**	**SME3**	**SME4**	**Min**	**Max**	**Avg**	**StDev**	**99% Lo**	**95% Lo**	**90% Lo**	**90% Hi**	**95% Hi**	**99% Hi**
issue	0.30	0.25	0.25	0.50	0.25	0.50	0.36	0.13	0.03	0.11	0.15	0.57	0.61	0.69
not	0.70	0.75	0.75	0.50	0.75	0.50	0.64	0.87	0.97	0.89	0.85	0.43	0.39	0.31

with no automation issue														
	SME1	SME2	SME3	SME4	Min	Max	Avg	StDev	99% Lo	95% Lo	90% Lo	90% Hi	95% Hi	99% Hi
issue	0.01	0.01	0.10	0.15	0.01	0.15	0.07	0.07	0.00	0.00	0.00	0.18	0.20	0.25
not	0.99	0.99	0.90	0.85	0.99	0.85	0.93	0.93	1.00	1.00	1.00	0.82	0.80	0.75

The SME model elicitation for the node Aircraft Automation Issues is summarized in Table 42.

Table 42. SME Probabilities and Confidence Bounds for the Node Aircraft Automation Issues.

	SME1	SME2	SME3	SME4	Min	Max	Avg	StDev	99% Lo	95% Lo	90% Lo	90% Hi	95% Hi	99% Hi
issue	0.01	0.01	0.10	0.15	0.01	0.15	0.07	0.07	0.00	0.00	0.00	0.18	0.20	0.25
not	0.99	0.99	0.90	0.85	0.99	0.85	0.93	0.93	1.00	1.00	1.00	0.82	0.80	0.75

The SME model elicitation for the node Inappropriate Aircraft Operations is summarized in Table 43.

Table 43. SME Probabilities and Confidence Bounds for the Node Inappropriate Aircraft Operations.

	SME1	SME2	SME3	SME4	Min	Max	Avg	StDev	99% Lo	95% Lo	90% Lo	90% Hi	95% Hi	99% Hi
issue	0.30	0.10	0.10	0.30	0.10	0.30	0.20	0.12	0.00	0.00	0.01	0.39	0.43	0.50
not	0.70	0.90	0.90	0.70	0.90	0.70	0.80	0.88	1.00	1.00	0.99	0.61	0.57	0.50

The average SME model elicitation for the node Pilot Operational Issues is summarized in Table 44. The HFACS contribution to the CPT is considered separately.

Table 44. Transposed Conditional Probability Table for the node Pilot Operational Issues.

unstab app	pilot hfacs	inapp ac ops	auto	Pilot Ops Issues	No Pilot Ops Issues
yes	yes	yes	yes	0.99	0.01
yes	yes	yes	no	0.83	0.18
yes	yes	no	yes	0.79	0.21
yes	yes	no	no	0.63	0.38
yes	no	yes	yes	0.81	0.19
yes	no	yes	no	0.74	0.26
yes	no	no	yes	0.50	0.50
yes	no	no	no	0.39	0.61
no	yes	yes	yes	0.59	0.41
no	yes	yes	no	0.45	0.55
no	yes	no	yes	0.46	0.54
no	yes	no	no	0.15	0.85
no	no	yes	yes	0.55	0.45
no	no	yes	no	0.39	0.61
no	no	no	yes	0.23	0.78
no	no	no	no	0.01	0.99

The SME panel developed blanket multiplication factors (mfac) for the HFACS contributors for RE events relative to those previously recorded for RI events. The SME elicitation for the ATC and pilot multiplicative factors is summarized in Table 45.

Table 45. SME multiplicative factors and confidence bounds for HFACS contributions to RE relative to RI events.

	SME1	SME2	SME3	SME4	Min	Max	Avg	StDev	99% Lo	95% Lo	90% Lo	90% Hi	95% Hi	99% Hi
atc hfacs mfac	0.10	0.20	0.10	0.20	0.10	0.20	0.15	0.06	0.00	0.04	0.06	0.24	0.26	0.30
pilot hfacs mfac	0.80	1.10	1.0	1.0	0.80	1.10	0.98	0.13	0.65	0.73	0.77	1.00	1.00	1.00

The revised marginal probabilities for the RE / ATC / HFACS contributions are summarized in Table 46.

Table 46. RE / ATC / HFACS contributions.

RE HFACS	issue	not	Avg Mfac	issue	not
ATC Cert	0.0100	0.9900	0.1500	0.0015	0.9985
ATC OTJ	0.0600	0.9400	0.1500	0.0090	0.9910
ATC State	0.0700	0.9300	0.1500	0.0105	0.9895

The revised marginal probabilities for the RE / Pilot / HFACS contributions are summarized in Table 47.

Table 47. RE / Pilot / HFACS contributions.

RE HFACS	issue	not	Avg Mfac	issue	not
Pilot Cert	0.0200	0.9800	0.9800	0.0196	0.9804
Pilot OTJ	0.0300	0.9700	0.9800	0.0294	0.9706
Pilot State	0.0400	0.9600	0.9800	0.0392	0.9608

The average SME model elicitation for the node Pilot Error is summarized in Table 48.

Table 48. Transposed Conditional Probability Table for the node Pilot Error.

airport issues	weather issues	atc issues	pilot issues	Pilot Error	No Pilot Error
yes	yes	yes	yes	0.80	0.20
yes	yes	yes	no	0.31	0.69
yes	yes	no	yes	0.65	0.35
yes	yes	no	no	0.19	0.81
yes	no	yes	yes	0.60	0.40
yes	no	yes	no	0.16	0.84
yes	no	no	yes	0.38	0.62
yes	no	no	no	0.08	0.92
no	yes	yes	yes	0.71	0.29
no	yes	yes	no	0.16	0.84
no	yes	no	yes	0.63	0.37
no	yes	no	no	0.07	0.93
no	no	yes	yes	0.48	0.52
no	no	yes	no	0.03	0.97
no	no	no	yes	0.32	0.68
no	no	no	no	0.00	1.00

The SME model elicitation for the node Mechanical Failure is summarized in Table 49.

Table 49. SME Probabilities and Confidence Bounds for the Node Mechanical Failure.

	automation			yes										
	SME1	SME2	SME3	SME4	Min	Max	Avg	StDev	99% Lo	95% Lo	90% Lo	90% Hi	95% Hi	99% Hi
mech failure	0.2	0.25	N/A	0.30	0.20	0.30	0.25	0.05	0.12	0.15	0.17	0.33	0.35	0.38
no failure	0.8	0.75	N/A	0.70	0.80	0.70	0.75	0.95	0.88	0.85	0.83	0.67	0.65	0.62
	automation			no										
	SME1	SME2	SME3	SME4	Min	Max	Avg	StDev	99% Lo	95% Lo	90% Lo	90% Hi	95% Hi	99% Hi
mech failure	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.00	0.05	0.05	0.05	0.05	0.05	0.05
no failure	0.95	0.95	0.95	0.95	0.95	0.95	0.95	1.00	0.95	0.95	0.95	0.95	0.95	0.95

The SME model elicitation for the node RE Event Initiated is summarized in Table 50.

Table 50. SME Probabilities and Confidence Bounds for the Node
RE Event Initiated.

	Mechanical Failure			**yes**		**Pilot Error**		**yes**						
	SME1	**SME2**	**SME3**	**SME4**	**Min**	**Max**	**Avg**	**StDev**	**99% Lo**	**95% Lo**	**90% Lo**	**90% Hi**	**95% Hi**	**99% Hi**
RE Event	0.90	0.99	0.99	0.95	0.90	0.99	0.96	0.04	0.85	0.87	0.89	1.00	1.00	1.00
No Event	0.10	0.01	0.01	0.05	0.10	0.01	0.04	0.96	0.15	0.13	0.11	0.00	0.00	0.00
	Mechanical Failure			**yes**		**Pilot Error**		**no**						
	SME1	**SME2**	**SME3**	**SME4**	**Min**	**Max**	**Avg**	**StDev**	**99% Lo**	**95% Lo**	**90% Lo**	**90% Hi**	**95% Hi**	**99% Hi**
RE Event	0.70	0.55	0.75	0.70	0.55	0.75	0.68	0.09	0.45	0.51	0.53	0.82	0.84	0.90
No Event	0.30	0.45	0.25	0.30	0.45	0.25	0.33	0.91	0.55	0.49	0.47	0.18	0.16	0.10
	Mechanical Failure			**no**		**Pilot Error**		**yes**						
	SME1	**SME2**	**SME3**	**SME4**	**Min**	**Max**	**Avg**	**StDev**	**99% Lo**	**95% Lo**	**90% Lo**	**90% Hi**	**95% Hi**	**99% Hi**
RE Event	0.60	0.40	0.40	0.55	0.40	0.60	0.49	0.10	0.22	0.29	0.32	0.66	0.69	0.75
No Event	0.40	0.60	0.60	0.45	0.60	0.40	0.51	0.90	0.78	0.71	0.68	0.34	0.31	0.25
	Mechanical Failure			**no**		**Pilot Error**		**no**						
	SME1	**SME2**	**SME3**	**SME4**	**Min**	**Max**	**Avg**	**StDev**	**99% Lo**	**95% Lo**	**90% Lo**	**90% Hi**	**95% Hi**	**99% Hi**
RE Event	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.01	0.01	0.01	0.01	0.01	0.01
No Event	0.99	0.99	0.99	0.99	0.99	0.99	0.99	1.00	0.99	0.99	0.99	0.99	0.99	0.99

The SME model elicitation for the node Weather Issues is summarized in Table 51.

Table 51. SME Probabilities and Confidence Bounds for the Node Weather Issues.

	SME1	SME2	SME3	SME4	Min	Max	Avg	StDev	99% Lo	95% Lo	90% Lo	90% Hi	95% Hi	99% Hi
Issue	0.85	0.7	0.75	0.7	0.70	0.85	0.75	0.07	0.57	0.61	0.63	0.87	0.89	0.93
Not	0.15	0.3	0.25	0.3	0.30	0.15	0.25	0.93	0.43	0.39	0.37	0.13	0.11	0.07

8.0 Model Baseline Execution

8.1 Runway Incursion Model

The most recent SME session (July 2014) resulted in a fully vetted BBN model for both RI and RE events. Moreover, the SME panel elicitation of marginal and conditional probabilities has also been completed. Thus, all the ingredients for a fully vetted and fully populated set of baseline models have been obtained. In order to demonstrate how a BBN model would function, random values for all of the conditional probability tables have been inserted into the final RI model so that model operations can be simulated as shown in Figure 4. The node probabilities are shown overlaying the model structure from Figure 2. In this case, the marginal (leaf node) probabilities for all of the contributing factors have been set to zero, and the reaction time has been set to “long” (i.e., more than 8 seconds) for the collision scenario “crossing in front of departure”. The model indicates that the probability of an accident or near miss (red node at middle right) is about 22% for this random scenario.

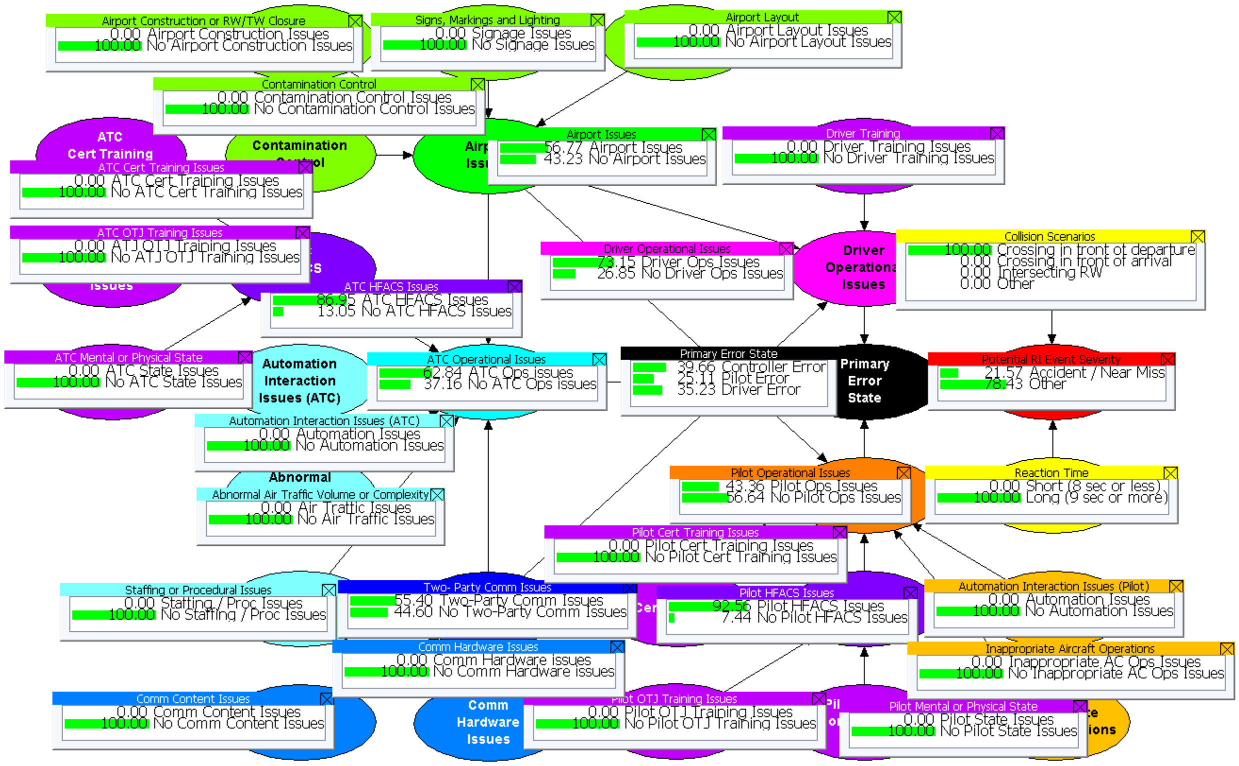

Figure 4. Sample RI Model Execution (baseline scenario).

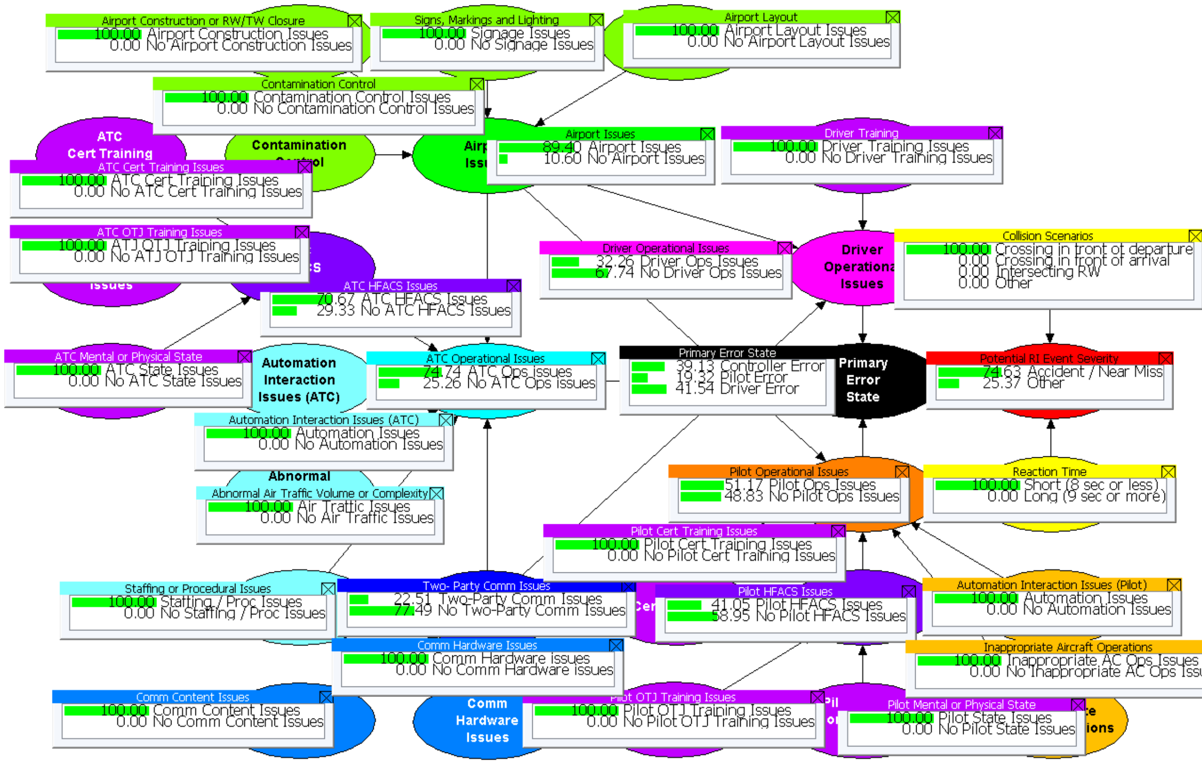

Figure 5. Sample RI Model Execution (worst-case scenario).

In Figure 5, the same example has been shown again, but with all the leaf node marginal probabilities set to 1 (all the issue are a certainty) and the reaction time has been set to short for the same collision scenario. In this random, worst-case, the probability of an accident or near miss is increased to about 75%.

8.2 Runway Excursion Model

Figure 6 illustrates a sample execution of the RE model with average probabilities employed, as described in section 6 of this report. The node probabilities are again shown as an overlay to the model structure presented in Figure 3. The sample execution shown in Figure 6 indicates that under the assumptions used to construct this model, there is about a 10% chance of an RE event.

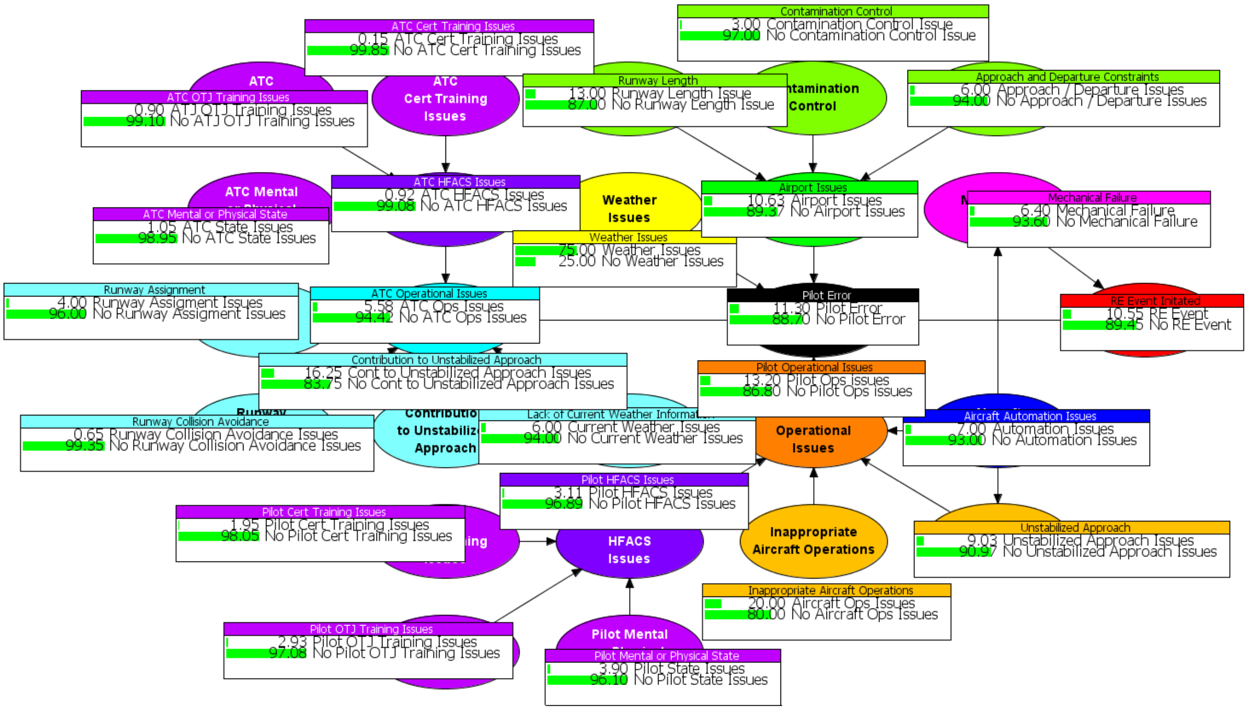

Figure 6. Sample RE Model Execution (average probabilities).

9.0 Model Sensitivity Analysis

9.1 Runway Incursion Model

Figure 7 illustrates a typical sensitivity analysis for the RI model. In order to accomplish this sensitivity analysis, the Hugin tool parametrically varies the strength of the marginal and conditional probability table values. Then sensitivity values are determined at the maximum strength, the minimum strength and at the baseline (or average) CPT values. In figure 7 below those nodes where blue coloring is observed indicate response sensitivity at the maximum CPT values, those with red coloring indicate response sensitivity at the minimum CPT values, and those with green coloring indicate response sensitivity at the average (or baseline) CPT values. In each case, the intensity of the observed colors indicate the strength of the observed response sensitivity. Under the assumptions present in the model (i.e., nodes, links and CPT values as previously discussed), the node Potential RI Event Severity is, as expected, sensitive to the node Primary Error State; however, only very limited sensitivity discrimination among the other nodes to the left is possible. Yet, some degree of sensitivity must exist for every node in the diagram.

Thus, in order to examine more fully the sensitivities across the entire diagram, Figure 7 illustrates only the sensitivities for the node Primary Error State. The strongest sensitivities for this node are with respect to the Pilot Operational Issues, the Pilot Physical or Mental State, Comm Content Issues, and the Airport Layout.

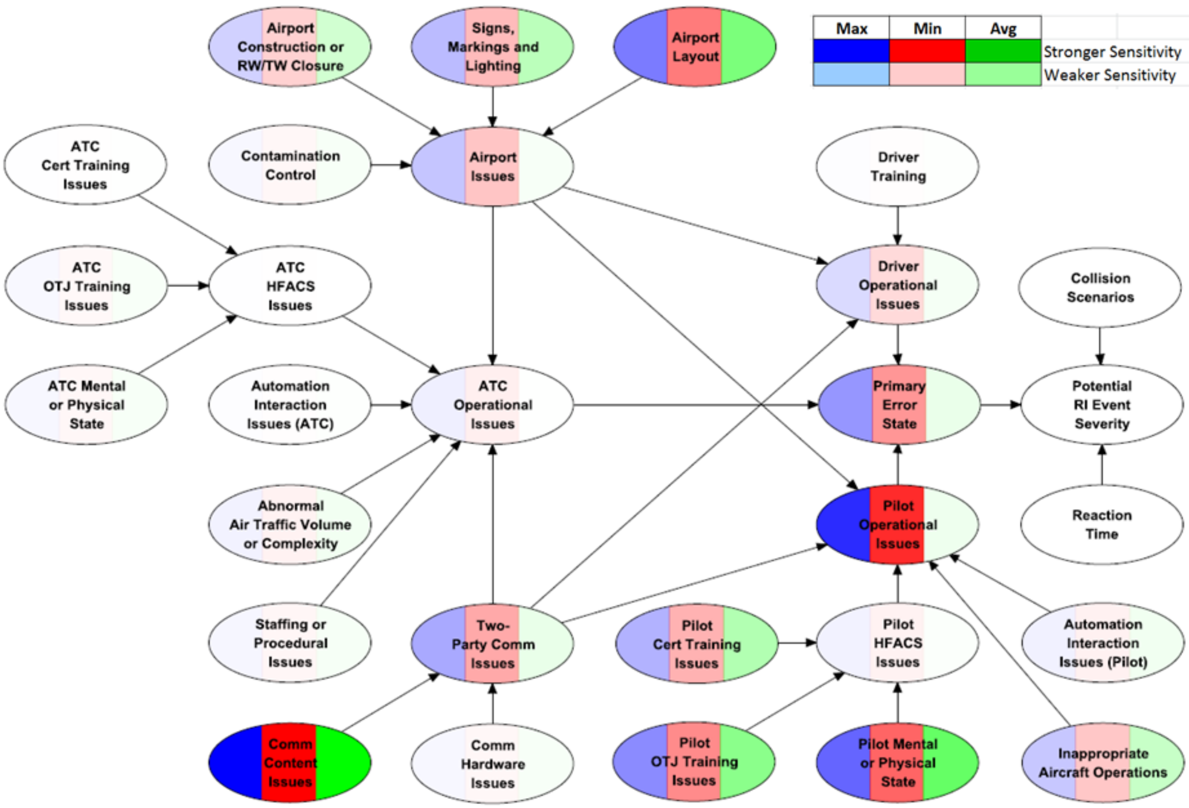

Figure 7. Sample RI model execution sensitivity analysis.

9.2 Runway Excursion Model

Figure 8 illustrates a typical sensitivity analysis for the RE model. Under the assumptions present in the model (nodes, links and CPT as previously discussed), Figure 8 illustrates that an RE Event Initiated is mostly dependent upon mechanical failure and then upon pilot error, runway length and automation issues.

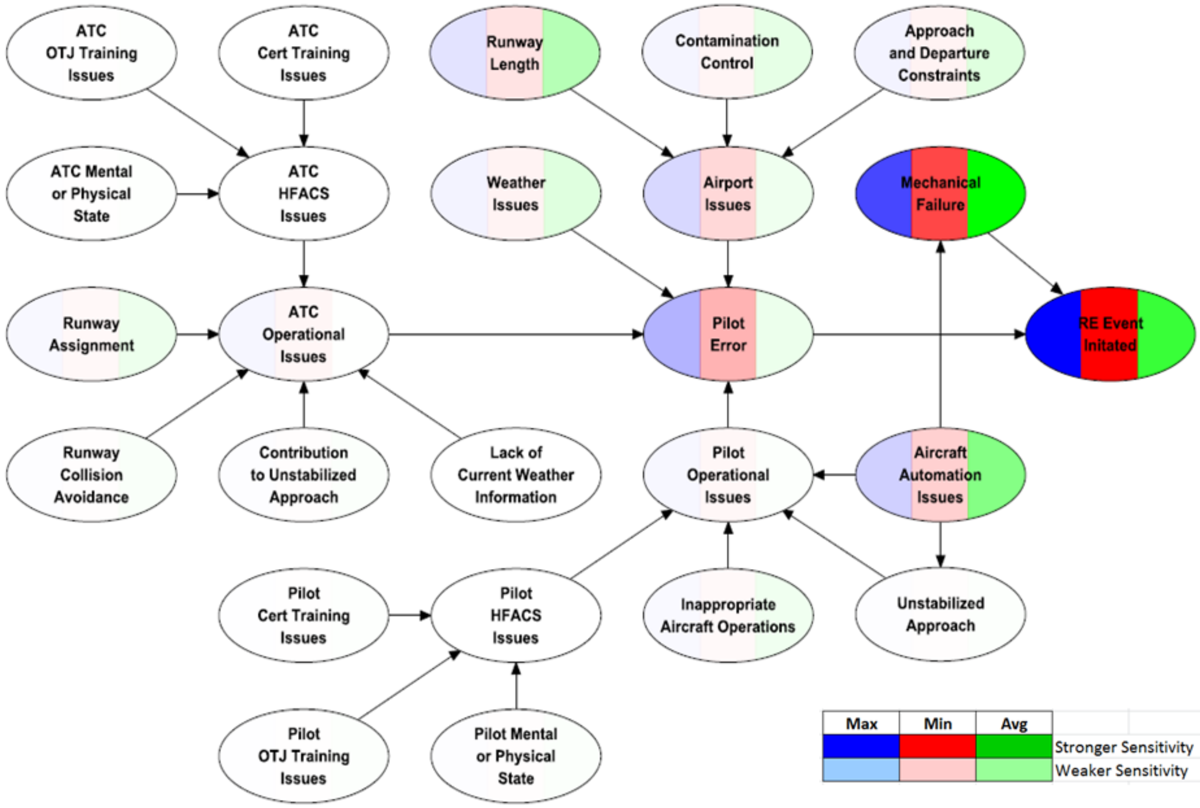

Figure 8. Sample RE model execution sensitivity analysis.

10.0 Conclusions

The RUNSAFE Bayesian Belief Network (BBN) model for Runway Incursion (RI) and Runway Excursion (RE) events has been presented. Numerous considerations surrounding the process of developing the RI and RE models have been documented in this report. The resulting RUNSAFE model (both RI and RE event models) has been thoroughly reviewed by a Subject Matter Expert (SME) panel through multiple SME knowledge elicitation sessions. Numerous improvements to the model structure (definitions, node names, node states and the connecting link topology) were made by the SME panel. The structural details of the resulting RUNSAFE BBN models for RI and RE events have been documented within this report. A few sample executions of the final RI and RE models, using random conditional probability tables have been presented for the baseline and worst-case scenarios; the resulting probability of an accident or near miss increases substantially for the worst-case scenario, compared with the baseline scenario. Finally, a parameter sensitivity analysis for a given scenario was performed to show the risk drivers.

11.0 Recommendations

It is recommended that the model structures presented herein and the CPT values developed by the SME panel be validated by comparison to available data , be expanded to include the injection of technology products intended to improve runway safety, and that SME input be used to characterize the impact of these technology products. It is also recommended that the resulting BBN for RI and RE events be used by NASA to generically model the causes of RI and RE events and to assess the effectiveness of technology products being developed under NASA funding.

12.0 References List

1. *Aviation Safety Program website*, http://www.aeronautics.nasa.gov/programs_avsafe.htm (accessed 10/22/2014), now the Airspace Operations and Safety Program website, http://www.aeronautics.nasa.gov/programs-aosp.htm (accessed 3/6/2015).

2. NextGEN, The Federal Aviation Administration, NextGEN website, http://www.faa.gov/nextgen/, (accessed 3/6/2015).

3. http://www.asias.faa.gov/pls/apex/f?p=100:32:0::NO::P32_REGION_VAR:1 – definition of RI event and severity categories (accessed 10/22/2014).

4. *Order 7050.1, Runway Safety Program,* The Federal Aviation Administration,http://www.faa.gov/documentLibrary/media/Order/FAA_Order_7050.1B.pdf (accessed 10/22/2014) – RI and RE event definitions, RI event severity classifications

5. Green, Lawrence L., *Analysis of Runway Incursion Data*, AIAA 2013-4400, presented at 13th the American Institute of Aeronautics and Astronautics (AIAA) / Aviation Technology, Integration, and Operations (ATIO) Conference, Los Angeles, CA, August 12-14, 2013.

6. Green, Lawrence L., *Development, Validation and Execution of a Bayesian Network for Runway Incursions,* AIAA 2014-2158, presented at the 14th American Institute of Aeronautics and Astronautics (AIAA) / Aviation Technology, Integration, and Operations (ATIO) Conference, Atlanta, GA, June 16-21, 2014.

7. Green, Lawrence L., Development of a Bayesian Belief Network Runway Incursion and Excursion Model, Proceedings of the American Society for Engineering Management

2014 International Annual Conference, S. Long, E-H. Ng, and C. Downing eds., Virginia Beach, VA, October 16-17, 2014.

8. Second Workshop on the Investigation and Reporting of Incidents and Accidents, IRIA 2003, NASA/CP-2003-212642, Compiled by Kelly J. Hayhurst and C. Michael Holloway, Langley Research Center, Hampton, Virginia, September 2003.

9. Luxhøj, J. T., Shih, A. T., Jones, S. M., Ancel, E., and Reveley, M. S., "Safety Risk Knowledge Elicitation in Support of Aeronautical R&D Portfolio Management: A Case Study," *American Society for Engineering Management (ASEM) 33rd International Annual Conference,* Virginia Beach, VA, Oct 17-20, 2012.

10. Luxhøj, J. T., Jalil, M., and Jones, S. M., "A Risk-Based Decision Support Tool for Evaluating Aviation Technology Integration in the National Airspace System," *Proceedings of the AIAA's 3rd Annual Aviation Technology, Integration and Operations (ATIO) Technical Forum,* Denver, CO, November, 17-19. 2003.

11. Luxhøj, J. T., "Probabilistic Causal Analysis for System Safety Risk Assessment in Commercial Air Transport," *Proceedings of the Workshop on Investigating and Reporting of Incidents and Accidents (IRIA),* Sept 16-19, Williamsburg, VA, p.17 NASA/CP-2003-212642, 2003.

12. Ancel, E., and Shih, A. T., "The Analysis of the Contribution of Human Factors to the In-flight Loss of Control Accidents," *12th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference,* Indianapolis, IN, Sept 17-19, 2012. American Institute of Aeronautics and Astronautics 9

13. Shih, A. T., Ancel, E., and Jones, S. M., "Object-oriented Bayesian Networks (OOBN) for Aviation Accident Modeling and Technology Portfolio Impact Assessment," *American Society for Engineering Management (ASEM) 33rd International Annual Conference,* Oct 17-20, 2012.

14. Runway Transgressions at Non-Towered and Tower Closed Airports, NASA Aviation Safety Reporting System (ASRS), Publication 61, July 2003.

15. The Boeing Company, Statistical Summary of Commercial Jet Airplane Accidents, 2013.

16. Cardosi, K., Chase, S., and Eon, D., "Runway Safety", U.S. Department of Transportation, Volpe Center, Cambridge, MA, Feb. 12, 2010.

17. Torres, K. R., Metscher, D. S., and Smith, M., "A Correlational Study of the Relationship between Human Factor Errors and the Occurrence of Runway Incursions", International Journal of Professional Aviation Training & Testing Research, Vol. 5, (1) © 2011 Published by Professional Aviation Board of Certification.

18. The Federal Aviation Administration, "Wrong Runway Departures", Aviation Safety Information Analysis and Sharing (ASIAS), Office of Aviation Safety, AVS–4 July 2007.

19. Air Line Pilots Association International, “White Paper: Runway Incursions A Call to Action”, March 2007.

20. *Runway Incursion database website*, The Federal Aviation Administration, http://www.asias.faa.gov/pls/apex/f?p=100:28:0::NO:28:: (accessed 10/22/2014).

21. The FAA Aviation Safety Information Analysis and Sharing (ASIAS) System website, http://www.asias.faa.gov/pls/apex/f?p=100:1: (accessed 3/9/2015)

22. Federal Aviation Administration Air Traffic Activity System (ATADS) website: https://aspm.faa.gov/opsnet/sys/main.asp (access Nov. 2014).

23. Chapman, R., “Runway Incursions 2000-201: Is Safety Improving?” East Michigan University, Retrieved from http://www.miqrogroove.com/writing/runway-incursions/fulltext.pdf, Copyright © 2010 by Robert Chapin.

24. *A Study of Runway Excursions from a European Perspective*, NLR-CR-2010-259, May 2010, NLR Air Transport Safety Institute, Anthony Fokkerweg 2, 1059 CM Amsterdam, P.O. Box 90502, 1006 BM Amsterdam, The Netherlands, Telephone +31 20 511 35 00, Fax +31 20 511 32 10, Web site: http://www.nlr-atsi.nl.

25. *Hindsight 12*, http://www.eurocontrol.int/sites/default/files/publication/files/101112-HS12.pdf (accessed May 2014).

26. *Final Runway excursions Part 1: A worldwide review of commercial jet aircraft runway excursions*, TRANSPORT SAFETY REPORT Aviation Research and Analysis Report – AR-2008-018(1) Australian Transport Safety Board.

27. *AIRPORT COOPERATIVE RESEARCH PROGRAM ACRP REPORT 3 Analysis of Aircraft Overruns and Undershoots for Runway Safety Areas*, Transportation Research Board of the National Academies.

28. *Minimising the likelihood and consequences of runway excursions*, TRANSPORT SAFETY REPORT Aviation Research and Analysis Report – AR-2008-018(1) Runway excursions Part 2: Australian Transport Safety Board.

29. *Running out of runway Analysis of 35 years of landing overrun accidents*, National Aerospace Laboratory NLR-TP-2005-498.

30. *Report on the Design and Analysis of a Runway Excursions Database*, A Research Project Conducted for the Flight Safety Foundation by Safety Management Specialties, May 26, 2009, 5648 NE Caddis Drive, Hillsboro, Oregon 97124, (877) 767-7679.

31. *The Strategic Runway Safety Plan*, Report to Congress Pursuant to FAA Modernization and Reform Act of 2012 (Pub. L. No. 112-95, Section 314(a), U.S. Department of Transportation, FAA, November 2012.

32. Runway Excursion Modeling and Analysis: A Web-Based Geographic Information System Solution." Professor William Ziegler advised the student team, http://emerald.ts.odu.edu/Apps/FAAUDCA.nsf/Binghamton%20University.pdf?OpenFileResource, 2012,(accessed May 2014).

33. *Los Angeles International Airport North Airfield Safety Study*, Final Report Prepared by: Dr. Arnold Barnett (Chairman), et. al. May 2010.

34. A Method for Rating the Severity of Runway Incursions, Cardosi, Kim , Hannon, Daniel and Sheridan, Thomas, U.S. Department of Transportation, Volpe Center, 55 Broadway, Cambridge, MA.

35. Goodheart, Benjamin Jeffery, *Identification of Causal Paths and Prediction of Runway Incursion Risk Using Bayesian Belief Networks,* ACRP 11-04 Graduate Research Award, Embry-Riddle Aeronautical University, Daytona Beach, FL October 2, 2013for TRB 2014 Annual Meeting.

36. *Reducing the Risk of Runway Excursions*, Report of the Runway Safety Initiative, Flight Safety Foundation, MAY 2009.

37. Microsoft Corporation, Excel website: http://products.office.com/en-us/excel (accessed Nov. 2014).

38. The Stat-Ease, Inc website: http://www.statease.com/ (accessed 2/11/2013). (renumbered)

39. HUGIN Expert A/S website: http://www.hugin.com/ (accessed Nov. 2014)

40. Green, L. L., "Uncertainty Analysis of Historical Hurricane Data", AIAA-2007-1101, 2007.

41. Green, L. L.; Rickman, S. L.; Remark, B. J.; Vander Kam, J. C.; Kowal, J.; Johnson, K. L.; and Bouslog, S. A.: NASA/TM-2014-218262, May 2014.

42. Green, L. L.: The Challenges of Credible Thermal Protection System Reliability Quantification, Paper #77, Session 8B in Cross-Cutting Technologies III, The 10th International Planetary Probe Workshop (IPPW-10), San Jose, CA June 2013.

43. Green, L. L.: Uncertainty Analysis of Historical Hurricane Data. AIAA 2007-1101. Presented at the 45th AIAA Applied Aerospace Sciences Conference and Exhibit, Reno, NV, January 8-11, 2007.

44. Green, L. L., Cruz, J.: Uncertainty Analysis for a Jet Flap Airfoil. Paper Number SISO-06F-SIW-010. Published at the Simulation Interoperability Standards Organization, 2006 Fall Simulation Interoperability Workshop, Orlando, FL, September 10-15, 2006

45. "Attempted Takeoff From Wrong Runway Comair Flight 5191, Bombardier CL-600-2B19, N431CA, Lexington, Kentucky, August 27, 2006" National Transportation Safety Board ACCIDENT REPORT NTSB/AAR-07/05, PB2007-910406.

46. Wiegmann, Douglas A. and Shappell, Scott A., *A Human Error Approach to Aviation Accident Analysis*, Ashgate Publishing Limited, Burlington VT, 2003. (also, http://www.hfacs.com, accessed Nov. 14, 2013)

47. Chow, Amy and Gulding, John. Capacity Variation Algorithms for Simulation Modeling and Performance Analysis, AIAA 2013-4355, presented at 13th the American Institute of Aeronautics and Astronautics (AIAA) / Aviation Technology, Integration, and Operations (ATIO) Conference, Los Angeles, CA, August 12-14, 2013.

48. Rudisill, Marianne, "Line Pilots' Attitudes About and Experience with Flight Deck Automation: Results of an International Survey and Proposed Guidelines, Published in: (1995) Proceedings of the Eighth International Symposium on Aviation Psychology. Columbus, OH: The Ohio State University Press.

49. SKYbrary Runway Excursion website,

http://www.skybrary.aero/index.php/Runway_Excursion, accessed Nov. 14, 2013.

REPORT DOCUMENTATION PAGE	Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
01- 05 - 2015	Technical Memorandum	

4. TITLE AND SUBTITLE	
Development and Execution of the RUNSAFE Runway Safety Bayesian Belief Network Model	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
Green, Lawrence L.	5e. TASK NUMBER
	5f. WORK UNIT NUMBER 284848.02.01.07.04

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT NUMBER
NASA Langley Research Center Hampton, VA 23681-2199	L-20556

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
National Aeronautics and Space Administration Washington, DC 20546-0001	NASA
	11. SPONSOR/MONITOR'S REPORT NUMBER(S) NASA-TM-2015-218705

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category 03
Availability: NASA STI Program (757) 864-9658

13. SUPPLEMENTARY NOTES

14. ABSTRACT

One focus area of the National Aeronautics and Space Administration (NASA) is to improve aviation safety. Runway safety is one such thrust of investigation and research. The two primary components of this runway safety research are in runway incursion (RI) and runway excursion (RE) events. These are adverse ground-based aviation incidents that endanger crew, passengers, aircraft and perhaps other nearby people or property. A runway incursion is the incorrect presence of an aircraft, vehicle or person on the protected area of a surface designated for the landing and take-off of aircraft; one class of RI events simultaneously involves two aircraft, such as one aircraft incorrectly landing on a runway while another aircraft is taking off from the same runway. A runway excursion is an incident involving only a single aircraft defined as a veer-off or overrun off the runway surface.

15. SUBJECT TERMS

Aviation safety; Bayesian belief network; Runway excursion; Runway incursion; Runway safety

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)
					19b. TELEPHONE NUMBER *(Include area code)*
U	U	U	UU	75	(757) 864-9658

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