SENSITIVITY ANALYSIS OF EVENT SEQUENCE DIAGRAMS FOR AIRCRAFT ACCIDENT SCENARIOS

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Abstract

The Integrated Safety Assessment Model (ISAM) is being developed to provide a baseline risk assessment for the National Airspace System and to evaluate safety implications of proposed changes. The causal risk model in ISAM is a hybrid model of event sequence diagrams (ESDs) and fault trees and represents accident and incident scenarios. ISAM contains several thousand parameters. This paper evaluates the significance of these parameters within the model with respect to several importance metrics in order to identify the most important parameters. The analyses are conducted for pivoting events and underlying fault tree events of individual ESD as well as across all ESDs based on both the accident frequency and the fatality frequency.

Introduction

The national air transportation system provides an extremely safe mode of transportation. As the system evolves, changes to the system – for example, new procedures and technologies or gradual shifts in traffic or aircraft equipage – have the potential to alter the level of safety. The Integrated Safety Assessment Model (ISAM) [1] is being developed by the FAA to provide a baseline risk assessment for the National Airspace System and to evaluate safety implications of proposed changes, such as NextGen operational improvements.

The model architecture of ISAM includes a set of event-sequence diagrams (ESDs) and supporting fault trees. Each event-sequence diagram represents a different initiating event – for example, an incorrect configuration during take-off – and provides an estimate for the risk related to the initiating event based on enumerating a sequence of pivoting events that may subsequently occur. A pivoting event is a downstream branching point in the tree – for example, whether or not the flight crew rejects the take-off. Each path through the tree then terminates at an end event, representing either a safe outcome or some type of incident or accident, such as a runway excursion.

ISAM contains thousands of parameters representing probabilities within the event trees and fault trees. These parameters must be populated with numerical values. The objective of this paper is to conduct a sensitivity analysis of parameters within ISAM in order to identify the most important parameters. Such an analysis can be used to guide future data collection and research efforts – for example, to prioritize efforts on accurately quantifying parameters that have a significant impact on the final safety outputs. The analysis in this paper considers multiple importance metrics to identify parameters that consistently rate as having a high impact across all metrics. A common-event analysis is also conducted across all event sequences simultaneously to identify parameters that have the most impact on the overall safety.

The rest of this paper is organized as follows: Further details of ISAM are described in the next section. Then the importance measures and analysis methodology are described. Results are given first for individual event-sequence diagrams. Then results are given across the ISAM model as a whole. Finally, results are given to identify the most important parameters within the underlying fault trees. The last section provides conclusions.

Integrated Safety Assessment Model

The Integrated Safety Assessment Model [1] provides a baseline estimate of risk for the National Airspace System using a causal risk model. ISAM also has several models that are combined to develop a future risk forecast. These include a program model of NextGen improvements and their impacts, several future traffic forecasts, a model of hazards and their relationships to initiating events in the ISAM fault trees, and an influence model that links those hazards to historical risks and can be used to estimate the impact of future operational changes on risk. The causal model of ISAM is structurally based on the Causal model for Air Transportation Safety [2,3] and the Integrated Risk Picture [4], but is modified and adapted to represent scenarios in the United States. Some preliminary versions of the ESDs used in

ISAM are given in [5]. ISAM is listed as one of 21 recommended methods and toolsets for risk assessment in air transportation for the FAA [6]. A related model in [7] uses Bayesian networks to develop a safety model using Air Traffic Safety Action Program data.

ISAM consists of two main models, a causal risk model and an influence model. The causal risk model, which is a hybrid model of event-sequence diagrams and fault trees (Figure 1), represents accident and incident scenarios and provides an estimate of the baseline risk. The influence model is used to capture the effects of NextGen Operational Improvements on safety related events. This paper considers a sensitivity analysis of the causal model only.

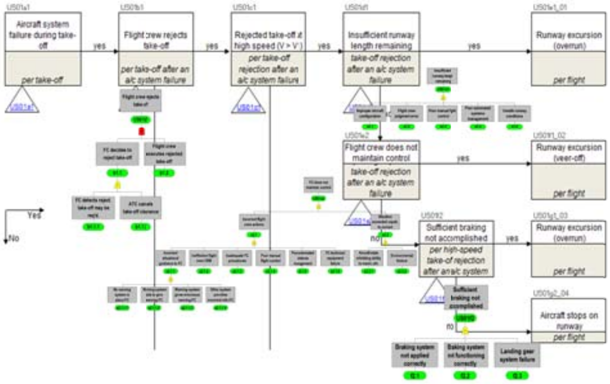

Figure 1. Example of hybrid model

The causal model contains a total of 35 event-sequence diagrams and associated fault trees to capture all possible accident scenarios. Each ESD has a unique initiating event (Table 1 gives a partial list). A full list of the initiating events is given in the Appendix. (The numbering is not consecutive; there are 35 ESDs even though the numbering goes up to 43.) Each ESD contains several end states and multiple intermediate pivoting events.

As shown in Figure 2, the initiating event and end states are quantified as frequencies (events per flight). The pivoting events are quantified as conditional probabilities. Frequencies of the initiating events and end states are generated using historical accident and incident information, such as National Transportation Safety Board data, Accident/Incident Data System, Service Difficulty Reports, and post-hoc interpretation of radar surveillance collected by the FAA The pivoting-event probabilities are inferred by solving a system of equations to make the frequencies of the initiating events and the end states consistent. (There are more unknown pivoting-event probabilities than constraints, so some additional constraints are obtained by making some assumptions to "evenly distribute" the probabilities among the pivoting events.)

Table 1. Example ESDs in ISAM

ESD	Initiating Event
US 01	Aircraft system failure during take-off
US 02	Air-traffic-control event during take-off
⋮	⋮
US 19	Unstable approach
US 21	Aircraft weight and balance outside limits during approach
⋮	⋮
US 42	Landing on a taxiway
US 43	Landing on the wrong runway

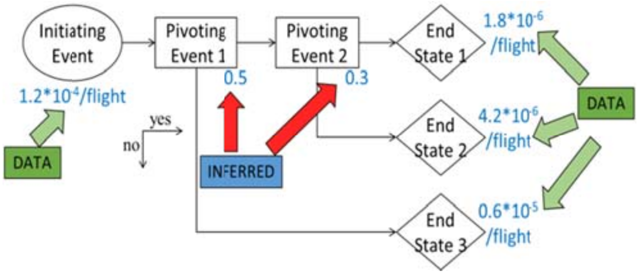

Figure 2. Principle of how ESDs are constructed

Importance Measures

In order to identify important parameters within ISAM, importance measures from probabilistic safety assessment are applied. Various importance measures have been introduced and used for several decades in risk analysis (e.g. [8]-[10]). Ref. [11] summarizes several measures to identify important events in complex systems. We apply here three commonly used measures, shown in Table 2. To define notation, let $\wp_i$ be the state of event i, where $\wp_i = 1$ generally corresponds to the failure of event i and $\wp_i = 0$ generally corresponds to the success of event i. Let $P(base)$ denote the frequency of accidents in the baseline case, where all probabilities in the model are populated with their baseline values. Let $P(\wp_i = 0)$ and $P(\wp_i = 1)$ denote the frequencies of accidents in the case that the probability of a *single* event i is changed from its baseline value to zero and one respectively.

The Fussell-Vesely (FV) metric measures the percent change in accident frequency when the probability of a particular event becomes zero. The Risk-Achievement-Worth (RAW) metric compares the accident frequency when one of the events is set to 1 (typically a failed condition) to the accident frequency in the baseline case. Lastly, the Birnbaum-Importance (BI) metric measures the difference in the accident frequencies between the cases when a single probability is set to 1 and when it is set to 0.

Table 2. Importance Measures

Measure	Principle
Fussell-Vesely (FV)	$\frac{P(base) - P(\wp_i = 0)}{P(base)}$
Risk Achievement Worth (RAW)	$\frac{P(\wp_i = 1)}{P(base)}$
Birnbaum Importance (BI)	$P(\wp_i = 1) - P(\wp_i = 0)$

We apply the importance measures in Table 2 to each of the pivoting events in an ESD (not including the initiating event), and then rank the pivoting events for each ESD in order of significance. We apply the same method to the fault trees to rank the importance of fault-tree events. Fault trees are located underneath each pivoting event and underneath each initiating event.

The importance measures explained so far are highly dependent on the baseline probabilities of events inferred by historical accident data, which may not be perfectly representative of the true accident frequencies, since accidents in air transportation are very rare events. In particular, some of the end-event frequencies are populated with zero values, since no accidents have been historically observed for some specific paths in the event trees. But this does not mean that the *true* probabilities are zero – that is, such event sequences might still occur in the future.

Factorial design can be used to generate an importance measure that is less sensitive to the baseline values. Factorial design analyzes the effects of multiple factors on the responses, or dependent variables. Each factor usually has two levels, a high value and a low value. In a full-factorial design, an experiment is conducted for all 2^n combinations of levels that each factor can have, where n is the number of factors or parameters. We perform the factorial design method on each ESD in ISAM for the purpose of finding events that have larger main effects on accident scenarios than others. Some recent studies to evaluate the sensitivity of parameters within safety models in air transportation using factorial design are [12], [13]. The detailed method is as follows:

- Define low and high probabilities for each event (e.g., in this paper, the low value is 0 and the high value is 1).
- Compute the accident frequency for all combinations (2^n) of event probabilities.
- Compute the main effect of each pivoting event by subtracting the average accident frequency for an event with its low probability from the average accident frequency for an event with its high probability.
- Rank the effects of events in each ESD.

This method is applied to the pivoting events in the ESDs, but not to the underlying fault trees, since the number of combinations to be analyzed increases exponentially with the number of factors. There are many more parameters in the fault trees than the event trees. While the results of this approach do not depend on the baseline values, the results do depend on the particular high and low values chosen in the first step.

Results on Individual ESDs

Accident Frequency Based Results

Importance measure and factorial design methods are conducted for all 35 ESDs in ISAM, one at a time. The full results for one sample ESD (Figure 3) are presented in this section, and then overall results across all ESDs are summarized. The first ESD (US-01) involves an aircraft system failure during take-off as the initiating event.

First, the importance measures are computed for each pivoting event in each ESD, and the pivoting events are ranked based on each measure. Figure 4 shows ranks of the pivoting events in the sample ESD based on the importance measures and factorial design analysis. The ranks based on RAW, BI and factorial design look very similar, whereas the rank from FV is quite different.

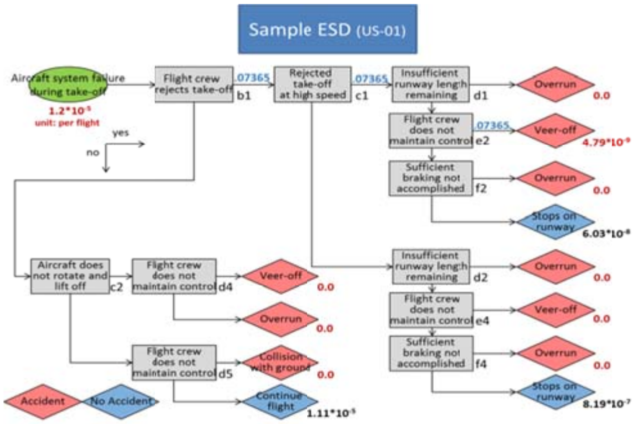

Figure 3. Sample ESD

The FV measure identifies three events as significant (b1, c1, and e2) and all other events as equally unimportant. In fact, the FV importance measures for some events are numerically zero. This shows a limitation of the FV measure as applied to ISAM. Only three pivoting events among the 11 events have a non-zero baseline probability and the other eight have a zero probability. From Table 2, the FV measure is zero for pivoting events in which $P(base)$ is the same as $P(\wp_i = 0)$ – i.e., for pivoting events having a zero probability. Thus, the FV measure has a limitation for the sensitivity analysis of ESDs in ISAM since there are many pivoting events with zero probability. Thus, this measure is not used in most of the analysis.

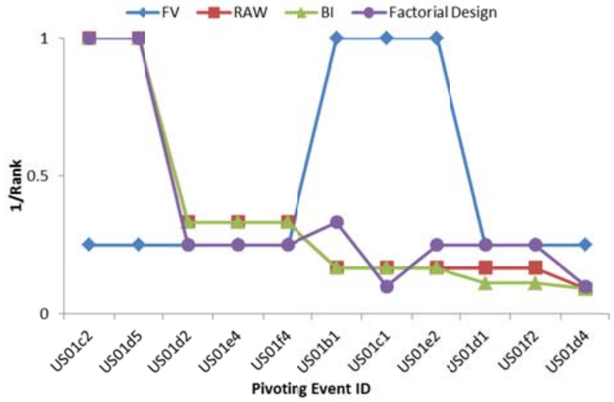

Figure 4. Result Ranks of Sample ESD

From the other two measures, RAW and BI, the most significant pivoting events in the sample ESD are 'Aircraft does not rotate and lift off (c2)' and 'Flight crew does not maintain control after lifting off (d5)'. RAW and BI show a very similar ranking of pivoting events not only in the sample ESD but also across the other ESDs of ISAM.

The factorial design ranking is also similar to these two rankings. Based on a 0-1 factorial design (where 0 is the low probability for each pivoting event and 1 is the high value), 'Aircraft does not rotate and lift off (c2)' and 'Flight crew does not maintain control after lifting off (d5)' are indicated as the most significant events in the ESD, while 'Rejected take-off at high speed (c1)' and 'Flight crew does not maintain control after a failure of lifting off (d4)' are the least important pivoting events. As shown in Figure 4, the most significant pivoting events identified by the 0-1 factorial design analysis are the same as the ones based on the RAW and BI importance measures, even though the rest of the pivoting events are ranked differently. This phenomenon occurs frequently throughout all ESDs.

Looking across all ESDs in ISAM, a key observation is that ESDs with the same structure have similar rankings of events, based on the RAW and BI measures. For example, the structure of the ESD in Figure 3 (US-01) is identical to the structure of six other ESDs, such as US-02 and US-05. These seven ESDs are describing possible accident scenarios for the take-off phase with different initiating events. While the numerical values in the ESDs are different, the same pivoting events, c2 and d5, are identified as the most significant ones in the seven ESDs, based on the RAW and BI measures.

The 0-1 factorial design analysis also shows similar results for similar ESD structures. This is because the factorial design only depends on the structure of the ESDs because 0 and 1 probabilities are assumed. Figure 5 shows more examples of common results by ESD structure, based on RAW/BI importance measures and the 0-1 factorial design analysis. Yellow boxes indicate significant events and grey ones indicate less significant events.

For a given structure, a pivoting event is selected as the most significant if the pivoting event is observed as the first rank in a majority of the ESDs by the RAW, BI and 0-1 factorial design analysis. The ESD on the top panel of Figure 5, for example, is the second-most frequently used structure in ISAM, and is used for events initiated in the landing and approach phase. Within this structure, 'Flight crew does not initiate rejected approach (b1)' and 'Flight crew does not maintain control after rejected approach (c2)' are the two most significant pivoting events, while 'Structural failure after off-nominal landing without rejected approach (f1)' is least important.

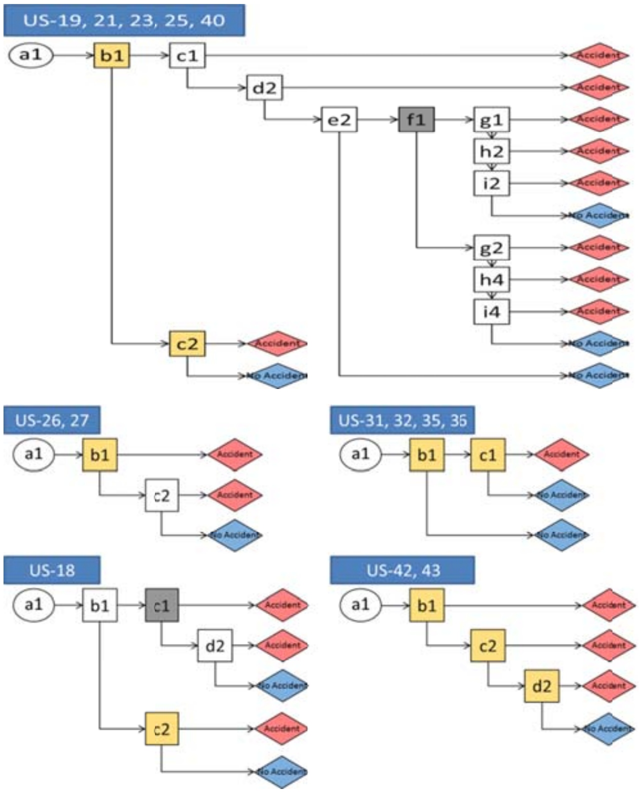

Figure 5. Common Results by Structure of ESDs

Fatality Frequency Based Results

All results shown so far are based on *accident frequency* – that is, where the importance measures in Table 2 are calculated based on changes to the total accident frequency in a given ESD (i.e., identifying which end events in an ESD classify as accidents, and adding up their respective frequencies). However, not all accidents are the same. For example, a collision with the ground is different than a runway excursion. In order to distinguish the consequences of different accidents, accident fatality probability data, which shows the probability of a fatality when a given type of accident in ISAM occurs, is used. Each accident frequency is multiplied by a fatality probability to produce a fatality frequency. All other data and the logic of analysis remain the same as before, but now the importance measures are computed with respect to *fatality frequency* rather than accident frequency.

We note that the historic accident fatality probabilities vary depending on accident scenarios even if the accident types, e.g., over-run or veer-off, are the same. In particular, some accident scenarios have a zero fatality probability. Rather than using a zero fatality probability, the average of non-zero fatality probabilities for the same type of accident is used for the fatality frequency.

Solid lines in Figure 6 illustrate the fatality-frequency based ranks of pivoting events in the sample ESD based on the BI measure and the 0-1 factorial design analysis. Both measures indicate 'Flight crew does not maintain control after lifting off (d5)' as the most significant pivoting events. As the second most important event, however, the BI measure identifies 'Aircraft does not rotate and lift off (c2)', while the 0-1 factorial design indicates 'Flight crew does not maintain control after a failure of lifting off (d4)'.

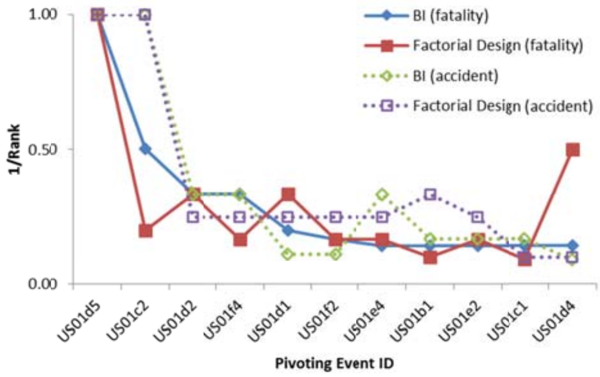

Figure 6. Rank Comparison (Fatality vs. Accident)

Compared to the accident frequency based results (dotted lines in Figure 6), 'Flight crew does not maintain control after lifting off (d5)' remains as the most significant pivoting event from both measures, whereas the remaining pivoting events are ranked quite differently from the accident frequency based results. 'Flight crew does not maintain control after a failure of lifting off (d4)', for instance, is the least significant pivoting event from the accident frequency based 0-1 factorial design analysis. However, it is the second most important event based on fatality frequency. As another example, using the BI measure, event d4 is ranked as least important using the accident-based results, while events b1, c1, e2, e4 and d4 are all ranked as least important using the fatality-based results.

In general, the fatality-based results are similar to but not exactly the same as the accident-based results. Many of the most significant pivoting events in the accident-based results remain as significant events in the fatality-based results. The fatality-based analysis tends to identify more events as insignificant. Even though some ESDs share the same structure, the fatality-based results can yield different results within the same structure group – more so than was observed with the accident-based results. Thus, it cannot be concluded that the structure of the ESD alone determines the importance of events. In particular, the fatality-based metrics provide more precision in identifying significant events over the accident-based metrics.

Analysis across ESDs

The methodologies discussed so far only consider importance measures with respect to *individual* ESDs, analyzed one at a time. System-wide effects are not considered. In ISAM, there are many pivoting events that appear multiple times in multiple ESDs. Some events even appear more than once in the *same* ESD. ISAM contains a total of 205 pivoting event nodes. But there are only 27 unique labels for these 205 events. Table 3 shows the labels of the 10 most frequently used pivoting events and the number of occurrences in ISAM.

Table 3. Common Labels of Pivoting Events

Label of Pivoting Events	# of Obs.
Flight crew does not maintain control	75
Sufficient braking not accomplished	32
Insufficient runway length remaining	27
Aircraft does not rotate and lift off	9
Flight crew rejects take-off	9
Rejected take-off at high speed (V > V1)	9
Aircraft does not land on runway	5
Aircraft lands outside nominal landing parameters	5
Structural failure	5
Air traffic control does not resolve conflict	4

Methodology

Events that appear multiple times across ESDs may be more important than events appearing in only one ESD, since the common events are involved more frequently in accident scenarios. In order to see which pivoting events are more significant with respect to all possible accidents, a common event sensitivity analysis is conducted. This is done by computing the relative change in total accident frequency after increasing the probabilities of pivoting events that have the same label by 1% simultaneously across all ESDs.

$$Sensitivity = \frac{\sum_{i=1}^{35}\left(\left(NewAccFreq\right)_i - \left(BaseAccFreq\right)_i\right)}{\sum_{i=1}^{35}\left(BaseAccFreq\right)_i}$$

For instance, the label of ‘Air traffic control does not resolve the conflict’ appears four times across ESDs, i.e. in US-31, 32, 35 and 36. We increase the probabilities of these events by 1% simultaneously, and then evaluate new accident frequencies of the ESDs. Figure 7 shows an example of how the calculation is carried out.

ESD	Initiating Event	Baseline Accident Freq.	New Accident Freq.	Sensitivity
US01	Aircraft system failure during take-off	5.10E-09	5.10E-09	
...	...	...	...	
US31	Aircraft are positioned on collision course in flight	4.80E-09	4.85E-09	
US32	Runway incursion involving a conflict	4.79E-09	4.84E-09	
US33	Cracks in aircraft pressure boundary	0.00	0.00	
US35	Conflict with terrain or obstacle imminent	1.92E-08	1.94E-08	
US36	Conflict on taxiway or apron	9.11E-07	9.20E-07	
...	...	...	...	
US43	Landing on the wrong runway	0.00E+00	0.00E+00	
Total		1.510E-06	1.519E-06	0.622%

Figure 7. Common Event Sensitivity Calculation

Discussion on “Common Labels”

Before giving results, we note that all results in this section rely on an assumption that pivoting events with the same label are treated in a similar manner, even if they are located in different places in ISAM. In actuality, each pivoting event is a *conditional probability* that depends on the specific sequence of events leading up to that event. For example, referring back to Figure 3, pivoting events d1 and d2 have the same label of ‘Insufficient runway length remaining’, but event d1 occurs after a rejected take-off at high speed whereas event d2 occurs after a rejected take-off at low speed. So these pivoting events are interpreted differently and are expected to have different numerical probabilities. In a similar manner, the ability of the flight crew to maintain control can be different in different phases of flight. Figure 8 illustrates this phenomenon, showing some examples of same-label events and how the probabilities of these events are different at different locations within ISAM.

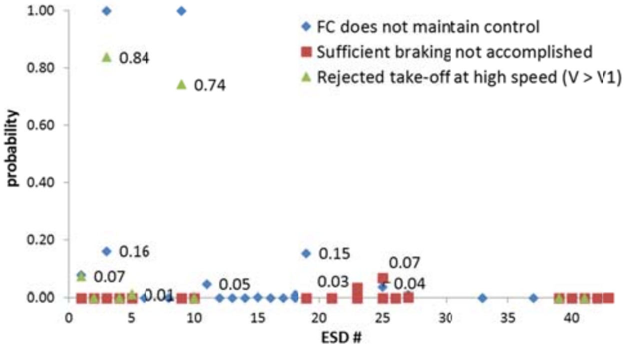

Figure 8. Various Probabilities of Common Events

What is being assumed here is not that same-label events are *exactly* the same. Rather, it is assumed that a *relative* change in one event affects all the others in the same way (i.e., a 1% change in one event coincides with a 1% change in all of them.) This does not require the baseline probabilities to be the same. Pivoting events having the same label often have the same underlying fault tree structure, which means that the pivoting events occur due to the same causes in different conditions. Thus, if a pivoting event is improved in one situation, the other pivoting events with the same label might be expected to improve as well. For example, training on rejected take-offs might shift the probabilities for all such related events, even if the baseline probabilities are different. In summary, we acknowledge that this is not a perfect assumption. But the opposite assumption – that same-label events are completely independent – is probably not accurate either. The truth is somewhere in the middle. A more critical evaluation of this assumption is a subject for future work.

Results

Table 4 shows the top 10 events, as identified by the sensitivity analysis. The pivoting event of 'air traffic control does not resolve the conflict' is the most significant event, which increases the overall accident frequency predicted by ISAM by 0.622% as the probabilities of the pivoting events increase by 1%. 'Flight crew or vehicle driver does not resolve the conflict' and 'Flight crew does not maintain control' are the next two most important pivoting events among 27 uniquely labeled pivoting events. Some common pivoting events, i.e. 'Flight crew does not initiate rejected approach' and 'Rejected take-off at high speed (V > V1)', have a negative sensitivity, which means that the accident frequency is expected to go down if the probabilities of these events are increased.

Table 4. Results of Common-Event Sensitivity

Label of Pivoting Events	Sensi-tivity	# of Obs.
Air traffic control does not resolve the conflict	0.622%	4
Flight crew or vehicle driver does not resolve the conflict	0.606%	2
Flight crew does not maintain control	0.187%	75
Flight crew does not detect and extinguish fire	0.076%	1
Flight crew does not initiate rejected approach	-0.069%	4
Rejected take-off at high speed (V > V1)	-0.065%	9
Sufficient braking not accomplished	0.054%	32
Aircraft lands outside nominal landing parameters	0.054%	5
Insufficient runway length remaining	0.035%	27
Flight crew rejects take-off	0.020%	9

Not surprisingly, many of the events in Table 3 (i.e., events appearing multiple times throughout ISAM) appear in the list of most significant events in Table 4 with respect to the sensitivity analysis. Nevertheless, there are some events that appear in Table 4 even though they appear only one or two times throughout ISAM – e.g., 'flight crew does not detect and extinguish fire'. This can be explained by considering the base accident frequencies of the ESDs themselves. Some ESDs count more than others, so a critical event within an ESD that has a (relatively) high accident frequency can rank as significant.

Figure 9 shows the base accident frequency of each ESD in ISAM. (Note: ESDs that are not shown in the figure have a zero accident frequency.) As shown in the figure, more than 50% of accidents in the National Airspace System occurred due to the scenarios in the ESD US36 whose initiating event is ‘Conflict on taxiway or apron’, and the two most sensitive common pivoting events, i.e. ‘Air traffic control does not resolve the conflict’ and ‘Flight crew or vehicle driver does not resolve the conflict’, appear in the ESD US36.

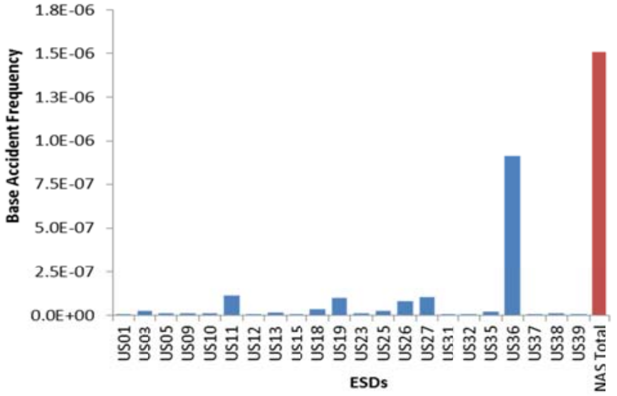

Figure 9. Base Accident Frequency of ESDs

More generally, the sensitivity of a common pivoting event is related to the sum of accident frequencies of ESDs in which the event appears. As shown in Figure 10, this sum tends to decrease as the sensitivity of the event decreases.

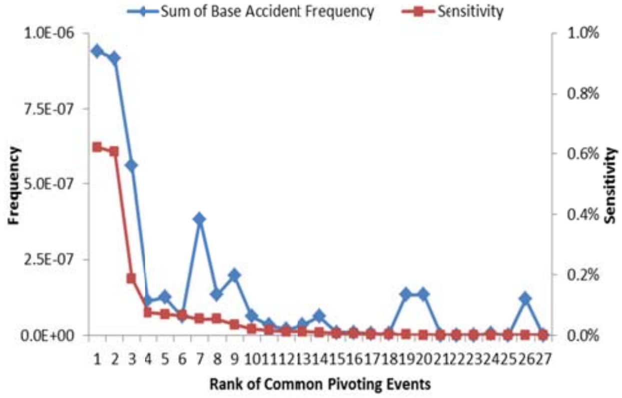

Figure 10. Sensitivity vs Accident Frequencies

One more possible factor that affects the sensitivity of a common pivoting event is the complexity of ESDs including the event. The sum of base accident frequencies for the 4th most common pivoting event, ‘Flight crew does not detect and extinguish fire’, is less than those for the 5th and 8th most common pivoting events, which are ‘Flight crew does not initiate rejected approach’ and ‘Aircraft lands outside nominal landing parameters’ respectively. The latter two events appear in one of the more complicated ESD structures (top panel of Figure 5), whereas the former event appears in a very simple ESD structure. Thus, the complexity of ESDs, in which a common pivoting event appears, reduces the sensitivity of the event.

Table 5 shows the common-event sensitivity results based on the fatality frequency, which is described in the previous section. ‘Flight crew does not initiate rejected approach’ is the most significant pivoting event followed by ‘Flight crew does not maintain control’. Most of the top 10 significant pivoting events in the fatality-based sensitivity results are also in the top 10 list in the accident-based results (comparing Tables 4 and 5).

Table 5. Fatality based Common Event Sensitivity

Label of Pivoting Events	**Sensi-tivity**	**# of Obs.**
Flight crew does not initiate rejected approach	-0.525%	4
Flight crew does not maintain control	0.498%	75
Sufficient braking not accomplished	0.174%	32
Air traffic control does not resolve the conflict	0.163%	4
Aircraft lands outside nominal landing parameters	0.130%	5
Flight crew does not execute avoidance maneuver successfully	0.129%	1
Insufficient runway length remaining	0.082%	27
Flight crew does not detect and extinguish fire	0.081%	1
Structural failure	-0.055%	5
Flight crew does not execute wind shear escape maneuver	0.042%	1

Analysis for Fault Trees

Fault trees are placed under every initiating event and pivoting event in ISAM. These trees serve as sub-models to determine the probabilities of the pivoting events. This section considers a similar sensitivity analysis for fault trees. The methodology is the same as before, but applied to the nodes in the fault trees rather than to the pivoting events. Factorial-design analysis is not done here, because the number of fault-tree elements (on the order of thousands) makes the number of combinations to try too computationally challenging.

Results of Individual ESD

An importance-measure analysis is conducted for all fault tree events in each individual ESD. The number of fault-tree events under an initiating event or a pivoting event varies from a few to more than one hundred. Due to the structure of the fault trees and the baseline probabilities, many of the fault tree events in an ESD have the same computed importance measure, so an explicit ranking of fault tree events is not very useful. Instead, we present high level findings.

- Fault-tree events under the initiating event tend to be more significant, provided the accident frequency of the ESD is non-zero.
- Most of the fault trees are composed of "or" gates. But if there is an "and" gate in a fault tree, events below the "and" gate are much less significant. This is because a failure of the "and" gate only occurs if every event underneath it fails, so each sub-event is less important.
- Importance measures are the same for fault tree events under a pivoting event that has a zero probability. Also, if the accident frequency for an ESD is zero, fault-tree events under the initiating event are all zero.

Results across ESDs

A similar analysis of common events is conducted for fault-tree events across all ESDs in ISAM. As discussed previously, pivoting events with the same label have the same underlying fault tree. Even though there are 3,454 fault-tree event nodes in ISAM, there are only 226 unique labels for these events. 133 of these labels appear more than once, while the rest are unique. Table 6 shows the 12 most frequently appearing labels.

Table 7 shows the top ten fault-tree events as identified by the sensitivity analysis. The event 'Avoidance essential' is the most significant event. This node describes a situation where corrective action must be taken to prevent an accident – e.g., two aircraft are on course for a collision, so some type of avoidance is necessary to avoid the accident. The interpretation of the sensitivity value is that if the failure probability of every node in ISAM with this label is increased by 1%, then the overall accident frequency increases by 0.622%. Most of the significant fault tree events appear a relatively small number of times throughout all ESDs.

Table 6. Common Labels of Fault Tree Events

Label of Fault Tree Events	# of Obs.
No warning system in place-flight crew	200
Warning system fails to give warning-flight crew	200
Warning system gives erroneous warning-flight crew	200
Inadequate flight-crew procedures	197
Ineffective flight-crew cockpit resource management	197
Flight-crew technical equipment failure	196
Other system provides incorrect information-flight crew	181
Poor manual flight control	156
Poor automated systems management	155
Aircraft state inhibiting ability to maintain control	77
Environmental factors inhibiting ability to maintain control	76
Maintenance conducted incorrectly	56

Table 7. Results of Fault Tree Event Sensitivity

Label of Fault Tree Events	Sensi-tivity	# of Obs.
Avoidance essential	0.622%	4
Conflict in non-movement area	0.412%	1
Avoidance action creates new conflict	0.211%	4
Communications technical equipment failure	0.112%	33
Incorrect flight crew/driver response to controller action	0.111%	2
Other aircraft deviation	0.111%	4
Situation exceeds capability to correct	0.107%	11
Flight crew/driver fails to take correct avoidance action	0.106%	2
Flight crew/driver misjudges avoidance action	0.106%	2
Flight crew fails to take correct avoidance action	0.106%	2

Conclusions

This paper presented multiple metrics for sensitivity analysis of event sequence diagrams for aircraft accident scenarios, which are developed in ISAM. The sensitivity analyses are conducted for pivoting events and underlying fault tree events of individual ESD as well as across 35 ESDs based on both accident frequency and fatality frequency to identify the most important events. For individual ESD analysis, three importance measures and factorial design analysis are performed to rank pivoting events and fault tree events separately in each ESD, while the common-event sensitivity is measured across all 35 ESDs.

For individual ESDs, the accident-based analysis highlights the significance of the ESD structure. ESDs with the same structure tend to have the same pivoting events that are identified as most important, even though the numerical values within the trees are different. The fatality-based analysis yields a similar result, but the commonality among same-structure ESDs is not as pronounced. The higher fidelity of the data (quantifying different types of accidents by their fatality rates) provides more precision in identifying important pivoting events.

For the sensitivity analysis across all ESDs the assumption that events having the same label are really the same was made even though the interpretations of events may vary in different places of ISAM. Events may be evaluated as important for a variety of reasons: They may create a significant effect within an important ESD (i.e. one that contributes significantly to the total fatality/accident metric), or they may appear multiple times throughout ISAM. A relationship between the number of observations and the importance of an event is not clearly detected. Many important pivotal events in the single-ESD analysis are also significant in the common event analysis – for example, 'Air traffic control does not resolve the conflict', 'Flight crew does not maintain control', 'Sufficient braking not accomplished', 'Insufficient runway length remaining.' To a lesser extent, a similar observation is made for fault tree events. Top events for fault trees include 'Communications technical equipment failure', 'Other aircraft deviation', and 'Situation exceeds capability to correct'. For pivotal events, the top 10 list is similar using accident and fatality metrics, but this was not observed for the fault-tree events.

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Disclaimer

The opinions and results in this paper are solely those of the authors.

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Appendix I

35 Event Sequence Diagrams in ISAM

ESD	Initiating Event
US 01	Aircraft system failure during take-off
US 02	Air-traffic-control event during take-off
US 03	Aircraft directional control by flight crew inappropriate during take-off
US 04	Aircraft directional control related system failure during take-off
US 05	Incorrect configuration during take-off
US 06	Aircraft takes off with contaminated flight surface
US 08	Aircraft encounters wind shear after rotation
US 09	Single engine failure during take off
US 10	Pitch control problem during take-off
US 11	Fire onboard aircraft
US 12	Flight crew member spatially disoriented
US 13	Flight control system failure
US 14	Flight crew member incapacitation
US 15	Ice accretion on aircraft in flight
US 16	Airspeed, altitude or attitude display failure
US 17	Aircraft encounters adverse weather
US 18	Single engine failure in flight
US 19	Unstable approach
US 21	Aircraft weight and balance outside limits during approach
US 23	Aircraft encounters wind shear during approach or landing
US 25	Aircraft handling by flight crew inappropriate during flare
US 26	Aircraft handling by flight crew inappropriate during landing roll
US 27	Aircraft directional control related systems failure during landing roll
US 31	Aircraft are positioned on collision course in flight
US 32	Runway incursion involving a conflict
US 33	Cracks in aircraft pressure boundary
US 35	Conflict with terrain or obstacle imminent
US 36	Conflict on taxiway or apron
US 37	Wake vortex encounter
US 38	Loss of control due to poor airmanship
US 39	Runway incursion involving incorrect presence of single aircraft for takeoff
US 40	Air-traffic-control event during landing
US 41	Taking off from a taxiway
US 42	Landing on a taxiway
US 43	Landing on the wrong runway