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AN APPROACH FOR SAFETY ASSESSMENT IN UAS OPERATIONS APPLYING STOCHASTIC FAST-TIME SIMULATION WITH PARAMETER VARIATION

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ABSTRACT

This paper presents an approach for safety assessment in unmanned aerial system (UAS) operations that uses stochastic fast-time simulation and selected published ground impact fatality/casualty models to calculate fatality risk. The application of simulation allows a sensitivity analysis measuring how different aspects and phases of a UAS operation impact the risk calculations for each of the ground impact models. Specifically, this approach consists of modelling and simulating UAS operations over a defined populated region applying stochastic parameters, such as flight track dispersion, altitude, failure rate, performance variation, and latency due to situational awareness (e.g. BVLOS). Then, published ground impact models are applied to determine the risk in terms of fatalities. This process provides risk metrics in a range, where it is then left to the decision makers as to what constitutes acceptable risk in a given situation.

1 INTRODUCTION

The demand for unmanned aerial systems (UAS) with an almost unlimited range of missions has been continually growing in the last few years. Their use has been applied not only to private and recreational uses, but also to public, military and commercial users. According to a recent forecast on number of UAS vehicles published by DoT (2013), commercial users represent a large growth sector especially for mini and small UAS categories, reaching a total of 175,000 vehicles by 2035. Integrating them into the National Airspace System (NAS) and assessing the impacts of such sudden growth is a challenging and vital task.

In its omniscient origin, the International Civil Aviation Organization (ICAO) "predicted" the need for a proper regulatory framework for UAS over 72 years ago, when article 8 of 1944's Convention on International Civil Aviation (commonly known as "Chicago Convention") states that "no aircraft capable of being flown without a pilot shall be flown without a pilot over the territory of a contracting State without special authorization by that State and in accordance with the terms of such authorization" (ICAO, 2011). Today, ICAO (2011) defines UAS as "an aircraft and its associated elements which are operated with no pilot on board".

Lately, a great deal of effort has been done worldwide, especially in United States and Europe, in order to develop standards and recommended practices for UAS operations which cover aspects such as safety, security and liability, in order to guarantee the development of this emerging aviation segment. One of the major concerns about its integration into the NAS is assessing UAS safety, according to Melnyk et al. (2014). Since UAS is a fairly recent segment of aviation, the available data related to operations such as flight hours, number of accidents and incidents, failure rates, etc. is insufficient in order to build up reliable statistics about its level of safety as compared to airline flights and general aviation. Also, there no agreement on the most suitable methodologies to fully understand the risks and impacts of UAS operations.

Recent studies have been developing methodologies using Target Level of Safety (TLS) as a possible way to assess the UAS's risks. These studies assume a desirable TLS in compliance to similar regulations and calculate the required mean time between failures (MTBF) for an UAS in order to meet this TLS. However, to calculate the probability of occurrence of undesirable outcomes, the methodologies are mostly based on analytical formulations which may not fully represent the complexity of the operations. The metric used to measure the outcomes is usually the number of fatalities caused by a UAS crash given its failure rate for a number of flight hours or number of operations. Since an UAS operation may be subject to different operational conditions which may interfere completely in its operations, the methodologies presented in these studies may not be able to incorporate these nuances and dynamic interactions. Therefore, the use of fast-time simulation allows a wider comprehension of the risk involved in such operations, as well as consideration for potential mitigation actions in order to bring such risk to a desirable level.

The objective of this paper is to estimate the risk for UAS operation in a urban area for different operational conditions using fast-time simulation and ground impact models. The analysis is a three part process: the first part simulates an UAS operation and determines, considering a failure rate, which regions along its trajectory may be more susceptible to an accident; the second part calculates fatality metrics using the ground impact models, and the third and final part estimates the number of casualties which the accident, if it occurs, may cause in a determined region using metrics from both the simulation and a ground impact model. The study also makes considerations about the operations of an UAS in the studied area in order to develop mitigation actions.

This paper is presented as the following: section 2 shows a literature review covering the most significant publications in this field; section 3 describes the methodology used in this study, detailing the simulation scenarios and the ground impact models; section 4 shows the high-level results for the safety analysis and conclusions that can be extracted from these results.

2 LITERATURE REVIEW

Section 2.1 presents some relevant concepts and hypotheses used in this study. Section 2.2 presents some UAS classification comments. Section 2.3 reviews some relevant studies in this field.

2.1 Safety Objectives

Risk can be defined as the combination of the probability of occurrence of undesirable outcome and the associated severity. The safety objectives for an risk analysis on UAS often work within a definition of whether if it can meet levels of safety which are tolerable by society. ICAO (2011) defines safety as "the state in which the possibility of harm to persons or of property damage is reduced to, and maintained at or below, an acceptable level through a continuing process of hazard identification and safety risk management". The likelihood and the severity can be classified in five categories each, as shown in Tables 1 and 2. The combination results in a risk matrix which classifies it in accordance to its level, as shown in Figure 1. The green zone refers to risks within an acceptable level, the yellow refers to a risk level that is only acceptable if mitigation actions are taken place and the red zone refers to a intolerable risk level.

The use of TLS is one way of measuring the safety of the system. Fortes, Correia and Müller (2013) mention that the TLS is the desirable safety level which a system must achieve and it can be understood as a comparable landmark which defines if the system can be considered "safe" (and, if not, it's a way to determine how close it is to being safe). In UAS operations safety assessment, the most common approach is to determine an equivalent level of safety compared to manned aerial vehicles. Clothier and Walker (2006) mention that this idea seems reasonable due to the fact that manned aircraft have been operating under acceptable safety standards for over half a century. However, the main indicator for this analysis is the number of fatalities caused by the UAS impact on the ground or a mid-air collision. On the other hand, it is important to consider the primary differences between manned and unmanned aircraft operations from a safety perspective. Firstly, events which may cause injuries or fatalities has a severity classification as hazardous, at least. Secondly, the severity classification in manned operations has a much more wider meaning. Dalamagkidis, Valanis and Piegl (2008) mentions that the classification of severity embodies injuries and fatalities for both people on-board and on the ground, and the metrics for quantifying an accident's severity does not consider only the number of fatalities. Therefore, in order to use an equivalent approach, using the number of fatalities on ground caused by manned aircraft seems more reasonable.

Studies have been using the value of 10^{-7} fatalities per flight hour for TLS in safety assessment for UAS operations. This value is justified by statistics from National Transportation Safety Board (NTSB) data from 1998 to 2004 of manned operation. Clothier and Walker (2006) mention that for the number of fatalities on ground caused by manned aircraft accidents calculated from NTSB data is 1.48×10^{-7} fatalities per flight hour.

Table 1: Description of severity levels. Source: Adapted from FAA (2012).

Severity Level	Definition
Catastrophic	Multiple fatalities
Hazardous	Fatal injury / multiple serious injuries
Major	Physical distress or injuries to persons
Minor	Physical discomfort to persons
Minimal	Negligible safety effect

Table 2: Description of likelihood levels. Source: Adapted from FAA (2012).

Likelihood	Definition
Frequent	Expected to occur routinely ($>10^{-3}$)
Probable	Expected to occur often. Anticipated to occur one or more times during the entire system/operational life of an item (10^{-3} to 10^{-5}).
Remote	Expected to occur infrequently. Unlikely to occur to each item during its total life. May occur several times in the life of an entire system or fleet (10^{-5} to 10^{-7}).
Extremely Remote	Expected to occur rarely. Not anticipated to occur to each item during its total life. May occur a few times in the life of an entire system of fleet (10^{-7} to 10^{-9}).
Extremely Improbable	So unlikely that it is not anticipate to occur, but is not impossible. Not expected to occur during the entire operational life of an entire system or fleet ($<10^{-9}$).

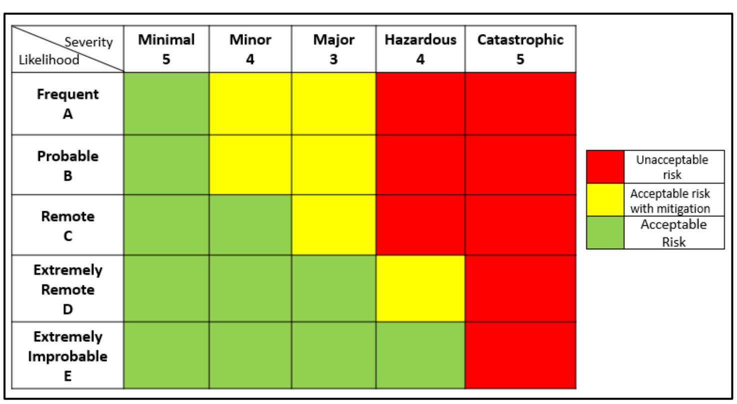

Figure 1: Risk Matrix. Source: Adapted from FAA (2012).

2.2 UAS Classification

The use of an UAS classification is not only important to differentiate them but also to create regulatory standards which fits the range of different UAS, as mentioned by Dalamagkidis (2015). Different metrics for UAS classifications have been proposed by authors in order to fit the focus of the analysis being conducted, such as mean takeoff weight (MTOW), size, operational capabilities, etc.

For safety studies focused on ground impact assessment, MTOW is perhaps the most appropriate metric to be used. Most of the models for fatalities estimation in ground impact are energy-based models, which rely on UAS's mass.

Dalamagkidis (2015) presents a classification, as shown in Table 3, used in his work about ground impact analysis.

Table 3: UAS Classification according to its MTOW. Source: Adapted from Dalamagkidis (2015).

Category	MTOW
Micro	Less than 1 kg
Mini	Up to 1 kg
Small	Up to 13.5 kg
Light/Ultralight	Up to 242 kg
Normal	Up to 4,332 kg
Large	Over to 4,332 kg

2.3 Recent Studies

As mentioned before, different studies have been done analyzing the risk involved with UAS operations to the general public, focusing on ground and midair collision impacts.

Weibel and Hansman (2004) develop a methodology for ground and midair collision and, assuming an TLS of 10^{-8} of fatalities per flight hour, calculate the required MTBF to navigate through different parts of NAS. In other words, the authors estimate the necessary reliability for different types of UAS to be able to safely fly over different areas across the NAS. The estimation of number of fatalities is mainly based on the population density in which the UAS flies over. However, the studied areas are discretized over large locations, interfering in the estimation of desirable reliability. King, Bertapelle and Moses (2005) consider a similar approach (finding a desirable reliability) but the fatalities which the UAS may cause are weighted according to each area. As a result, each area has a small contribution in the final estimated reliability. Dalamagkidis, Valavanis and Piegl (2008) advanced in the fatalities estimation by considering that a curve of kinetic energy *x* lethality probability. The authors mention that empirical data have shown that objects of different mass can have a different effect upon impact, even if the kinetic energy measured at the time of the impact is the same. Melnyk et al. (2014) uses a better distribution of the areas, breaking it down according to its usage type: residential, commercial, open areas etc. Therefore, differentiating from other studies, the protection effect for each of area is different, yielding more reasonable values in regards to fatalities.

3 METHODOLOGY

The risk methodology process has three parts:

1. Use fast-time simulation to create a 4-D UAS mission profile within a dynamic ATM environment;
2. Use ground impact models to calculate the number of fatalities, using metrics aggregated from the simulation;
3. Calculate risk metrics using results from the fast-time simulation and the ground impact models.

Section 3.1 provides an overview of the chosen simulation tool and the fast-time simulation model scenarios. Section 3.2. describes the published ground impact models selected for the analysis. Section 3.3 describes the risk calculations..

3.1 Fast-Time Simulation Tool and Scenarios

The model used in this paper is RAMS Plus, an ATM fast-time discrete event simulation model. RAMS Plus was chosen to support this paper based on availability and familiarity with the analysts.

The RAMS Plus model provides gate-to-gate ATM simulation to measure performance benefits for ATM management decision support. RAMS Plus is a commercially available software product that is applied worldwide to quantify existing and proposed ATM systems.

For this paper, RAMS Plus simulates full 4D movement of each aircraft through time, and each aircraft's dynamic interaction with other aircraft, airspace structures, airspace procedures and rules. Some of the features applied for this paper include 4D profile calculation using UAS performance tables, 3D airspace structures, resource request and competition, priority-based separation strategies to differentiate the UAS, time and distance based conflict search algorithms, rule based conflict resolution, time-based metering, stochastic distributions for failure rates and stochastic position variance. The result is a range of outputs that can be used to create unlimited views of aggregated metrics, measurements, and quantifications to describe the system's behavior and the UAS impact.

The study was conducted considering a hypothetical UAS surveillance mission over a densely populated region in the San Diego metropolitan area. The UAS departs from San Diego International Airport (KSAN) and flies over about 19 different areas, as shown in figure 5. The studied area was divided based on zip code tabulation areas (ZCTA), in 2010, provided by California State Data Center, Department of Finance. This demographic data gives information for each zip code, the region's area volume and the population. Each region shown in figure 2 has its population presented in table 4, in people per square mile. Concerning the third ground impact model previously presented, the following subdivision was considered for the region: 30% for residence and commerce and 20% for vehicle and open areas.

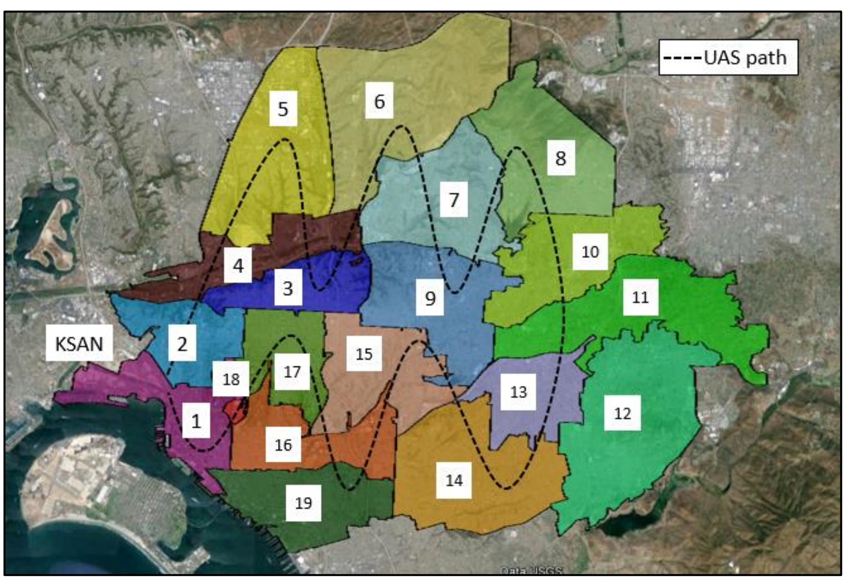

Figure 2: UAS's mission and region's division.

The dotted line in figure 2 represent the UAS' planned trajectory. The mission is estimated to last approximately 1.1 hour. However, with the stochastic applications to simulate adverse factors, the mission position and duration varies between simulation iterations. It was assumed a stochastic distribution of 15% for performance's variance for climb, cruise, and descent speeds and rates. For the positional variance it was assumed a normal distribution with a mean of 0.5 nm and a standard deviation of 0.1 nm around each waypoint in its trajectory. Other stochastic parameters are used for position intent and conflict prediction to model and measure situational awareness and latency in conflict avoidance, however, these features are not described in this paper.

Table 4: Population density for the studied areas. Source: California State Data Center (2010)

ID	ZIP Code	(People/mile^2)	ID	ZIP Code	(People/mile^2)
1	**92101**	7867.10	**11**	**91941**	3942.06
2	**92103**	8245.50	**12**	**91977**	6038.86
3	**92116**	9136.22	**13**	**91945**	6484.26
4	**92108**	4402.30	**14**	**92114**	7942.77
5	**92123**	3284.96	**15**	**92105**	12533.53
6	**92124**	2904.44	**16**	**92102**	9347.35
7	**92120**	3954.18	**17**	**92104**	11720.04
8	**92119**	3365.93	**18**	**92134**	1069.30
9	**92115**	9003.15	**19**	**92113**	10639.84
10	**91942**	6523.63			

The Raven-like UAS performance tables were inserted into the model in order to create realistic UAS 4D profiles. Such performance parameters are displayed in the table 5 below.

Table 5 – Raven-like UAS's specifications. Source: Joint Planning and Development Office (2012).

MTOW(lb)	4.2	**Width (ft) *estimated**	1.0
Wingspan (ft)	4.3	**CruiseSpeedRange(KTAS)**	17 to 40
Length(ft)	3.7	**Cruise Altitude AGL (ft)**	100 to 500
Airfoil thickness (ft)	0.1	**A_{exp}(mile^2)**	3.00E-07

The simulations were performed using six different failure rates for each of the ground impact methods, with 100 iterations per each failure rate. The failure rate is represented as failure rate per flight hour.

3.2 Ground Impact Fatality Estimate: Three Methods

3.2.1 Method 1 - Weibel and Hansman (2004)

Weibel and Hansman (2004) proposed a formulation in order to calculate an expected level of safety (ELS) based on the event tree in Figure 3. It is based on an eventual UAS's catastrophic failure during an operation over a populated area, resulting in fatalities. However, in order for the fatality occur, the UAS's kinetic energy must be greater than 73 J. Otherwise, the ground impact does not yield fatalities.

The proposed model, as seen in equation (2), calculates ELS using the following parameters: MTBF which can also be expressed as the inverse of failure rate, population density (ρ) of impacted area, exposure area (Aexp) defined by the UAS' shape and attitude during strike, penetration factor which varies according to the probability of the debris penetrate a shelter (in an open area, over a house, over a car etc.) and mitigation factor (P_{mit}) which varies from 0 to 1 and represents mitigation actions that can be taken at any point of the event tree in order to lower ground impact consequences (presented in equation 2).

$$ELS = \frac{\rho \times A_{exp} \times P_{pen} \times (1 - P_{mit})}{MTBF} \quad (2)$$

Analyzing the equation above (2), it is possible to divide it in two parts: the first one refers to the UAS failure rate (MTBF-1) and the second part refers to the number of fatalities caused by a ground impact. Therefore, it is possible to calculate the number of fatalities through the following equation:

$$Fatalities = \rho \times A_{exp} \times P_{pen} \times (1 - P_{mit}) \quad (3)$$

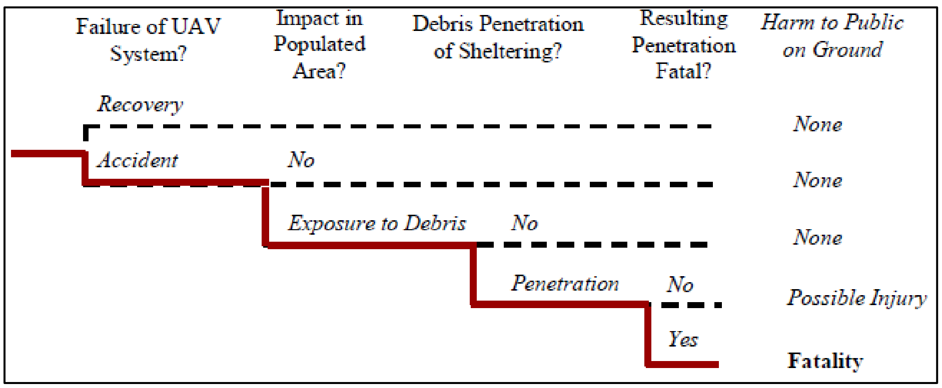

Figure 3 : Ground impact event tree. Source: Weibel and Hansman (2004).

For this study, values of 1 and 0 were used for P_{pen} and P_{mit}, respectively, similarly to Weibel and Hansman study.

3.2.2 Method 2 - Dalamagkidis, Valanis and Piegl (2008)

For this ground impact method. the authors based their estimation of number of fatalities in a ground impact accident using curves of probability of fatality versus kinetic energy. These curves estimates the probability of an impact causing a fatality for a given amount of energy. They mention that "*experimental data have shown that objects of different mass can have different effect on people, even if the kinetic energy imparted at the time of the impact is the same*". The authors determines an equation that best-fit these curves, shown by equation (4).

$$P(fatality) = \frac{1}{1 + \sqrt{\frac{\alpha}{\beta}}\left[\frac{\beta}{E_{imp}}\right]^{\frac{1}{4p_s}}} \quad (4)$$

Where:

- $p_s \in (0, 1]$ determines how exposed is the population to an impact (in this example it was used 0.2)
- α parameter is the impact energy required for a fatality probability of 50% with $p_s = 0.5$ (in this study it was used 10^6 J, same value as the authors' study)
- β parameter is the impact energy threshold required to cause a fatality as ps goes to zero (in this study it was used 100 J, same value as the authors' study)

Since equation (4) yields the probability that an impact may cause a fatality, a random number generation process (similar to a Monte Carlo simulation) using this probability, was used to determine if the fatality happens or not for each simulation.

3.2.3 Method 3 - Melnyk et al. (2014)

For this ground impact method, the authors consider the area flown by the UAS subdivided in four types of areas: Residence, Commercial, Open, and Vehicle. Each area has different protection characteristics and population density which impact in the number of fatalities. The calculations were based on the event tree presented in figure 4.

An initial random number generation process, using the percentage of subdivision of areas, was done in order to determine the subarea which was impact during the UAS' failure. Then, each sub-area has its energy threshold identified, which determines whether the fatality happens or not: if the UAS kinetic energy is over this value, a fatality happens, otherwise it does not.

For impacts in residential sub-areas, the necessary kinetic energy for UAS's penetration is 813 J (considering houses with wooden roofs. If the kinetic energy is smaller than this value, a fatality does not happens. Otherwise, it means that debris have penetrated the house and there might be a chance of fatality. In this case, a probability of 30% (same value assumed by the authors) is considered. Then, a random number generation process is conducted for this probability in order to verify if such fatality occurs.

The same steps described above were done for both Commercial Area and Vehicle. However, the impact energy for penetration are, respectively, 13558 J (for concrete roofs) and 273 J (for auto steel roofs). For open areas, it is used the same binary condition as Weibel and Hansman's method. The threshold value for UAS's kinetic energy is the same (73 J).

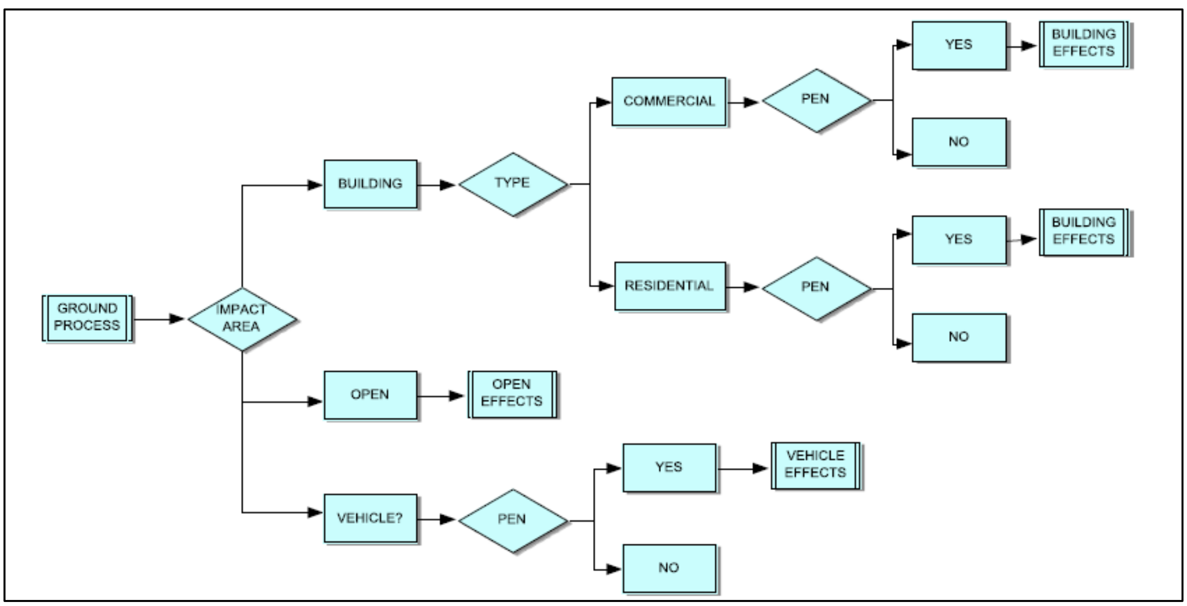

Figure 4 : Ground impact event tree. Source: Melnyk et al. (2014).

3.3 Risk Calculation Based On Simulations

The UAS mission profile was designed using fast-time simulation, assuming a failure rate on its operation. Therefore, for each simulation iteration, the simulator considers this failure rate using random number generation to determine if or when a failure occurs. The simulation yields the total hours flown by the UAS and the time/location where the failure occurred. Due to the dynamic factors which an UAS mission is subject to within the ATM environment, there are different factors which may affect the UAS' flight path. The scenario also incorporates a stochastic distribution in order to vary the UAS flight profile and performance between each iteration, representing other factors that may cause these dispersions (such as weather, UAS's pilot experience, etc.).

The area flown by the UAS is divided in regions with known population densities. This information along with the failure location are the main components to determine the number of fatalities for each iteration that has such UAS failure.

Finally, the summation of the number of fatalities for each iteration *i*, divided summation of total flight hours for each iteration *i,* yields the risk of occurrence R_{final}, as shown in equation (1).

$$R_{final} = \frac{\sum_i (Fatalities)_i}{\sum_i (Flight\ Hours)_i} \tag{1}$$

4 SENSITIVITY ANALYSIS RESULTS

As noted previously, the simulations were performed using six different failure rates for each of the ground impact methods, with 100 iterations per each failure rate. The failure rate is represented as failure rate per flight hour. Figure 5 summarizes how the failure rate impacts the average total flight. Obviously an increase in failure rate decreases the average flight time: for a greater failure rate, the chances of UAS crashing and not completing its mission are higher. The dispersion for the total flight time decreases as failure rate increases, as well. This can be explained by the fact that with higher failure rate values, the UAS essentially crashes just after a departure. At this point, performance variation and profile dispersion have no influence.

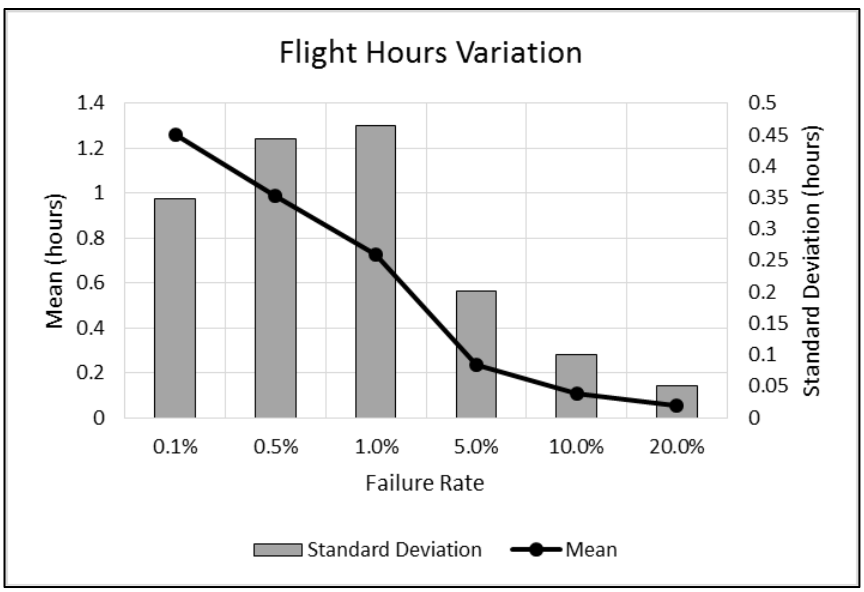

Figure 5: UAS Mean Flight Time Per Failure Rate.

Table 7 summarizes the results of risks for different failure rate and ground impact methods. The results show interesting differences among the methods, where within the three presented methods, the first one is expected to be more conservative. This fact is due to its approach of considering a threshold for fatality occurrence, that is, the fatality will certainly occur if UAS kinetic energy is above a determined value. The other two methods work with probabilities of occurrence of fatalities for different kinetic energies. Also, method 3 considers a subdivision of the impacted area and giving different characteristics to it. This is reflected directly in our results: for different failure rates, method 1 yields risks between 10 and 10^2 times greater than methods 2 and 3.

Another important fact related to this analysis is that severity for these simulations can be classified as hazardous, as shown in table 6. Therefore, an acceptable probability of occurrence for these would be equal or lower than 10^{-9}, which does not occur in any method.

Table 6: Fatalities Per Flight Hour: Results for three methods.

Fatalities/FH	Failure rate (%)					
	0.1	**0.5**	**1.0**	**5.0**	**10.0**	**20.0**
Method1	2.05E-04	1.03E-03	2.05E-03	7.19E-03	1.65E-02	3.81E-02
Method2	9.26E-06	9.11E-05	1.61E-04	3.33E-04	1.40E-03	2.04E-03
Method3	9.42E-06	2.33E-05	4.90E-05	1.39E-04	3.42E-04	2.05E-03

Finally, the convergence to a somewhat steady state is shown in figures 6, 7 and 8. It is interesting to notice that the convergence in methods 2 and 3 differs greatly from method 1. For these methods, the risk value stabilizes after 80 simulation iterations. This can be explained by the use of a random number generation process for the calculation of number of fatalities. This leads to an oscillation of results for the initials numbers. In the other hand, method 1 needs between 20 and 40 iterations to decrease its oscillation to a stabilized level. Also only methods 2 and 3 consider "shelter effects" that gives some kind of protection to a person hit by UAS crash. Therefore, an accident may not necessarily yield a fatality, where in turn it would then be necessary to have a greater number of simulation iterations to reach a steady state. These conditions better represent real-world situations when a person is hit in an UAS crash, as they may have some kind of protection which would minimize the injuries.

Other interesting fact extracted from these figure is how the failure rate affects each method. As the failure rate increases, a greater number of simulation iterations is necessary to obtain a stabilized value. Method 2 and 3 are even more sensible to this fact, especially for failure rates of 10 and 20 %.

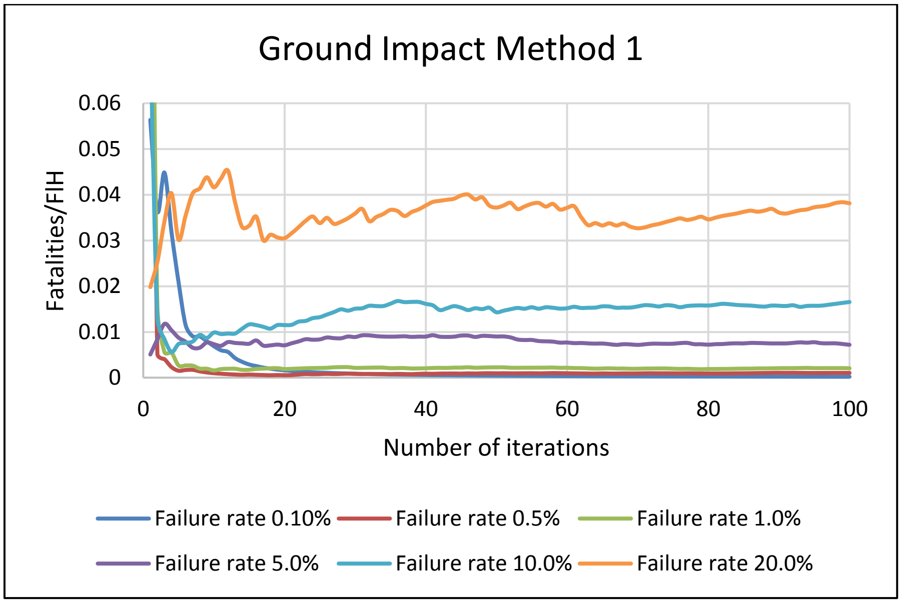

Figure 6 : Convergence for Method 1for number of iterations.

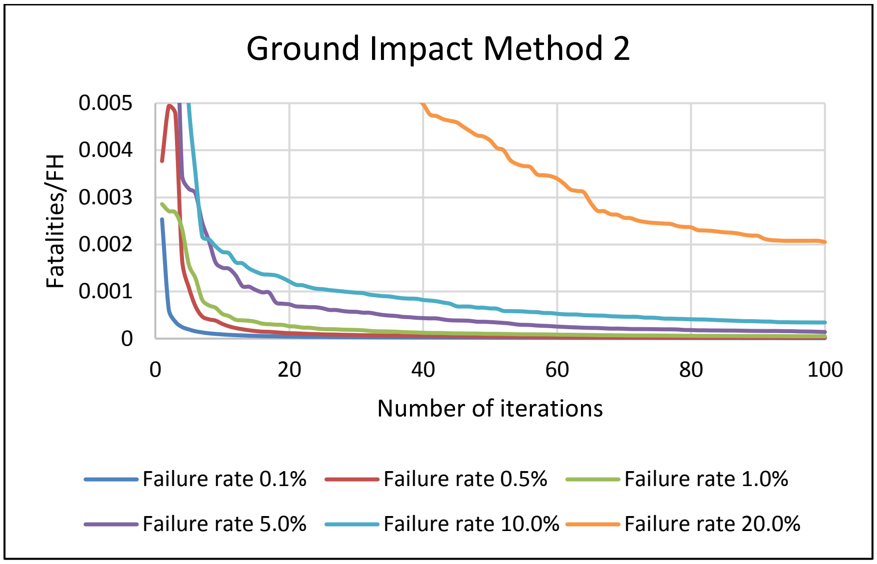

Figure 7 : Convergence for Method 2 for number of iterations.

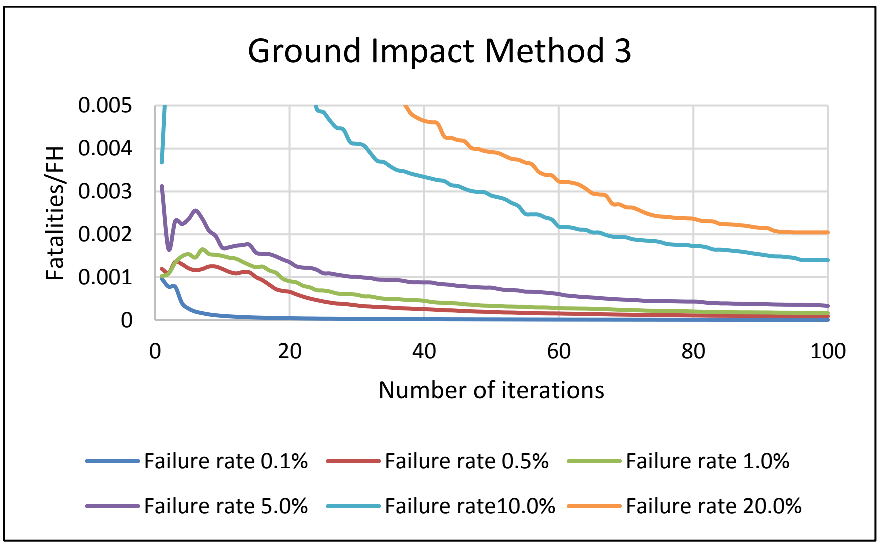

Figure 8 : Convergence for Method 3 for number of iterations.

5 FINAL COMMENTS

The integration of UAS in the NAS is a major concern to airspace regulators, especially regarding the safety aspects of the UAS operations. Several studies in this field have been published recently, where this paper addresses a methodology that incorporates the use of fast-time simulation to assess the risk involved with such UAS operations in regards to published ground impact models. This approach incorporates many UAS-specific aspects that are often ignored in analytical models.

This study helps understand the differences between the three selected ground impact models, and to assess the sensitivity of these ground impact models. Further consideration to real world applications of the process described here would address the applicability of each ground impact method and its relative merits and value to the given UAS situation, and also consider a ground impact model for casualties/injuries. These insights are essential to determine mitigation actions for all stakeholders in the safety assessment and policy-making process.

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REFERENCES

California State Data Center. 2010. "Census 2010 Demographic Profile Summary File". California Department of Finance.

Clothier, R. A. and Walker, R. A. 2006. "Determination and Evaluation of UAV Safety Objectives." In *Proceedings of the 21st International Unmanned Air Vehicle Systems Conference*, 18.1-18.16, Bristol, United Kingdom.

Dalamagkidis, K. 2015. "Classification of UAVs." In *Handbook of Unmanned Aerial Vehicles* edited by K. P. Valavanis and G. J. Vachtsevanos, 83-91. Netherlands: Springer Science.

Dalamagkidis, K., Valavanis, K. P., Piegl, L. A. 2008. "Evaluating the Risk of Unmanned Aircraft Ground Impacts." In *Proceedings of the 16th Mediterranean Conference on Control and Automation Congress Centre*, 709-716, Ajaccio, France.

International Civil Aviation Organization (ICAO). 2011. "Circular 328 AN/190: Unmanned Aerial Systems(UAS)", Montreal, Canada.

Federal Aviation Administration – FAA. 2012. "Order 8040.4A Safety System Management Policy", United States.

Fortes, J. L. C.; Correia, A. R. ; Müller, C. .2013. "Impacts of Different Operational Conditions in Risk Assessment for an Airport." In *Proceedings of the Air Transport Research Society ATRS World Conference*, Bergamo, Italy.

JPDO Joint Planning and Development Office. 'UAS Operational Scenarios", 2012.

King, D. W., Bertapelle, A., Moses, C. 2005. *UAV Failure Rate Criteria For Equivalent Level of Safety.* In *Proceedings of International Helicopter Safety Symposium*, 1-9, Montréal, Canada.

Melnyk, R., Schrage, D., Volovoi, V., Jimenez, H., 2014. *A Third-party Casualty Risk Model for Unmanned Aircraft System Operations*. Reliability Engineering and System Safety. V. 124, 105-116.

U.S Department of Transportation (DoT). 2013. "Unmanned Aircraft System (UAS) Service Demand 2015 – 2035." Technical Report V. 1.0. United States.

Weibel, R. E., Hansman, R. J. 2004. "Safety Considerations for Operation of Different Classes of UAVs in the NAS." In *Proceedings of the AIAA's 4th Aviation Technology, Integration and Operations (ATIO) Forum*. Chicago, Illinois, 1-11.

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