Modeling Risk-Based Approach for Small Unmanned Aircraft Systems

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With the rapid acceleration of small Unmanned Aircraft System (sUAS) technologies and the ever-growing demand for operating sUAS in the National Airspace System (NAS), the Federal Aviation Administration (FAA) is seeking quantitative risk assessment methods to enable sUAS to safely access airspace and avoid highly restrictive operational or technical waivers. The purpose of this research is to provide a quantitative risk assessment model that the FAA can use to streamline the waiver approval process, to support regulatory development, and facilitate safety risk analysis. An accurate risk assessment model, one that accounts for different types of sUAS vehicles and operational missions, will enable the FAA to approve operations faster and with fewer constraints. MITRE has developed the sUAS Airworthiness Assessment Tool (sAAT), which quantifies the risk of fatality to third-party people on the ground from sUAS operations by combining characteristics of the intended vehicle type with the planned operations. The sAAT risk assessment model builds on past efforts to quantify both the operational parameters and safety criteria for sUAS. The sAAT model has a modular architecture that can incorporate updated or new algorithms and constants as new knowledge of sUAS operations and advances in sUAS technologies become available.

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Nomenclature

$P_{fatality}$	=	Probability of fatality on impact
P_{fail}	=	Probability of vehicle failure
A_{lethal}	=	Lethal crash area upon vehicle failure
ρ_{people}	=	Population density for region of interest
S	=	Shelter factor
C	=	Estimated sUAS risk assessment
m	=	Mass of sUAS vehicle
g	=	Average gravitational constant
ρ	=	Density of air at sea level
θ	=	Angle of inclination from the horizontal
A	=	Cross-sectional area of vehicle
C_D	=	Vehicle drag coefficient
C_L	=	Vehicle lift coefficient
F_D	=	Drag force
F_L	=	Lift force
E_0	=	Impact energy yielding 50 percent chance of fatality

I. Introduction

In June 2016, the FAA finalized 14 CFR Part 107 regulation for small Unmanned Aircraft Systems (sUAS: weighing less than 55 lbs.)[1].While some of the following restrictions may be waived, Part 107 operations generally stipulate that sUAS operations must be conducted within visual line of sight, with only one sUAS aircraft at a time, only during daytime hours, at altitudes below 400 feet above ground level (AGL), outside of controlled airspace, not from a moving vehicle, and not directly over a person or people.

Lacking a comprehensive sUAS risk model, the FAA developed the Part 107 rules based on an assumed worst-case scenario wherein a sUAS vehicle failure would always achieve its maximum kinetic energy prior to impact and would always result in a collision with a third-party (uninvolved) individual on the ground. These worst-case assessments produce overly conservative risk estimates and limit the ability of the FAA to enable the growing demand for sUAS operations. Therefore, the FAA is seeking a risk-based approach to conduct safety assessments and to streamline its approval process for small UAS commercial operations [2].

The purpose of this research is to provide a quantitative risk-based assessment model that will enable the FAA to better address the growing demand for sUAS operations. This model, referred to as the sUAS Airworthiness Assessment Tool (sAAT), evaluates the risks by accounting for the characteristics of both the sUAS vehicle and the intended mission. The sUAS vehicle characteristics include factors such as vehicle type (multirotor/fixed wing/hybrid) reliability, size, cruise speed, and weight class. These sUAS vehicle characteristics determine the effect on the overall risk based on the behavior of the sUAS vehicle when its airborne operations degrade or fail (such as loss of control or lift). This model is concerned with ground-based risk only, i.e., risk to people on the ground. Air-based risk to other aircraft is the subject of ongoing research.

The intended mission is characterized by mission profiles. Mission profiles provide the means for a risk analysis assessment to compare operational categories without referring to specific flight operations. There are a set of eight standard mission profiles (described in Section A. Mission Profiles), which capture the range of potential operations, and include factors that describe the intended operational use of the sUAS—such as mission area, duration, and density of people within the route of flight. The mission profiles were developed based on the applications submitted to the FAA by sUAS commercial operators for Part 107 waivers [1] and FAA Rule 333 exemptions[7] [20].

The density of the population within the route of flight is a significant operational risk factor within the mission profiles and the focus of this document. Higher population density leads to a proportionally higher operational risk. This correlation has been shown throughout previous research studies conducted across the UAS industry, including [3], [5] [18], and [19], to name a few. The sAAT uses a pedestrian density model, which is based on the LandScan™ Global Population Database [7] developed by the U.S. Department of Energy's Oak Ridge National Laboratory.

The sAAT has utility beyond the risk factors described in this document. For example, its modular architecture can incorporate new or improved algorithms and improved constants as new research findings and additional data sources for sUAS operations become available.

II. A Risk-Based Approach

The overall operating paradigm of the UAS industry has little in common with that of manned aircraft. The current approach to airworthiness and safety standard rating is inappropriate for sUAS vehicles and operations. Applying the current FAA design standards-based process used for manned aircraft does not readily translate for small UAS vehicles. Those design standards are not scalable to accommodate the rapid growth and technological advancement of sUAS vehicles.

A risk-based approach combines both the type of vehicle and the desired mission profiles to determine a risk classification and the airworthiness qualifications (see Fig. 1). This approach should reduce the time and costs of certification, while being broad enough to consider the range of highly diversified vehicles. At the same time, the approach must be thorough enough to ensure that the sUAS meets acceptable safety levels of the intended mission.

The sAAT is a data-driven risk model that provides a comprehensive evaluation of the sUAS mission. It assesses risk by combining the characteristics of both sUAS vehicle and its proposed mission. Vehicle characteristics are physical

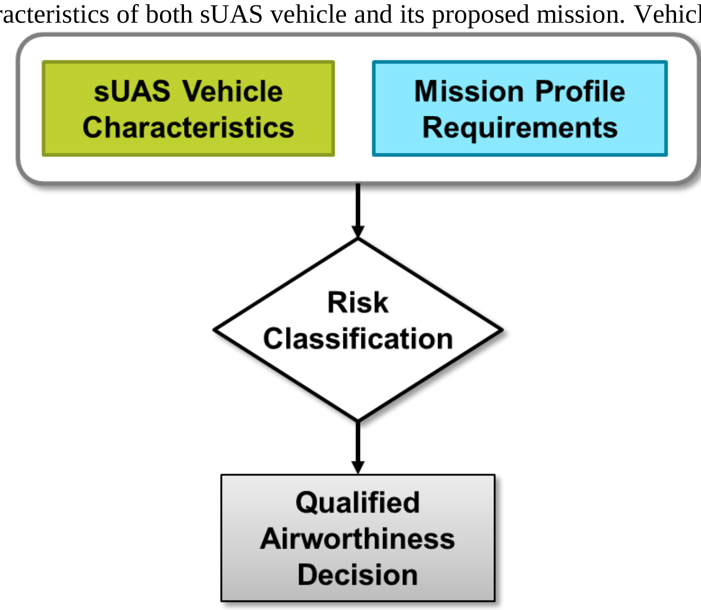

Fig. 1 Small UAS Risk-based Approach

[7] Section 333 of the *FAA Modernization and Reform Act of 2012* (FMRA) grants the FAA authority to grant case-by-case authorization for certain unmanned aircraft to perform commercial operations.

attributes of the aircraft, such as weight and maximum speed. Mission characteristics describe the operating parameters of the desired mission. The sAAT analyzes this information and predicts the probability of fatality to a third-party. A third party is defined as a member of the public that is not a participant in the sUAS flight activity and is involuntarily exposed to an aircraft accident [3], for example, a bystander that happens to be near the planned area of operation of the sUAS.

The FAA has embraced the idea of a risk-based approach and is exploring the concept and the possibilities for implementation [2]. The sAAT supports the development of a risk-based approach to establish vehicle performance thresholds for an intended mission profile. This document leverages the research efforts performed by other organizations for various aspects of sUAS safety risk, such as ground collision severity [14], vehicle component reliability [3], and airworthiness type certification [4]. To develop the initial risk model, MITRE collaborated with George Mason University (GMU) and industry partners. We continue to work in collaboration with the sUAS industry, NASA, and the FAA to refine and improve the sAAT risk model as new findings are published. These include the Nanyang Technological University (NTU) report, "Experimental and Simulation Weight Threshold Study for Safe Drone Operations" [6].

Key elements of sUAS safety risk analysis in this document include:

- Determining the mission variables that impact risk
- Determining the vehicle characteristics that impact risk
- Creating a risk model based on vehicle and mission characteristics
- Developing a concept for the process of airworthiness safety risk analysis and approval for sUAS from the perspective of the operator, manufacturer, and regulator.

A. Mission Profiles

The standard mission profiles, which enable users to compare relative operations without referring to specific flight operations, include the mission characteristics (e.g., location, distance from origin, and duration of flight) that describe the intended operational use of the sUAS. As depicted in **Error! Reference source not found.**, the risk model uses eight standard mission profiles:

- Sparse Operations
- Contained Area Operations
- Linear Area Operations
- Public Event Operations
- Network Operations
- Dynamic Operations
- Maritime Operations
- On-Airport Operations

These profiles encapsulate the majority of intended commercial and public use operations for sUAS and represent the range of the key parameters needed for a risk analysis. Each profile represents a varying degree of risk based on these general operating parameters.

Fig. 2 Standard Mission Profiles

The mission profile is divided into three operating regions: the launch and recovery volume, transit volume, and mission area/volume (see Fig. 3). The associated risk factors can vary within each region. The launch and recovery volume focuses on where the vehicle takes off and lands and may have an increased risk due to the proximity to the ground during this phase of the operation. The transit volume is the area used to get the sUAS to its intended volume of operation. Risk factors for the transit volume may vary based on the vehicle's speed, altitude, flight path, and duration as it travels across it. The mission volume is where the primary mission function is conducted. It represents the operating volume, along with its 3-dimensional safety buffers. The mission area represents the ground surface on which the collision risk to people on the ground is computed. In some cases, the launch and recovery volume, transit volume, and the mission area and mission volume could all be co-located in one volume of airspace, particularly for vertical spiral or grid type operations.

For the current version of the sAAT, the dimensions of the mission area are a key characteristic of the operational mission under consideration. Other risk factors within a mission area include the duration of time to be flown in the area, the density of the people in each region, and the type of flight pattern being flown.

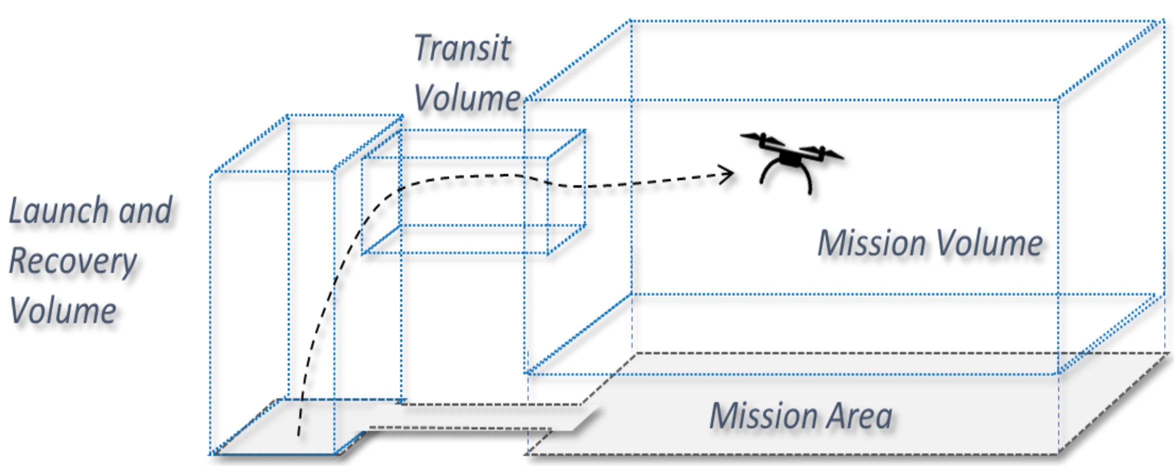

Fig. 3 Mission Profile Components

The density of people in the operating regions is a key factor determining the probability of hitting a third-party individual should there be a vehicle malfunction. This model distinguishes between *pedestrian density* and *population density*. Population density, usually obtained from census data, is a count of where people live and sleep; pedestrian density is where people are located during the intended sUAS operation.

For a realistic calculation of the pedestrian sUAS strike probability, the sAAT uses the LandScan™ Global Population Database [7]. This highly accurate geographically-based population distribution model provides a high resolution (1 km^2) population distribution. The LandScan™ population database provides the ambient (24-hour average) population distribution, which is updated annually to reflect changes in global population.

The mission profile pedestrian densities were originally based on the Science and Research Panel (SARP)[8] definitions [8], for Rural, Urban, and Open-Air Assembly. Rural describes an area of sparse population, such as majority farmland, forests, or parks. Urban is for more populated areas such as neighborhoods, cities, and parks. Open-Air Assemblies are very high-density areas where crowds of people will congregate, such as in stadiums and at media events.

Analyzing the natural break points in pedestrian counts from the LandScan™ database, we delineated the pedestrian density groupings for each type of area (Rural, Urban, and Open-Air Assembly) into three categories: low, medium, and high, as indicated in Table 1. The median number of people per square mile for each pedestrian group is indicated in the third column. The fourth column relates the percentage of the land area of the continental United States (CONUS) to each of the pedestrian groups. The far-right column indicates the percentage of total U.S. population that falls in each of the pedestrian groups.

Table 1. Pedestrian Density Categories

	Category	Median (ppl/mi^2)	% Contiguous US Land Area	% US Population
Rural	Low	0	95.78	10.5
	Medium	600	2.04	12.4
	High	1,733	0.98	16.1
Urban	Low	4,050	1.15	29.3
	Medium	17,169	0.051	19.2
	High	85,160	0.0017	7.5
Open Air Assembly	Low	1,219,882*	N/A	4.4
	Medium	1,904,935*	N/A	0.7
	High	2,589,990*	N/A	0

*not median, but chosen people density value

[8] UAS Executive Committee – Senior Steering Group (SSG) – Science and Research Panel (SARP) is a cross-agency working group that reviews the research priorities and proposed federal regulations for UAS operations. It consists of officials from FAA, DoD, NASA, and DHS with the authority to commit their agencies to action. The SSG ensures that research activities of mutual interest to both the public and civil UAS communities are appropriately coordinated.

For increased accuracy, the model can also apply a shelter factor to the pedestrian density. A dense urban residential area may officially be listed having 10,000-15,000 people per square mile according to the U.S. Census and within LandScan^{TM} data. However, it may be likely that there are a small percentage of people outside, and a large percentage of people will be sheltered inside of buildings, thus protected from impact [9] [10]. A sUAS does not typically have enough energy or mass to penetrate a typical structure and, as a result, people indoors are not considered at risk [5]. To factor in these variations, the model uses a shelter factor in the calculation of exposed pedestrians at risk.

The data for the mission profile variables are based on commercial sUAS operational demand and subject matter expertise derived values. Table 2 outlines the key attributes of each mission profile. To determine the risk of fatality, the model evaluates the number of unsheltered people located within the actual sUAS mission volume and thus at risk of possible impact by the vehicle.

Table 2. Mission Profile Attributes

Attribute	***Values or measurement units***
Population Density Category	Rural
	Urban
	Open Air Assembly
Operational Region	Length (miles)
	Width (miles)
Pedestrian Behavior	Percent Transiting (i.e., crossing the Mission Area)
	Percent Loitering (i.e., moving within the Mission Area)
	Percent Fixed (e.g., sitting in seats in a stadium)
Beyond Visual Line of Sight (BVLOS)	Yes/No
Flight Duration	≤15 minutes
	16 - 30 minutes
	>30 minutes
Planned Cruise Altitude	Percent time < 100 AGL
	Percent time 101-400 AGL
	Percent time > 400 AGL
Planned Vehicle Trajectory	Percent time Linear flight
	Percent time Grid -preprogramed flight path
	Percent time Hover

B. Vehicle Characteristics

Small UAS vehicle characteristics are a major component of the risk assessment logic. Table 3 outlines the key vehicle attributes that are factored into the model's risk calculations. The sAAT uses these attributes in the computation of the probability of a vehicle striking a person and the kinetic energy of that impact. The sUAS vehicles are grouped in categories, based on size and weight class. These weight classes are derived from research conducted for the SARP [8]. Some of values for the vehicle characteristics have nominal values, which are based on subject matter expertise for attributes such as Average Grid Speed.

Vehicle Striking a Person: The probability of the vehicle failing or malfunctioning during the flight is one of the key probabilities in the risk model. The higher the failure rate, the greater the probability of a third-party person being struck by the vehicle. Vehicle reliability is incorporated into the risk calculations using mean time between failures (MTBF). Utilizing MTBF enables the model to calculate the probability of the vehicle failing and thus the risk of it striking a third party.

MTBF can be derived from many methods, such as analyzing the results of extensive flight testing, or using a component failure model that captures the failure rate of key components (as specific model data is generally proprietary). However, the sAAT model uses a basic MTBF parameter derived from industry-wide operations as a generic value to represent sUAS reliability as a whole [11]. This MTBF parameter can be refined in future versions of the sAAT model for increased accuracy as the sUAS industry shares updated vehicle performance data.

Kinetic Energy at Impact: Kinetic energy at the point of collision is another risk to third-party individual fatalities. Kinetic energy is a function of the vehicle's mass and speed. The speed of the collision is a function of the vehicle design itself, including the velocity, climb/descent angles, coefficient of drag, coefficient of lift, and vehicle dimensions.

Mitigation factors may be included in the overall risk model. These factors include the use of energy-absorbing or frangible materials or parachutes, geo-fencing, software for collision detection and avoidance, and vehicle design and construction materials. These factors can reduce the probability of a vehicle impact to a third party or reduce the force or energy of the impact by reducing the kinetic energy from the vehicle transferred to the individual. Operational mitigations may include operators avoiding highly populated regions or flying at lower altitudes and/or speeds to reduce the risk of a fatal collision. The inclusion of mitigations in the sAAT model will be the subject of future research.

Table 3. sUAS Vehicle Characteristics

Attribute	***Values or measurement units***
Vehicle Type	Fixed Wing
	Multi-rotor
	Hybrid
Vehicle Weight Class (GTOW)	Micro (≤ 0.55 lb.)
	Mini (0.56 lb. ≤ x ≤ 4.4.lb.)
	Limited (4.5 lb. ≤ x ≤ 20.9 lb.)
	Bantam (21 – 55 lb.)
Average Weight	lb.
Average Linear Speed	mph
Average Grid Speed	mph
Wingspan / Vehicle Width	Feet
Maximum Velocity	mph
C2 Range	ft./miles
Endurance	minutes
Mean Time Between Failure	vehicle failures per flight hour
Vehicle Angle of Inclination	degrees from horizontal
Drag Coefficient	0.01 - 1

III. sAAT Risk Model

The risk of fatality due to a sUAS failure is given by Eq. (1):

$$C = P_{\text{fail}} * \rho_{\text{people}} * S * A_{\text{lethal}} * P_{\text{collide}} * P_{\text{fatality}} \quad (1)$$

where C is the number of fatalities per flight hour, P_{fail} is the probability of vehicle failure per flight hour, ρ_{people} is the density of people at risk per square unit area, A_{lethal} is the lethal area of the vehicle on impact, and S is a shelter factor (a dimensionless quantity between zero and one), P_{collide} is the probability the collision was not avoided (a dimensionless quantity), and P_{fatality} is the probability of fatality [21].The sAAT model allows for the input of both the vehicle and mission profile parameters to produce an overall level of the combined risk of the planned operation.

Several assumptions are implied in the sAAT risk model. For instance, as with manned aviation certification, the sAAT logic assumes the vehicle is operated by a trained and proficient pilot who intends to follow regulatory requirements and operate in a safe manner. Another assumption is that there is only one sUAS or one fleet (for network operations) conducting missions in the operational area. Fig. 4 graphically denotes the sUAS failure-to-fatality process. The component probabilities of the sAAT model are listed here and described in the following sub-sections:

- Vehicle Failed to Maintain Flight Control (P_{fail})
- Pedestrians Exposed to Vehicle Flight operations ($\rho_{\text{people}} * S$)
- Vehicle on Collision Course with Pedestrian (A_{lethal})
- Collision Not Avoided (P_{collide})
- Collision Resulted in Fatality (P_{fatality})

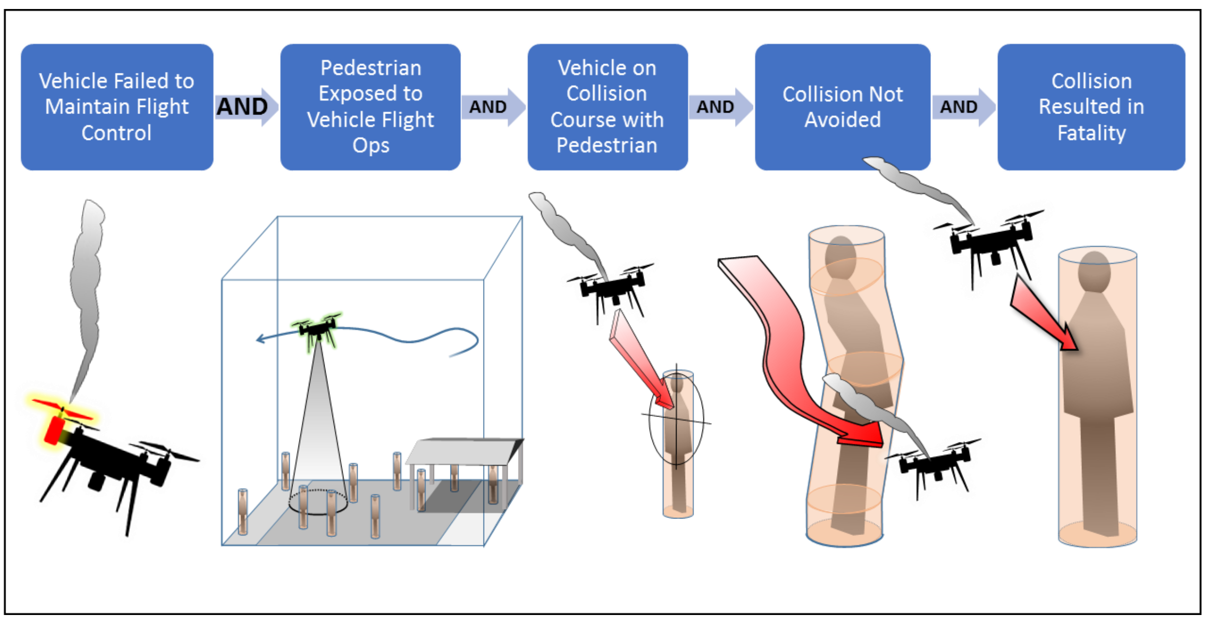

Fig. 4 sAAT Risk Probability Model

A. Vehicle Failed to Maintain Flight Control

The probability of the vehicle failing to maintain flight control (P_{fail}) represents the likelihood it behaves in a manner that was not intended. This may be due to loss of the control link between the ground station and the vehicle, component failure or damage to the vehicle, or loss of flight for other reasons. This probability is primarily dependent on the failure rate expressed as MTBF. In the current version of the sAAT model, the failure rate is used as proxy for P_{fail}. The failure rate of the sUAS vehicle is typically considered proprietary information and known only to the manufacturer. Due to lack of operational data on sUAS failure rates, the sAAT uses a set of nominal values for the failure rates based on equivalent failure rate of common electronics (such as computer disk drives), which is approximately 1E-2 failures per flight hour [12]. Using the assumption that the larger and heavier sUAS vehicles are more reliable and have higher quality components, each weight class was assigned with MTBF values that increase with the weight category. Table 4 shows the assumed mapping of the sAAT nominal failure rates (number of failures per flight hour) to sUAS weight categories.

Table 4. Nominal Vehicle Failure Rates by Weight Class

Weight Category	***Failure Rate Per Flight hour***
Micro (≤ 0.55 lb.)	1E-2
Mini (.56 – 4.4 lb.)	1E-3
Limited (4.5 – 20.9 lb.)	1E-4
Bantam (21-55 lb.)	1E-5

B. Pedestrians Exposed to Vehicle Flight Operations

The probability of a pedestrian being exposed to the sUAS operation (ρ_{people}) is the density of people at risk per square unit area of the operation. For operations that cover areas with different densities of people, the sAAT uses the average of population density by square unit area.

For a given set of geodetic coordinates, the LandScan™ database is queried for points that are either within the operational area or nearest to the operational boundary (refer to Fig. 5). It is possible that a given flight path may traverse a particular block of population density more than once. Because the sAAT model associates the set of population densities with each leg of the flight path, repeated population densities are weighted according to the frequency, or number, of legs that traverse them. In this way, a simple form of weighted time averaging can be used as part of this risk assessment.

For geodetic coordinates that represent a flight path, the LandScan™ database is queried for points that are nearest to each segment, or leg, of the flight path, as indicated in Fig. 6.

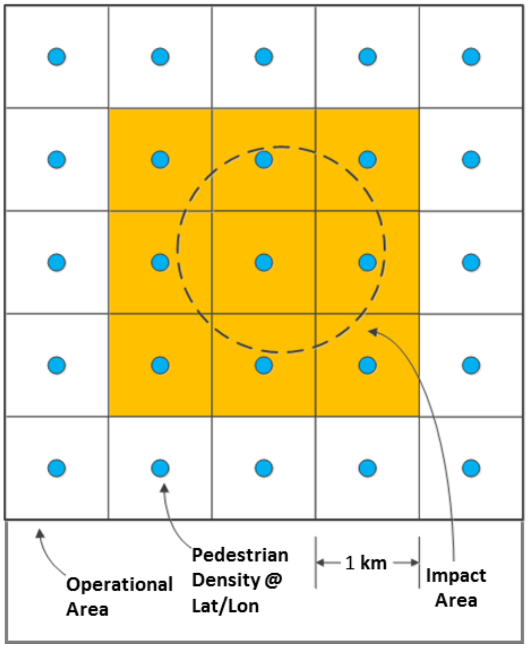

Fig. 3 Pedestrian Density Grid (1 km2), Given Geodesic Coordinates of an Area

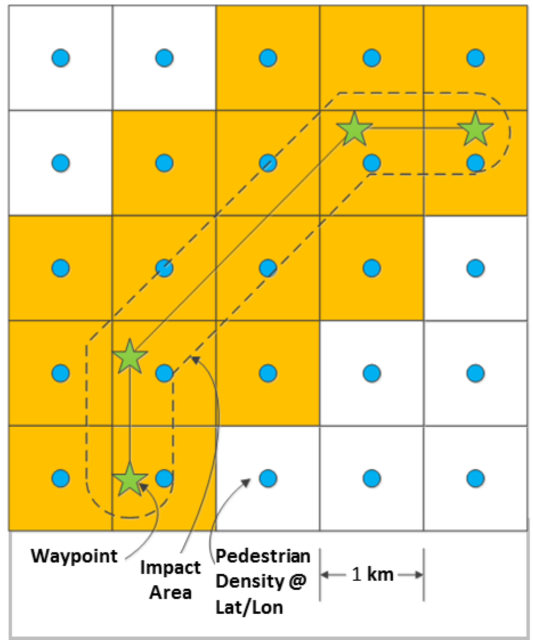

Fig. 4 Pedestrian Density Grid (1km2), Given Geodesic Coordinates of a Flight Path

C. Vehicle on Collision Course with Pedestrian

The probability that the vehicle is on a collision course with a pedestrian estimates the likelihood that a person will be struck by the vehicle. This probability is directly related to the vehicle reliability and the population density of the designated mission area. The impact area (shown by dotted lines in Fig. 5 and 6) is the region on the ground containing the possible vehicle crash location based on the height and speed of the vehicle at the time of failure. Additionally, distinctions are made between fixed-wing vehicles, which may glide when there is a failure, and rotor vehicles, which may drop parabolically when there is a failure.

As depicted in Fig. 7, the lethal impact area (A_{lethal}) is assumed to be a circular projection onto the ground relative to the operational altitude and expected horizontal movement as the vehicle descends or falls. The calculated lethal area is found using Eq. (2) where d_{horz} is the calculated horizontal distance from the point of failure.

$$A_{lethal} = \pi d_{horz}^2 \tag{2}$$

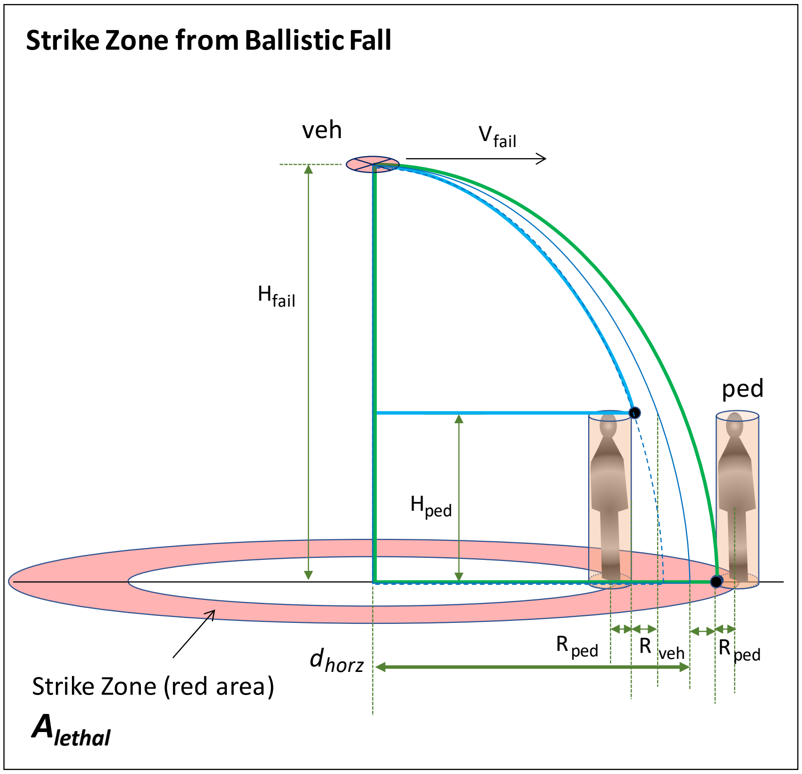

Fig. 5 Computed Strike Zone of a Falling sUAS Vehicle

The next set of equations compute the impact velocity of the vehicle [25]. The determination of the horizontal distance travelled is based on the vehicle type. For fixed-wing type vehicles, the sAAT uses the classic glide equation [23], shown in Eq. (3). The glide equation estimates the constant speed of the vehicle as it glides to the ground, which is the impact velocity (V_{impact}), where m is the mass of the vehicle, g is the gravitational constant, ρ is the density of air at sea level, A is the cross-sectional area, and C_D and C_L are the coefficients of drag and lift, respectively. For fixed-wing vehicles, the drag coefficient is assumed to be 0.5, which is the equivalent of a falling sphere.

$$v_{impact} = \sqrt{(2mg)/\left(\rho A\sqrt{C_D^2 + C_L^2}\right)}\ . \tag{3}$$

The horizontal distance (d_{horz}) is determined by the relationship in Eq. (4), which is the product of the vehicle altitude (h) with the ratio of the lifting force to the drag force.

$$d_{horz} = h\left|\frac{F_L}{F_D}\right| \tag{4}$$

The lift force (F_L), in Eq. 4, is found by the relationship below, where theta (θ) is the angle of inclination of the falling fixed wing vehicle from horizontal.

$$F_L = m\cos(2\theta) \tag{5}$$

Similarly, the drag force (F_D) is found by the relationship

$$F_D = m\sin(2\theta) \tag{6}$$

The sAAT model applies the same equation for hybrid vehicle types (i.e., vehicles that combine the features of a multi-rotor with a fixed-wing platform). For rotor type vehicles, the model uses the standard quadratic drag model for projectile motion, shown in Eq. 7 [21,25]. Equation 7a is the x-component of the acceleration, and Eq. 7b is the y-component of the acceleration of the vehicle at free fall, where dv/dt is vehicle acceleration, dr/dt is the vehicle velocity, and $\|v\|$ is the magnitude of the velocity.

$$\left(\frac{dv}{dt}\right)_x = -\frac{c}{m}\|v\|\left(\frac{dr}{dt}\right)_x \tag{7a}$$

$$\left(\frac{dv}{dt}\right)_y = -g - \frac{c}{m}\|v\|\left(\frac{dr}{dt}\right)_y \tag{7b}$$

where $c = \rho C_D A$

The quadratic drag model is a coupled differential equation that cannot be solved analytically, but can be solved numerically. The horizontal distance (d_{horz}) is a direct result of the numerical solution, and the impact velocity is the magnitude of the final velocity components. The drag coefficient is assumed to be 1.0 for all equations, which is the equivalent of a flat sheet falling straight down.

D. Collision Not Avoided

The current version of the sAAT assumes unity for the Collision-Not-Avoided probability, as little data exists to estimate the impact that various technical mitigations might have, or to quantify the reactions for pedestrians to avoid an emergent collision threat. However, future iterations of the model expect to test the sensitivity of this factor on the overall estimated risk.

Collisions by sUAS with a person on the ground may be avoided through different mitigations. The sUAS may have automatic features that are invoked during a lost link or loss of control situation, such as alert beepers or a pre-defined route to a safe landing area. Similar alarm techniques have proved to be successful for reducing collision risks for commercial ground vehicles, such as back-up alarms on larger vans and trucks [26].

People can avoid potential collisions with sufficient and timely situational awareness of the approaching failed sUAS, which gives them time to get under shelter or physically move away from the vehicle. In addition, there are operational mitigations, which are constraints that prevent the sUAS from operating over certain airspaces, populations, or sensitive locations. Much of the available work in this area focuses on either design of vehicle automation (typically for automobiles) to avoid detected pedestrians [27] or understanding behavioral dynamics of pedestrians to avoid collisions with other pedestrians [28]. For the purposes of the sAAT model, the contributing factors for this probability would be automated vehicle mitigations and operational mitigations.

E. Collision Resulted in Fatality

A collision is an event in which kinetic energy (KE) at impact is transferred from the vehicle to the pedestrian. A percentage of the KE is absorbed by the vehicle, depending on the materials, area, and angle of impact. The residual KE is how much was imparted to the person. Because of the large variety of materials involved, (e.g., skin, muscle, bone, metal, plastic, carbon composites, etc.) and all the possible angles an impact can occur, it is difficult to design definitive mathematical models for the residual KE. The current version of the sAAT computes the probability of fatal impact based on the terminal KE and the impact angle, velocity, and drag equations.

There are many models which look at lethal impact of KE values; however, the most influential of these models are Janser [13] and Feinstein [10]. These models were modified to better reflect the collision threat presented by sUAS by the FAA UAS Center of Excellence [14]. The resultant logistic regression function, shown in Eq. (8), relates the probability of fatality to the KE on impact [22].

$$P_{\text{fatality}} = 1/(1 + \exp(-k(E - E_0))) \tag{8}$$

The shape parameter, k, was derived via regression and presented by both the Range Commander Council (RCC) [15], [16] and by Janser [13]. Within the context of this research, k is typically held constant to maintain agreement with this prior work. However, the E_0 term, which represents the collision impact energy required for the probability of fatality to equal 50 percent can be adjusted within the model. The kinetic energy for E_0 is determined by the classic relationship between the mass and speed of an object, i.e., the vehicle weight and impact speed.

The sAAT fatality curve currently uses the RCC model that relates kinetic energy on impact to the chance of fatal injury, as shown in Fig. 8. The sAAT currently uses the value of 110 Joules (~81 ft.-lbs.) for the E_0 parameter. The shape of this fatality curve is shown as the blue line in Fig. 8, in which we highlight the 50 percent probability mark. According to the RCC, this is the impact energy that yields a 50 percent chance of fatality for an individual whose pose is in a sitting position, the highest risk position for a fatal impact. However, as part of the work performed by FAA's UAS Center of Excellence, Alliance for System Safety of UAS through Research Excellence (ASSURE) [14], has identified a range of studies with varying conclusions of what is considered a fatal level of impact energy. Because of the wide range of possible values of E_0, this parameter is a variable within the model based on the user's input. Fig. 8 shows two values for the E_0 parameter (95 Joules and 110 Joules).

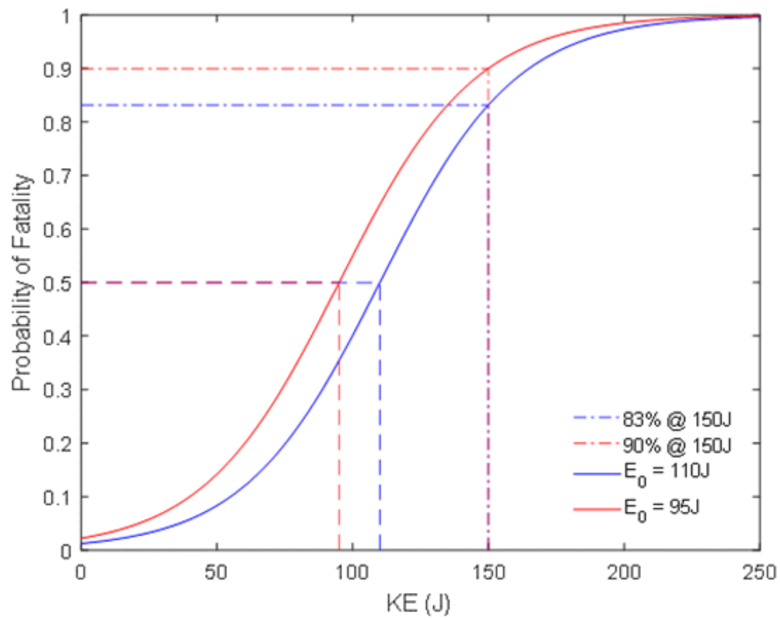

Fig. 6 Shape of Fatality Curve, Given Two Different Values for E_0 Parameter (95 Joules and 110 Joules)

F. Shelter Factor

The shelter factor parameter (*S*) is intended to quantify some percentage of the population that is safely covered by existing shelter. A study of the shelter factor, conducted by The MITRE Corporation [9], applied U.S. Geological Survey coverage maps to estimate shelter factors in populated areas. A previous U.S. Environmental Protection Agency (EPA) study [17] of individual habits found that at any given moment, on average, approximately 7.5 percent of the population is outdoors.

The sAAT model assumes that individuals within buildings are sheltered and therefore not at risk of fatality from a sUAS. A shelter factor (*S*) is a parameter in the risk equation that represents the percentage of people for a given area who are indoors (not exposed). A Shelter Factor of one (1) means that the pedestrians are entirely un-sheltered, while a factor of zero means that the population is entirely sheltered. In the current version of the sAAT model, the shelter factor is a variable based on mission profile, leveraging the EPA study of human activity patterns in the U.S. [17].

IV. sAAT Model Concept of Use

The sAAT model can support the approval processes of the regulator in various ways. The sAAT model provides the user with quantitative results, which can be examined to determine a more realistic measure of the safety of the system. As depicted in Fig. 9, the sAAT model can be used for three different purposes: a) to assess the relative risks of different standard sUAS mission profiles, b) to evaluate the risk associated with waiver applications, and c) to inform performance standards and policy development. The sAAT allows different types of users, such as regulators, safety analysts, and operators, to explore and analyze the risk of various operational scenarios.

- **Assessing relative risk of Standard Mission Profiles:** The sAAT risk model was developed to be an analytical tool for assessing the relative risk of various mission profile and vehicle combinations. The user interface enables the analyst to look at combinations of vehicles and mission profiles to find the combination that is within an acceptable level. The sAAT model constants, as well as parameters for the standard mission profiles and vehicle profiles, are configurable items to enable “what-if” types of studies. For each run, the analyst can modify any of the default parameters for the standard operational mission and generic vehicle type.

- **Evaluating risk associated with waiver applications**: Proposed commercial sUAS missions often require a waiver application to allow for currently prohibited missions. The model can support the evaluation of these applications. Both the applicant and the regulator (e.g., the FAA) can use the sAAT model to assess the risk of a proposed operation, based on the actual vehicle characteristics and location of the mission. The user enters either a flight path or a geospatially referenced shape of the area (such as a circle or rectangle). The sAAT uses this information to retrieve the specific population densities for the geographic area of interest. The user enters specific vehicle and operational information, and the sAAT computes the overall level of risk. The assessment may be used as part of a Safety Management System approach with various levels of risk acceptability based on the combination of mission profile and vehicle type. Fig. 10 depicts a rubric that can be used for evaluating waivers. As the risk of the sUAS operation increases, the higher the approval requirements (i.e., the more operational approval rigor) is needed. Lower risk operations that fall in the safe category can be approved easily, whereas the higher risk operations need more information and safety analysis.

- **Informing sUAS performance standards and policy**: With its quantitative analytical capabilities, the model can provide data to determine operational thresholds, certification requirements, and acceptable levels of safety. For instance, it may be possible to identify when increased failure rates still achieve target safety levels, such as in low pedestrian density regions. The model can also be used to refine mission profile parameters and pin-point vehicle certification requirements as sUAS operational data becomes available. This model can provide decision support for the development of policies, procedures, and regulations.

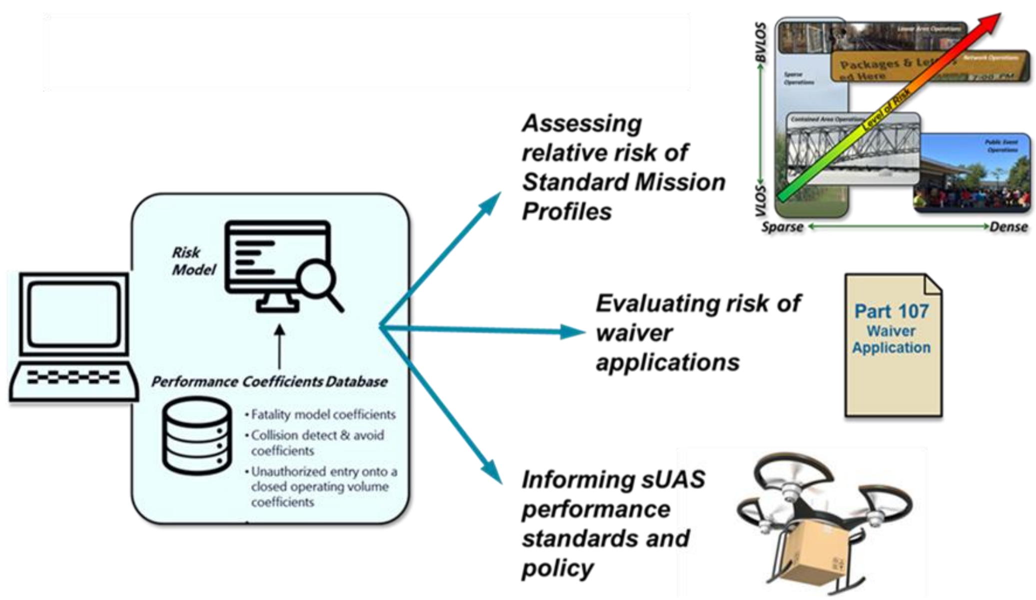

Fig. 7 sAAT Model Has Multiple Purposes

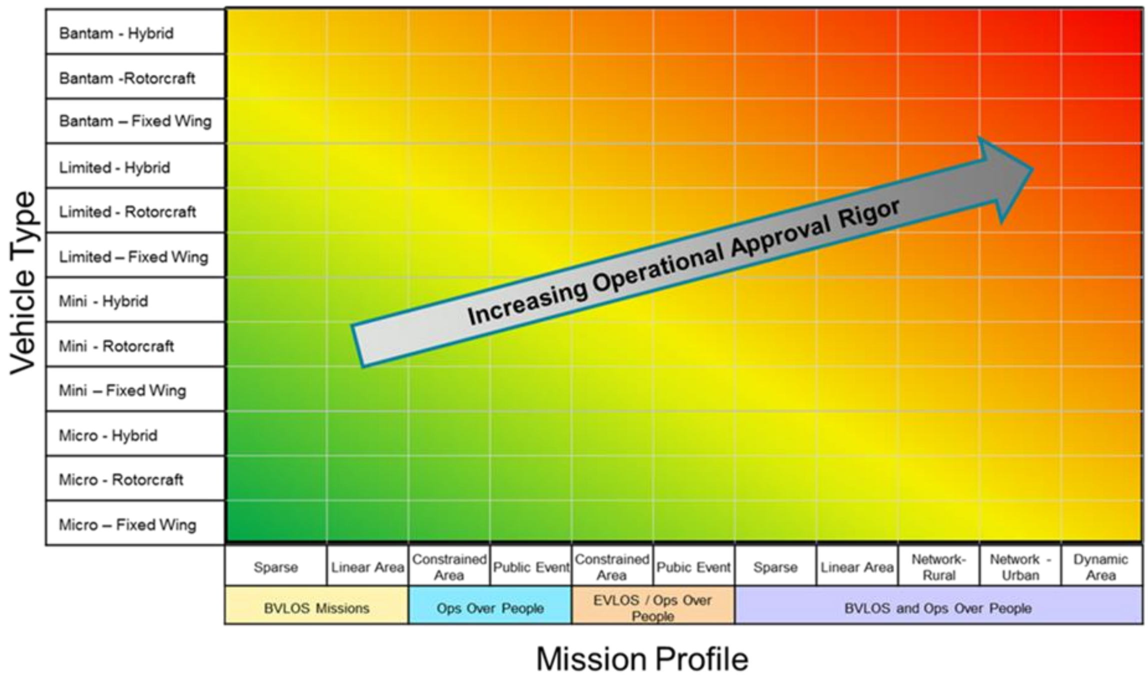

Fig. 8 Notional Operational Application Approval Methodology

A. sAAT Model Inputs

The model includes a user interface that will allow the end user to select standard mission profiles, vehicle characteristics, and computational variables, such as the level of energy determined to be fatal, for the risk analysis calculations. The basic input to the sAAT are the parameters defining the mission area and the vehicle characteristics. These parameters are captured either in the form of general-purpose mission profiles or as mission-specific values defined by the user. The required vehicle information includes gross-takeoff-weight (GTOW), cross-sectional area of the vehicle, maximum speed, and maximum operating altitude. Additionally, the user enters the vehicle type as either multirotor (e.g., a quadcopter), hybrid, or fixed-wing. Operational information includes the expected operating speed and altitude. The sAAT uses global maximum speed and altitude values if not otherwise specified as an input

The required information for the designated mission area includes the size, shape, geographic location, and associated population densities for the region of operation. The region of operation is a set of geodetic latitude and longitude points provided by the user that define either the boundary of operation or the path of operation. Boundaries of operation can be a user-defined circle, rectangle, or non-self-intersecting polygon. Paths of operation are a series of user-defined waypoints consisting of at least two points.

B. sAAT Model Outputs

The sAAT model presents three outputs: 1) Probability of Fatality (PoF) per flight hour to a third-party, 2) degree of risk, and 3) the sensitivity analysis of risk factors. In combination, these three outputs can aid the analyst in determining if the risk assessment meets the acceptable safety levels. Additionally, the sAAT model provides the user with outputs that identify the probability of an impact to a third party and the probability of the impact being fatal. The sensitivity analysis identifies the variables that had the most significant impact on driving the level of risk.

As illustrated in Fig. 11 the output graph relates the PoF (%) to the estimated impact KE (joules). The dark line that indicates 50 percent probability represents the upper threshold of acceptable risk. In this example, the PoF is 91.2 percent and estimated KE at impact of 165.5 Joules. The graph indicates, in this notional example, that the computed risk level is above the 50 percent threshold and is higher than the acceptable levels.

Fig. 12 depicts the Risk Meter, which shows the estimated level of risk against the spectrum of acceptable levels of risk. Estimated risk on the green area of the meter would represent low risk. A risk level in the yellow/orange may be acceptable with some operational constraints or mitigations. Risks indicated in the red area are unacceptable in the current configuration.

The model identifies the parameters that have the highest sensitivity in driving the overall level of risk. This allows for the near-real-time assessment of risk and helps support the determination of the acceptable risk level of sUAS operations. The Sensitivity Analysis output, as shown in Fig. 13, indicates which factors contribute the most to the risk. The risk factors and their associated rankings vary depending on the input data of the proposed sUAS operation. Factors are listed in rank order. Positive values on the right side of the y-axis contribute to higher risk. Negative values, measured towards the left of the y-axis, contribute to reducing the risk. In this example, the risk can be reduced the most by reducing the greatest contributors: population density and the weight of the vehicle.

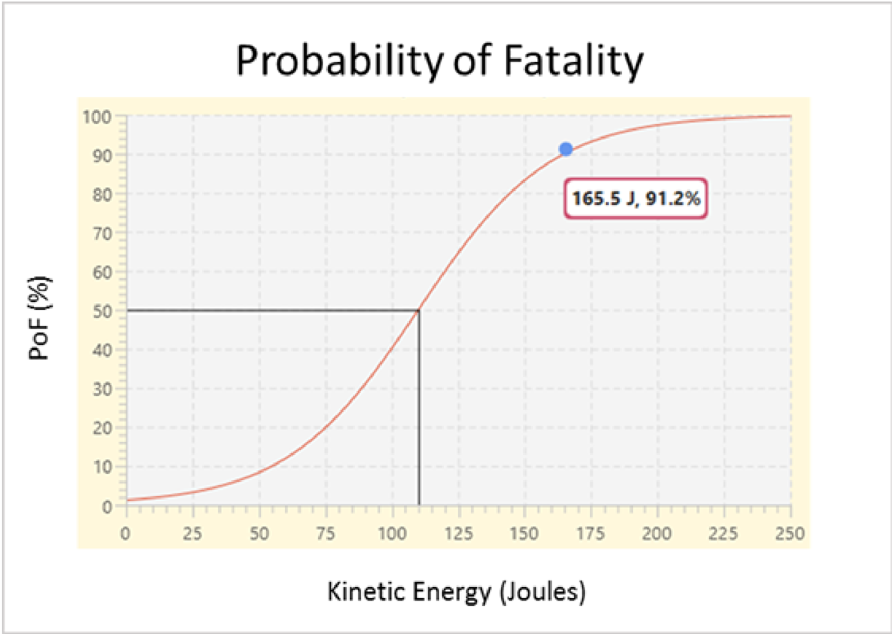

Fig. 9 Probability Curve with 50% Chance of Impact, Given 110 Joules

Fig. 10 sAAT Degree of Risk Relative to Desired Level of Safety

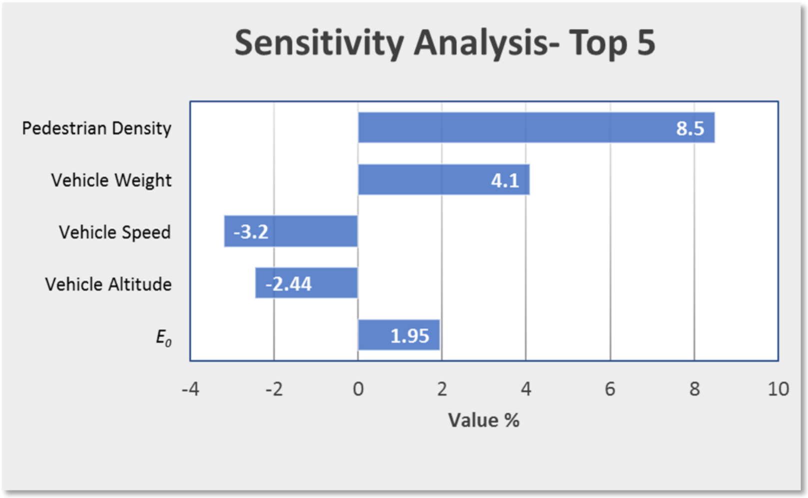

Fig. 11 sAAT Sensitivity Analysis Output

VI. Conclusion

The sUAS Airworthiness Assessment Tool (sAAT) was developed to help the FAA conduct its airworthiness safety risk analysis. The purpose of this research is to provide a quantitative risk assessment model that the FAA can use in the near term to meet today's needs, and use to prepare for the future. The sAAT provides quantifiable results, which can be examined to determine the actual safety of the system. This model combines the characteristics of both the sUAS vehicle and its proposed mission to assess risk.

Working with the FAA, the research team is developing a proof of concept for using the sAAT risk model to streamline the sUAS waiver approval process. Additionally, both the FAA and industry can potentially use the sAAT risk model for the engineering, design, certification and safety evaluation of dissimilar sUAS vehicles, including fixed wing, multirotor, and hybrid vehicles. The sAAT risk model is flexible enough to be used by both operators and the FAA as part of an operational risk assessment for the approval of sUAS implementation activities. The model allows for the efficient review and approval of operations while maintaining the desired target level of safety. The regulator can also use the sAAT model as a decision support tool for developing policy regulations, such as certification requirements, operational thresholds, and acceptable levels of safety.

Using a risk-based approach, the FAA can categorize the applications based on the type of mission, vehicle, and operation, allowing the FAA to focus on those waivers with the highest risk. The model can be used to identify risk mitigations and reasonable operational constraints, which will result in fewer restrictions and a reduced number of FAA required approvals.

Going forward, the research team will enhance the sAAT risk model to account for advances in technology, analysis of the ground and airborne collision severity, and technical risk mitigation capabilities. A phased approach is envisioned for the future development of the sAAT risk model. In the near term, the research will focus on refining the categorization of mission types based on actual operational data and incident statistics. The risk model will also be expanded by integrating air-to-air collision risk probability analysis. In addition, the research team will continue to consider how to improve parameters for sheltering, risk mitigations, vehicle reliability, and energy of fatality coefficients. As the complexity and accuracy of the risk model increases, more comprehensive assessments of sUAS risk can be conducted. It is expected that the model will serve both operators and regulators in establishing the guidelines for safe sUAS integration into the NAS.

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