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A third-party casualty risk model for unmanned aircraft system operations

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ABSTRACT

Unmanned Aircraft System (UAS) integration into the National Airspace System (NAS) is an important goal of many members of the Aerospace community including stakeholders such as the military, law enforcement and potential civil users of UAS. However, integration efforts have remained relatively limited due to safety concerns. Due to the nature of UAS, safety predictions must look beyond the system itself and take the operating environment into account. A framework that can link UAS reliability and physical characteristics to the effects on the bystander population is required. This study proposes using a Target Level of Safety approach and an event tree format, populated with data from existing studies that share characteristics of UAS crashes to enable casualty prediction for UAS operations.

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1. Introduction

The integration of Unmanned Aircraft Systems (UAS) into the National Airspace System (NAS) is extremely relevant to the Aerospace community for several reasons. First, the military is, and will become increasingly more reliant on unmanned aircraft in their fleets. Second, domestic government agencies have many potential uses for UAS in areas such as law enforcement, border security, and disaster relief support that remain largely underutilized. Third, the civil use of unmanned systems is an untapped market that could create an entire industry if the entrepreneurial spirit of the nation's citizens is released. This market is virtually nonexistent now and thus has the greatest room for growth.

Currently, there is a growing demand among potential UAS users to allow complete integration of unmanned aircraft into the NAS. Answering the call for integration from stakeholders, lawmakers made integration efforts mandatory. On February 14, 2012 President Obama signed a bill into law called the FAA Modernization and Reform Act. While the law covered several topics, the legislation specifically made UAS integration efforts mandatory. Yet the reality of UAS integration remains starkly different.

Despite the potential benefits of expanded access to the NAS, the use of UAS in the United States has remained largely limited to military operations in restricted areas and some public use for law enforcement or research. However, this usage occurs via a fairly restrictive Certificate of Waiver or Authorization (COA) process in accordance with FAA Order 8130.34B and the 2008 interim operational guidance for UAS [1,2]. Private or commercial use remains unauthorized.

A review of the literature related to UAS integration reveals safety as one of the primary concerns impeding progress on integration. More recently, privacy has become another major concern affecting the path of UAS integration. However, the issue of privacy is outside the scope of this article which will focus on a method to link safety to UAS failure rates and the operating environment of UAS.

To address the issue of safety, with respect to UAS integration, two underlying questions should be addressed first. First, what is the quantifiable definition of 'safe enough' for UAS operations and second, how does the industry measure or predict UAS safety levels. There is still no agreed upon method to fully understand the risks that UAS operations pose to the public that links UAS failure rates to potential third party casualty rates that also properly captures the operating environment in the analysis. Because UAS currently do not put people onboard the vehicle at risk, the safety concerns regarding their operation must focus on third-party bystanders on the ground and second-party airspace users. There have been several other studies on how to predict UAS safety levels in the past, which will be discussed in more detail in Section 2.0. However, as this paper will point out, previous studies lacked sufficient detail on the operating

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environment of the UAS and did not demonstrate a means to validate the prediction methods.

The purpose of this article is to demonstrate a framework for predicting UAS safety levels with respect to bystanders on the ground that is based on system failure rates and the environment that UAS operate in. The framework leverages existing data and information on manned and unmanned aircraft to develop a casualty prediction capability that can be validated. While this article discusses the use of the framework for third party casualty prediction, the framework was also used to predict casualty levels due to midair collisions with other airspace users as well as the risk associated when UAS lose link with an operator. This article solely focuses on casualties to third-party individuals due to UAS system failures.

The framework used for this study consists of a Target Level of Safety (TLS) approach to UAS regulations and certification coupled with an Event Tree (ET) format model to predict UAS safety. There are multiple arguments for the Target Level of Safety concept in the literature surrounding UAS integration. In fact, the national level Research and Development plan signed by the President of the United States indirectly mentions the approach in their near term goals for UAS integration. In that document, the goal for UAS is to “Define the appropriate target level of safety and the process for evaluation” [3].

The eventual goal of such a framework is to use acceptable safety levels to drive required maximum system failure rates for UAS to help develop certification standards. While a similar approach is used for manned aircraft certification, the main difference between the use of this approach for manned and unmanned aircraft is that the consequences of manned aircraft are largely confined to the crew and passengers aboard the aircraft. For unmanned aircraft, safety levels are a function of the environment they operate in and therefore, a method to help predict the safety implications of UAS failures in different ground environments is required to implement such an approach.

While this article focuses on U.S. domestic policy, the framework can be put to use to help shape UAS policy in any country. In fact, The Europeans, who are arguably ahead of the United States on the topic of UAS integration, also proposed using a TLS approach to analyzing this problem. A key component in the European's approach is that the safety target allows for a combination of design and operational requirements to achieve a target and that this approach eliminates the requirements to comply with a lengthy set of standards [4].

One of the more favorable endorsements of TLS is the report of the FAA sponsored Sense and Avoid (SAA) workshop. This workshop, which was only focused on the SAA issue and not all aspects of integration and safety, did recommend that the Target Level of Safety approach was the best option for establishing standards to comply with or meet the intent of 14 CFR Part 91.113 or ‘see and avoid’ [5]. Overall, the workshop focused on several reasons why TLS was the best choice. First, it is quantifiable so it would be less open to interpretation. Second, the TLS approach would help in the process of allocating failures to both equipment and procedures. Finally, the TLS approach provides for a comprehensive analysis of the system and the environment [5].

Interestingly, the FAA already employs a type of TLS process in the area of launch vehicles. The regulations on Reusable Launch Vehicles (RLVs) requires that an applicant demonstrate that the launch of any vehicle not pose a risk greater than a specific value [6,7]. This approach makes sense for RLVs because, in many cases, these designs may be unique or at least of such a low rate of production that certifying them using an approach similar to manned aircraft would be infeasible.

Haddon and Whittaker define the ‘Safety Target’ approach as a “top-down approach which focuses on safety critical issues which could affect achievement of the safety target” [8]. The advantages they cite to such an approach are the fact that the user can focus on important risks and do not have to comply with “a comprehensive code of requirements covering all aspects of the design” [8].

The National Airspace System is an exceedingly complex system and any attempt to model all aspect of this system would require a massive effort. However, several sources on this subject recommend the use of an ET model format in order to predict the casualties caused by UAS in the NAS and their interaction with the environment. Event trees are established tools that can be used to determine the probability and impact of specified failure events. They were originally detailed in a 1975 report by the Nuclear Regulatory Commission [9] but later used in many other applications. A more detailed discussion on Event Trees appears in Section 3.5.

It is important to note that the framework in this paper does not propose new methods for reliability, risk or safety analysis. The TLS approach and ET formats are well documented. However, what has been lacking to date is the incorporation of reliable data and information, using the TLS approach and ET formats, into a comprehensive framework. This is primarily because it is difficult to test and predict the results of UAS accidents and the fact that the scope of the potential casualties throughout the NAS is vast. This is similar to the problem addressed by Jonkman in attempting to predict the casualties caused by a natural disaster such as flooding [10] Similar to Jonkman's approach to flooding, this article demonstrates the use of a synthesis of available information from related, reliable sources to populate a framework that can enable UAS stakeholders to move forward and answer the as yet unaddressed questions of UAS safety.

2. Background: understanding the risk to bystanders due to UAS operations

This paper recasts stakeholder safety concerns in terms of the following questions:

1. How do we define and measure UAS safety?
2. Would UAS meet that level of safety if integrated at current failure rate levels?
3. What are the maximum system failure rates allowable for UAS to meet the defined safety levels?

Overall, a method to predict casualties caused by UAS operations is required. While there are other metrics that could be used to assess UAS integration such as the economic impact of UAS failures, or injuries, the fatality rate was chosen as the metric for this research for several reasons. One, it is generally considered the most important aspect of safety and therefore should be considered before any other metrics are used [10]. Second, data and information to predict fatalities was difficult enough to obtain. The requirements to determine economic risk would be even more difficult to obtain and more open to interpretation and were therefore beyond the scope of this effort. More importantly, using the fatality per hour metric aligned this research with several other safety methods to include the aforementioned Range Commander's Council and Nuclear Regulatory Commission. Finally, the primary concern of the FAA is public safety, not necessarily property damage or economic impact. Therefore, fatalities were selected as the metric of choice.

To estimate the actual safety levels of UAS operating in a fully integrated manner, several studies have tried to predict the bystander casualty rate due to UAS operations. Among them are efforts by Dalamagkidis [11], Weibel and Hansman [12], Waggoner [13], Clothier [14], Burke [15], and Evans [16]. Each attempted to predict and quantify the fatalities caused by UAS failures over various population densities by making assumptions about the nature of the ground environment. Although each used slightly different methods, there were several common themes.

A casualty estimation technique, based on an equation similar to Eq. (1), appeared in Burke's work [15] and the Range Commander's Council handbook on UAS risk [17]. In this equation, the value for E_c is a measure of the risk posed to third-party persons, or estimated casualty rate. The units for this metric are fatalities per flight hour (FH) or some interval of flight hours. The variable λ_{System} is the failure rate of the system for those failures that would cause an inability to maintain coordinated flight. It is important to note that the purpose of this article was not to predict failure rates for UAS since that would involve analysis of a particular system. The eventual goal, which will be discussed in more detail in Section 5.0, is to use the framework in this article to determine maximum allowable system failure rates to meet a proposed TLS, based on the characteristics of both the air vehicle and operating environment. All of the other terms account for the terminal effects an unmanned air vehicle would have on the public in the operating environment.

$$E_c = \lambda_{\text{system}} \times \rho_{\text{Population}} \times P(\text{Fatality}|\text{Impact}) \times A_{\text{Impact}} \times \text{SF} \qquad (1)$$

The remaining items below capture characteristics of the exposed population to yield a casualty figure related to the system failure rate. In other words:

1. How many people are in that area that could be affected ($\rho_{\text{Population}}$)?
2. What protection does shelter offer the people inside (SF)?
3. How large is the area affected by the air vehicle impact (A_{impact})?
4. Of the people affected, how many people are fatalities ($P(\text{Fatality}|\text{Impact})$)?

In Table 1 is a summary of all of the major studies and how they each account for the major parameters in Eq. (1). The right hand column shows the ways in which the study discussed in this paper estimated the parameters in order to create the capability to predict ground casualties caused by UAS operations. This effort demonstrated that moving beyond the basic equation outlined above and adding layers of realistic input to an event tree format made the model more accurate in predicting casualties and also capable of incorporating risk mitigation measures and strategies into the model to aid in decision-making.

All of the previous studies on this topic assumed that the population was uniformly distributed on the ground when accounting for the population density variable. To determine A_{impact}, or lethal area, the aforementioned studies used either physical dimensions of the air vehicle or used the dimensions of the vehicle in combination with the geometry of a gliding aircraft to determine a ‘swept area’. There was some discussion of the probability of lethality in the studies, but for the most part, the assumption was that everyone in the impact or swept area was a fatality, assuming that the vehicle had sufficient energy to cause a fatality in the first place. That topic will be discussed in more detail later. Finally, there is not definitive agreement on how to account for the shelter factor (SF) with some studies applying an assumption based on the air vehicle weight.

3. Modeling the effects caused by UAS ground impact

As mentioned previously, the authors implemented a model that used an Event Tree format to predict casualties on the ground caused by UAS operations. Doing so allowed for an expanded capability to more accurately portray the effects of UAS failures and to implement risk mitigation measures into the model, beyond what was possible simply by using Eq. (1) discussed earlier. For each of the main elements of the ground risk model, a discussion of the data used to populate the model follows.

3.1. *Population*

To account for population density, all previous studies used a uniform density value. Burke [15] also added a feature that used an average value for population density based on the percentage of time a UAS mission spent over various density categories. While a uniform population density is simpler to determine, it does not accurately reflect the way in which people actually spend their lives. Assuming that people are distributed uniformly throughout an area does not accurately reflect the amount of people under shelter compared to people in the open. A more accurate representation of the population density takes into account whether people are in the open, in their homes, in a car, or in some type of commercial building.

A two year study conducted from 1992 to 1994 on behalf of the U.S. Environmental Protection Agency tracked the behavior of people in a variety of settings on a daily basis. The purpose at the time of the study was to determine people's exposure to outdoor pollutants. However, the National Human Activity Pattern Survey or NHAPS resulted in a tremendous amount of data on how people spend their day in the United States. While the study was rich in information that covered human activity down to an hourly basis, a summary of the most pertinent data to this effort appears below in Table 2.

What it tells us is the percentage of time that people spend in the various locations below. The importance of this data can be demonstrated by looking at one category. In terms of land coverage, open space is by far the largest portion land mass in the United States. While this value diminishes in urban areas it is still a

Table 1
Ground risk parameter comparison.

Model parameter	Clothier [10]	Evans[a] [16]	Waggoner [13]	Burke [15]	Dalamagkidis [11]	Weibel [12]	Current Study
Population	Uniform	Uniform	Uniform	Uniform, time-weighted average	Uniform	Uniform	Distributed
Shelter effects	N/A	N/A	N/A	Linked to pop. density variable	Incorporated into casualty calculation	Estimate based on vehicle class	Energy-based (kinetic and chemical)
Impact area	Geometry-based (steep and gliding)	Weight-based (non-linear)	Geometry-based (gliding)	Geometry-based (swept area)	Geometry-based	Geometry based (planform area)	Weight-based (linear)
Casualties	All	30% in impact area	Left to user to determine	All above 49 ft-lbs of KE	Based on log curve from RCC	All, if pen. occurred	All in open areas, 30% inside shelter if penetrated
Validated	No	No	No	No	No	No	Yes, using GA and air carrier historical data

[a] Not originally intended for UAS.

Table 2
Population behavior pattern data.

Information	Percentage	Source
Time spent in Residence	68.7	National Human Activity Pattern Survey [18]
Time spent Outdoors	7.6	
Time spent in Vehicle	5.5	
Time spent in Office/Factory	5.4	
Time spent Indoors (other)	12.8	

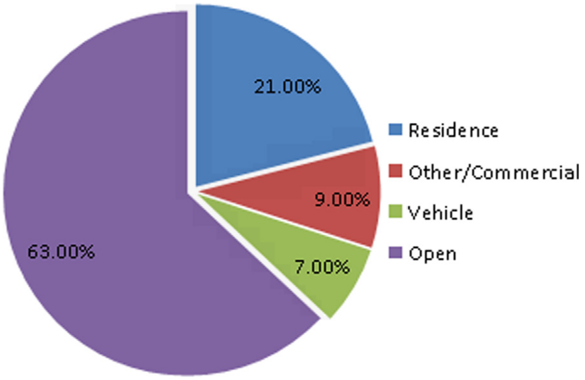

Fig. 1. Breakdown of ground area based on usage.

larger portion of land mass. However, people only spend on average 7.6% of their time outdoors. Thus the population density outdoors or in an unsheltered condition must be significantly lower than the average population density of an area.

To determine the population density in each category of the event tree, Eq. (2) was used. The local population density refers to the actual density in the open, in buildings, or in vehicles. If one uses open areas as an example, it is based on the overall population density of the area in question times the percentage of time people spend in the open divided by the percentage of land in a given covered by open space. Using Eq. (2) over a given area such as a town, the overall population would not be distributed uniformly but would be distributed more densely in some categories such as in Residences and less densely in Outdoors spaces.

$$\text{Pop Density}_{\text{local}} = \text{Pop Density}_{\text{overall}} \times \frac{\text{Time Spent Ratio}}{\text{Area Coverage Ratio}} \qquad (2)$$

To demonstrate the impact this method has on the local or specific population density for each shelter category, an example is offered. Fig. 1 shows a typical breakdown for a given area into major categories. Using the data from the NHAPS study in Table 2 for the amount of time spent in each major category and a nominal overall population density of 500 people per square mile, the localized population breakdown for each category appears in Fig. 2.

To demonstrate the importance of considering behavior patterns and shelter together, a hypothetical collision was estimated using the overall population density above of 500 people per square mile. The impact area of the crash was assumed to be 1000 ft^2. Three values for the number of expected casualties from this one impact were generated. The first value assumed a uniform population distribution. The second value allocated the impact area into portions based on the percentage of land coverage for each category from Fig. 1. The third value used the same approach as method two, but added a shelter factor that made it 90% likely that people in a residence would be fatalities and 50% likely that people in a commercial building would be casualties. These values are theoretical at this point, and are simply to illustrate a point.

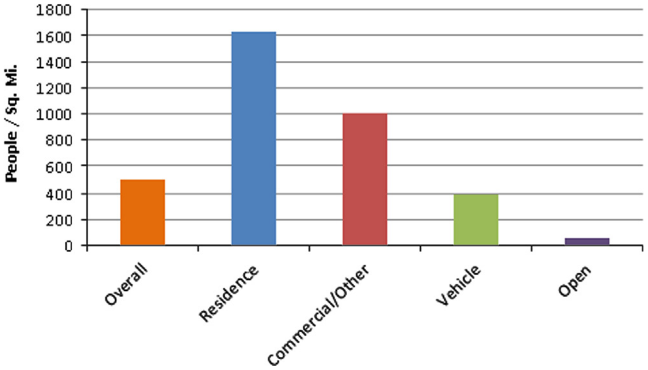

Fig. 2. Example population density breakdown by category.

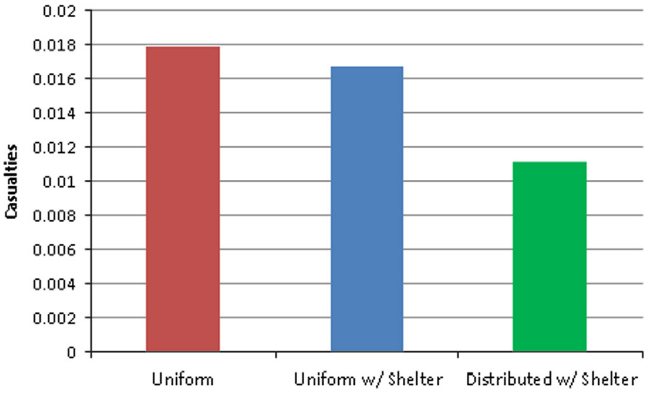

Fig. 3. Population distribution sample casualty comparison.

The results of the experiment appear in Fig. 3. When the uniform population distribution and no shelter is considered, the casualty rate is highest, as expected. Continuing with a uniform population distribution and using shelter factors, the casualty rates decrease by approximately 6.6%. However, when a logical approach to shelter factors is provided to the distributed case, the casualties are reduced by 37.7%, compared to the original case because a larger percentage of people are under some form of shelter. This fact plays an important role in predicting casualties in the ground risk model because to ignore the actual behavior patterns of people would cause casualty predictions to be too high, therefore restricting UAS operations unnecessarily.

3.2. *Shelter effects*

A key shortcoming of several previous ground risk studies was the lack of shelter inherent in the model, or an assumption about the ability of air vehicles to penetrate and cause casualties in a building. The exact composition and materials used in buildings throughout the country is a very complex situation that cannot be assessed in complete detail in a study of this manner. However, a very comprehensive study conducted by the Columbia Accident Investigation Board (CAIB), conducted in the wake of the Columbia tragedy that quantitatively assessed the risk to people on the ground based on debris falling from another shuttle reentry was useful to this framework.

The study used extensive GIS data for a large swath of land in the Texas and Louisiana area to determine ground usage, building types, roof construction and population patterns. Based on this information, the authors were able to group building types into one of two broad categories: Residential or Commercial, and assign a shelter value to each one. The Residential structures, comprising roughly 20% of all buildings have roofs made of wood or similar materials. Commercial buildings, on the other hand are made of concrete or steel. The material choice was critical to determine the ability to shelter occupants from an air vehicle crash.

A summary of the types of materials found in most buildings in the representative sample from the Columbia study can be found in Table 3. The majority of structures were wooden, with steel or light metal, and concrete making up the next two categories. The remainder was tile or other categories that would have the same properties of wood typically. These values were used to help determine the shelter breakdown in the ground risk model.

To determine whether an air vehicle was capable of penetrating various building materials, another study on shelter was used to determine the amount of energy different roof types could absorb. The study was conducted by the Department of Defense to determine the amount of shelter required to protect people from explosives. The pertinent data from the study appears in Table 4. To simplify calculations, the model characterized residential buildings as being made of materials between panelized wood and lightweight concrete (600–2000 ft-lbf absorption). This range takes into account both urban and suburban wooden residential structures as well as more urban high-rise and apartment-style residential buildings. Commercial buildings were modeled as 4″ Reinforced Concrete (RC). These values were seen as reasonable representations of the broad class of building materials used while also being conservative in nature. Vehicles were characterized as automobile steel for their absorption values.

Table 3
Roof material breakdown.

Information	Percentage	Source
Wood	58.4	NASA Columbia report [19]
Steel/light metal	4.9	
Concrete	9.2	

Table 4
Roof material absorption data.

Information	Ft-lbf	Source
14″ Reinforced concrete	200,000	DoD explosives study [20]
4″ Reinforced concrete	10,000	
2″ Lightweight concrete	2000	
Medium steel (18 gauge)	1000	
Wood panelized	600	
Light metal (22 gauge)	500	
Plywood and wood joist	300	
Gypsum/fiberboard/steel joist	200	
Steel (Automobile)	200	

To determine whether the air vehicle actually penetrates a structure or not, one needs to know the energy the vehicle possesses. The amount of kinetic energy was based simply on the mass of the air vehicle and a value of 1.4 times the maximum speed of the vehicle. This metric was proposed by Dalamagkidis in a paper on ground risk for UAS [21]. While it is certainly likely that a falling air vehicle could encounter the ground with less velocity than this, the value was chosen as a way to conservatively estimate the terminal velocity of a falling air vehicle without having to calculate the actual drag on the vehicle.

To illustrate the effect that using kinetic energy and shelter values based on material properties has on the analysis, an example is used. A four pound vehicle traveling at 60 knots would have approximately 640 ft-lbf of kinetic energy on impact. Assuming that all of that energy is transferred to the structure in question means that this relatively small vehicle would penetrate all of the roof materials in Table 4 up to and including wooden roofs. Based on the information from Table 3, wooden roofs account for almost 60% of the structures in the country. However, the Weibel report estimates that a nine pound air vehicle, having over twice the mass as the example, would only penetrate 10% of structures [12]. Clearly this is a discrepancy. Without any corroborating data to support the estimates proposed by other studies, the results based on DoD and NASA analysis offer the most credibility at this time.

3.3. *Impact area*

Perhaps one of the most critical, yet widely varying parameter in the ground risk model is the risk exposure area caused by a UAS impacting the ground. This parameter is important because, when used in conjunction with the population density parameter previously discussed, it determines the number of people exposed to risk on the ground in the event of an air vehicle impact.

While there are several different methods that have been proposed to estimate the exposure area, they fall into a few distinct categories. The first distinction is between hypothetical and empirical prediction methods. In the former, several studies have tried to predict what the impact profile of a UAS would be, typically based on the physical dimensions of the UAS. In the second category, several studies have used information from aircraft crashes in an attempt to determine a way to predict the impact area. These methods can be further broken down into weight-based, size-based, and aircraft category-based prediction techniques. A summary of the major techniques used appears below. Table 5.

Table 5
Comparison of impact area prediction methods.

Information	Equation	Source
Planform area	N/A	Weibel ICAT report [12]
Gliding area	$(W_{\text{span}}+2\times R_p)\times(L+D_{\text{glide}}+2\times R_p)$ $D_{\text{glide}}=H_p/\tan(\gamma)$	Clothier paper and lum paper [14] [18,19]
Steep area	$\pi\times(0.5\times W_{\text{span}}\times R_p)^2$	
Skid area	0.06 Mile Skid for GA Aircraft 0.3 miles for air carrier	Solomon paper [22]
Combination of skid and overflight	Based on wingpspans and mean skid distances	DoE standard [23]
Debris area in built up areas	1.0764 ft^2/lb MTOW	Ale and Piers [24]
Debris area in open areas	1.3455 ft^2/lb MTOW	
Impact area	0.25 ha per 100 t MTOW	Eddowes study [16]
Debris area	$\log(\text{area})=-8.53+0.80\times\log e$ (MTOW) Area (hectares), MTOW (kg)	NATS study [16]
Small aircraft steep impact	1.3 ha	RAND study [25]
Large aircraft steep impact	3.89–5.18 ha	
Small aircraft shallow impact	2.59–3.89 ha	
Large aircraft shallow impact	5.18–6.48 ha	
Other aircraft	0.12–0.92 ha (depending on type of fire effects)	ACARRE study [16]
Scheduled aircraft	0.95–19.95 ha (depending on type of fire effects)	

R_p=Radius of person, H_p=Height of personal, L=Acft length, γ=Glide angle.

In the geometric methods, the dimensions of the air vehicle are used. The planform method is self-explanatory. In addition to that method, the authors examined another method called the flat area method which simply uses the wingspan and length of the vehicle and assumes that the impact area is a rectangle based on those dimensions.

The gliding methods assume that the vehicle is gliding at some angle, typically based on lift to drag assumptions. The impact area consists of a rectangle as wide as the wing span of the vehicle and as long as the descent from the top of a person to the point of impact. In the steep geometric assumption, a circular shaped based on the vehicle wingspan is used which assumes a vertical descent. In addition, a hybrid model was explored that used an impact area value that was halfway between the steep impact area and gliding impact area calculations. Skid area calculations are similar but also use empirical or hypothetical data to account for the aircraft skid after impact. Both the gliding and skid area methods assume that the vehicle does not strike anything that impedes forward progress.

In the empirical category, one study analyzed the impact areas of several aircraft in an attempt to quantify third party risk near an airport in the Netherlands. Using information from actual crash sites, the authors, Ale and Piers developed a linear relationship between aircraft maximum takeoff weight and crash size [24]. It is important to note that this data was based on larger aircraft than would be expected of the air vehicles used as UAS. However, the fact that the impact areas are based on larger aircraft would actually tend to make the estimate more conservative when used for UAS but also take into account the reality that a crash could impact a larger physical area than simply the dimensions of the air vehicle itself. This method takes into account the fact that the air vehicle can explode or at least fragment causing casualties over a larger area. The values from this study appear in Table 6.

Similar studies by Eddowes and NATS also used crash data, in some cases from relatively few data points, to compare the weight of the vehicle to an impact area estimate. The Eddowes study analyzed approximately 30 crashes near Manchester and the NATS study used 126 crashes tried to determine if a non-linear relationship was a better fit than a linear one [16]. The RAND study on third party risk around airports by Brady and Hillestad used a combination of historical data and some hypothetical estimates on skid distance and the impact area used by the Department of Energy for nuclear facilities [25].

Since this parameter is so important to the ground risk model, the next section of this effort will examine which method promises to yield the most accurate results. While no database of crash impact areas from manned aircraft was available to compare the various prediction methods to actual crash data, it was possible to examine several aircraft crash reports from the NTSB to determine if the values will predict accurate results. The reports were selected because they represented a range of aircraft sizes and because there was sufficient information in the reports to calculate the impact areas. To determine the actual impact area, the description of the wreckage information in the reports was examined. In some cases the wreckage information was more explicit and in other cases it had to be determined based on a description of the length of the impact and the width of either the wingspan or fuselage. The reports for all of the crashes were obtained from the NTSB website and include a Cessna 310 [26], Cessna 501 [27], CASA 212 [28], Learjet 35 [29], DC-7 [30], 727 [31] and 747 [32].

Table 6
Impact area calculations.

Information	ft^2/lbf MTOW	Source
Debris area in built up areas	1.0764	Ale and Piers [24]
Debris area in open areas	1.3455	

Based on the results of the analysis, the two weight-based methods from Ale and Piers and the ACARRE (light orange) methods based on aircraft category (Scheduled/Other) follow roughly similar patterns. It is important to note that for the ACARRE calculations, the low value of each range was used to determine impact area, which ignored the fire area in that method. This is likely the cause of that method under-predicting the impact area of the larger aircraft. The skid area method from Solomon also followed the same general trend, but had a wider deviation for two of the data points.

All of the geometric methods consistently predicted smaller impact areas than the actual data. The geometric method that came closest to the result was the gliding approach. Overall, the two weight-based methods from Ale and Piers produce the predictions closest to the data. When the data from the accidents listed above is analyzed for a linear fit, the impact area does indicate a good fit based on vehicle weight. The results of the fit indicate a relationship of:

$$\mathrm{Area}(\mathrm{ft}^2) = -2475.466 + 1.001 \times \mathrm{Weight}(\mathrm{lbs}) \qquad (3)$$

The slope value is fairly similar to the value described by Ale and Piers in built up areas which is 1.0764 ft^2/lb. The regression data indicates a linear fit with an R^2 value of 0.997.

These examples serve to bolster the empirical data used by Ale and Piers in their study and provide the best available prediction of impact area for use in this study. While the skid area prediction method from Solomon is also very close, it uses a discrete value for skid length that would not provide continuous results. Therefore, the authors decided to use the Ale and Piers method due to the fact that with the data available to date it appears to provide the best predictive capability for impact area and is easy to implement in a model due to its linear relationship to weight. Further study needs to be completed on ensuring that an accurate, validated and credible method for predicting impact area is fully developed in order to refine this framework or any future frameworks like it.

To illustrate a point about the potential problem with several of the geometry-based approaches to impact area, an analysis of a theoretical air vehicle was conducted. The air vehicle was assumed to weigh 1 pound and be approximately 6 in. long with a 6 in. wingspan. When these values are used in the various impact area prediction techniques, the resulting values appear in Fig. 4. Without any corroborating data, it is still fairly safe to say that the estimates for impact areas produced by the gliding, hybrid and skid methods are not sound. Because these techniques use an estimate for the length of the impact area predicated on a glide or skid, these techniques will produce larger estimates for even extremely small vehicles.

3.4. Casualties

The next factor to consider is whether a UAS can cause a casualty or not when it impacts an area. The actual death or severe injury of a human caused by a falling object or debris is a highly complex problem that cannot be accurately modeled in a physics-based approach for a simpler risk model such as this one. However, the study of injuries caused by explosives and debris is fairly extensive. It is also important to discuss the difference between casualties in the open and those under shelter.

3.4.1. Casualties in the open

A Sandia report compiled by that organization for the Range Commander's Council developed data on the probability of fatality due to debris based on the area of the body impacted and the position of the body at the time of impact (standing, sitting, etc.). These values were based on extensive studies conducted in the 1960s that used human cadavers and animals as well as gelatin models to determine the impact of fragments on the human body [33].

A summary of all data obtained that related to fatalities caused by the kinetic energy of fragments or debris appears in Table 7. Overall, a value of approximately 50 ft-lbf appears to be an average value to cause a fatality. However, for even a small air vehicle that weighs 4 lbs traveling at 60 knots, the kinetic energy in a crash of that vehicle is equivalent to almost 640 ft-lbf. This means that the kinetic energy in one small UAS at relatively low flight speeds has more than ten times the energy required to cause a fatality. As a result, the assumption in the model was that any air vehicle with more than 58 ft-lbf of energy that crashed was capable of killing everyone in the crash impact area, unless they were protected by shelter. This would be true for all but the smallest of air vehicles.

3.4.2. *Casualties under shelter*

The authors also needed to determine a way to estimate casualties if the building was penetrated by the air vehicle. Once again, a physics-based approach that took into account the number of floors in a building, the internal construction materials and the energy dissipation of the total structure would be necessary to create a detailed model. However, to analyze this problem at the statistical level required a more general approach.

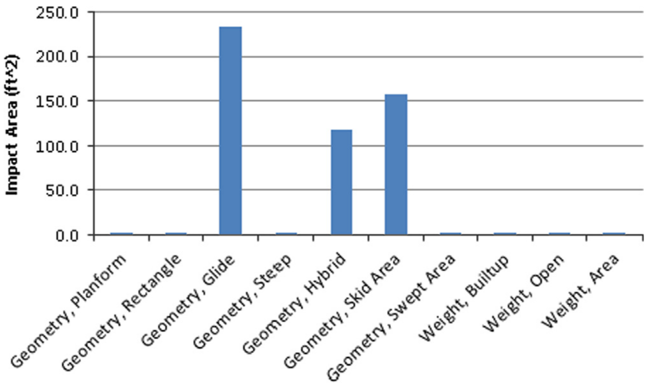

Fig. 4. Impact areas for theoretical one pound air vehicle.

As in previous cases, while no studies of UAS impact on buildings existed in the public domain, there were several studies on the casualty estimation for building collapses or damage from other causes. Four of the values in Table 8 offer mortality estimates in different types of buildings due to plane crashes. These values were published in a RAND study conducted in conjunction with the risk assessment previously mentioned for the population around an airport in the Netherlands. The mortality estimates were not statistics from actual aircraft crashes, however, but were based on previous studies conducted on nuclear facilities or other specific structures and estimated parametrically for the structures in question. Therefore, in order to seek further data to either corroborate or dispute the values in question, other studies were used. One such study used data from earthquake events to estimate the expected percentage of casualties in a building due to total collapse, which is the worst case scenario. Another study was conducted by DoD to estimate fatalities in a building collapse due to explosives.

What is evident from these studies is that the typical value for mortality rate under all of these different causes is approximately 30%. As a result, the authors used this factor as a casualty rate for any building that was penetrated by an air vehicle. In other words, 30% of the people inside any building penetrated by a UAS were deemed as casualties. The remaining 70% are not considered fatal casualties. It is important to note that the values in Table 8 assume a worst case scenario of a complete building collapse and is therefore a conservative approach to the problem.

3.5. *Predicting ground casualties using event trees*

Leveraging the studies and data outlined above to predict ground casualties requires a tool to incorporate both the behavior of UAS during a mishap and the effects of a mishap and subsequent impact. The purpose of this tool was not to predict UAS failures or failure rates, but was to better predict the events and effects of those failures.

Several sources in the literature surrounding UAS safety have recommended Event Trees to help predict casualties from UAS

Table 7
Fatality data for debris.

Information	Value	Units	Source
Energy for ‘hazardous’ debris	33	ft-lbf	Air force development and test center [34]
Energy for ‘hazardous debris’	35–50		
Energy required by fragment for 90% probability of fatality	85		General American report [33]
Energy required by fragment to be hazardous to humans	58	Joules	DODD 6055.9 [35]
Probability of fatality due to debris	Log normal distribution: α: 44 β: 0.3737	Ft-lbf	Sandia report [33]

Table 8
Building casualty data summary.

Information		Percent of occupants deemed fatalities	Source
Expected deaths due to building collapse		20–40	Earthquake study [36]
Maximum expected deaths due to building collapse		32	DoD explosives study [20]
Mortality rate for medium aircraft	Single-family to few-story apartment	40	RAND study [25]
	Office or high-rise apartment	30	
Mortality rate for small aircraft	Single-family to few-story apartment	20	
	Office or high-rise apartment	10	

incidents. Event trees are a well-known reliability tool that can be used to determine the probability and impact of specified failure events. An event tree represents a sequence of chronologically arranged nodes that graphically depict a series of events leading to multiple possible outcomes. The timeline corresponding the this sequence is often introduced for the sake of modeling convenience, as long as the actual order of the events is not important for the outcome. For example, a node can represent a single protection layer (and the possibility of its failure) when multiple independent protection layers are employed to prevent hazardous outcomes. In this context, the order in which the protection layers fail is immaterial. Each node corresponds to a single event with a finite number of exhaustive and mutually exclusive possible outcomes, depicted as distinct branches of a tree emanating from the node. Event trees are a modified version of the decision trees used in the decision analysis [37].

Event trees provide a compact and intuitive means for the probabilistic representation of a timeline of sequential events, which explains their widespread popularity in various fields. In particular, they were utilized in developing a simple and powerful method for pricing options [38], and became a mainstay of safety and risk assessments, as the methods introduced in WASH-1400 [9] eventually became accepted. A concept similar to event trees was introduced earlier in the United Kingdom [39], where it is referred to as “fault diagrams;” in which the resulting tree is oriented vertically, similar to fault trees. However, the introduction of event trees in WASH-1400 appears to be independent [40], and no reference to [39] was provided therein.

The use of event trees facilitated an effective decoupling of the logical and temporal aspects of the behavior of complex systems (such as nuclear plants) within the Probabilistic Risk Assessment (PRA) framework [40]. As a result, “local” fault trees could be associated with each node of an event tree, which provided a higher-level view of the possible timeline of events that could lead to an accident. While large “global” fault trees are thus avoided, and the overall modeling complexity becomes more manageable, the method can lead to significant errors if the temporal and logical aspects of system behavior are coupled and are not properly accounted for.

In general, two types of such coupling can be identified. In the first, some of the events at the distinct nodes might be dependent. For example, two protection layers can rely on the same common resource (i.e. electrical power source). The associated problem of quantifying the risks is somewhat more involved than a straightforward calculation used for event trees with independent nodes, but fast and accurate algorithms are currently available [41].

In the second type, the timing of events (that is not known a priori) is important for determining the outcome. For example, there might be two protection devices that need to be sequentially engaged and the delay associated with the engagement of the first particular protection device directly impacts the remaining allowed delay for the timely engagement of the second device. Similar issues arise when inspection and repairs of system components need to be taken into account. The associated problems become fundamentally dynamic and, while simple cases can be solved by time integration, in general, state-space methods, such as Markov chains [42] or Stochastic Petri Nets [43] are needed.

The event tree used for this study to estimate ground casualties for a UAS impact appears in Fig. 5. The tree shows the breakdown in where the UAS impacts, and then determines whether penetration of a shelter occurs, based on the energy model discussed above. The effects at the end of the tree branches are based on the impact area, local population density and building collapse data used in the model. To avoid the problems associated with coupling described above, the event tree was created to ensure that each of the branches were mutually exclusive.

4. Results

4.1. Validation efforts

As with any predictive model, it is critical to determine whether the effort can accurately predict the desired results. Due to the impracticality of testing the effects of UAS crashes and the relatively low information available on UAS incidents, data available from General Aviation (GA) accidents was used instead to validate the ground effects model described above. The effort began by gathering historical data on incidents and bystander fatalities caused by GA aircraft. Data for both the accident and fatality rates was extensive. The most important data used for this effort appears in Table 9.

A key component of the model is the population density variable. This value determines how many people are potentially

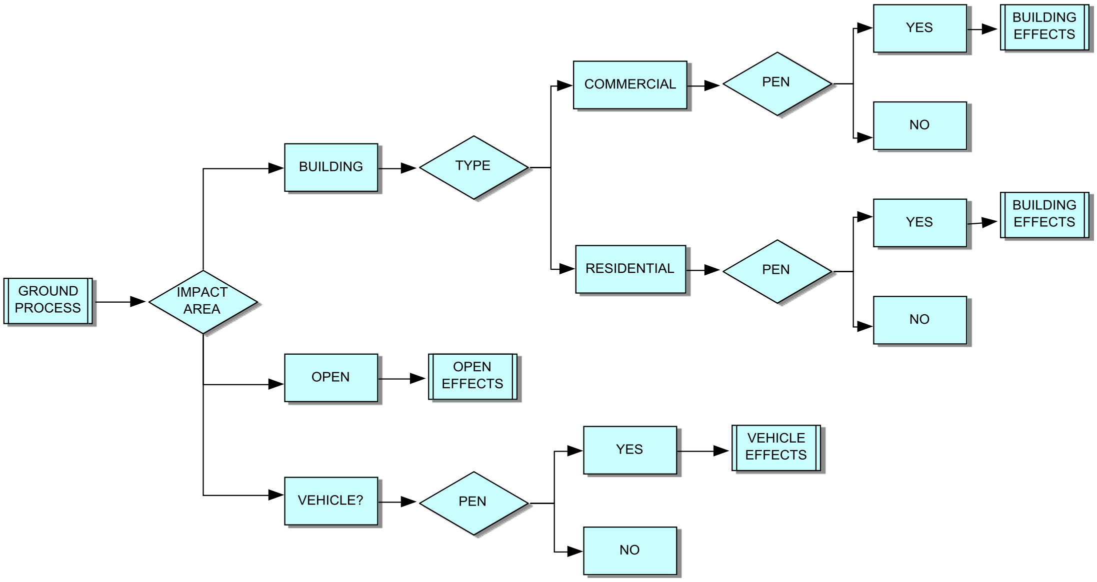

Fig. 5. Event tree for ground risk.

Table 9
General aviation accident data.

Information	Value	Units	Source
General aviation accidents [1984–2004]	1.541	Fatal accidents/100 k FH	Aircraft owners and pilots association website [35]
Ground fatalities caused by general aviation accidents [1984–2004]	0.0084	Fatalities/100 k FH	NTSB data from clothier paper [44]
Weight	2100	lbs	Based on average of aircraft from NTSB data
Wingspan	36	ft	
Length	29		

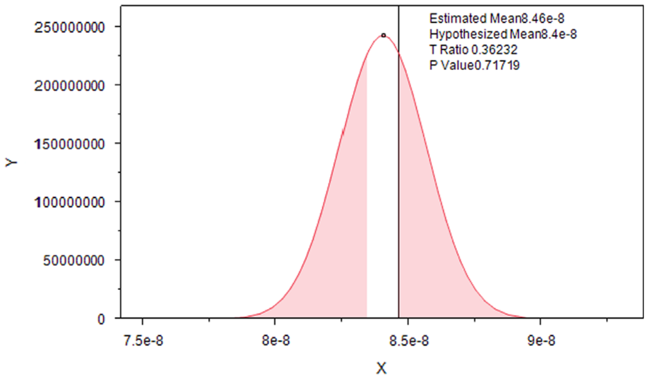

Fig. 6. Mean test for GA validation.

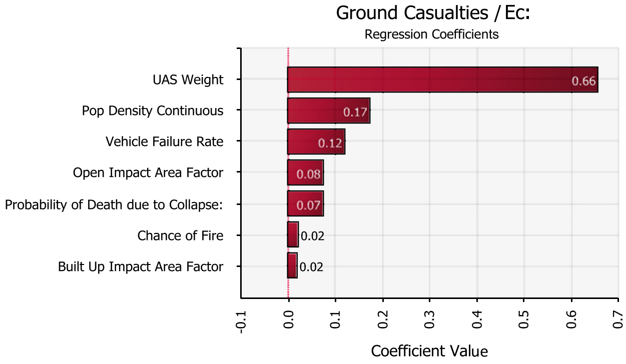

Fig. 7. Sensitivity analysis (full range).

at risk in the event of a UAS accident. The method developed for this study was to create a probability distribution using census data.

The parameters of the distribution were a mean of 90.26, standard deviation of 129.42, minimum of 1.2 and maximum of 9,856. All values were in people per square mile. The data to populate the distribution was obtained from the U.S. Census Bureau databases [45]. Once the method to determine population density was developed, the model was tested by running simulations using two different validation processes.

To determine the accuracy of the model, the accident rates for the GA aircraft during the time period in question was used. Then the predicted casualties from each model were compared to the actual number of third-party casualties caused by GA aircraft during the same period. The percent difference indicates whether the two models over or under-predicted casualties, relative to actual data. The results showed that the simple model using techniques currently in the literature, over-predicted the actual casualties that GA aircraft caused by approximately 23%. On the other hand, the model using the event trees and terminal effects data differed from actual data by less than 1%, a much closer result.

When compared to the actual value for the GA casualty rates, the sample data from the experiment demonstrates a *p*-value of 0.71719 for a two-sided *t*-test against the actual value of 0.084 casualties per million FH. This result demonstrates that it is plausible that the model results are consistent enough with the actual casualty rates from historical data and there is no reason to reject the null hypothesis that the mean of the model casualty results is the same as the historical data value for casualties [46]. Fig. 6.

To further ensure that the new model was able to predict valid results for bystander casualties, the model was used again with data from Air Carrier accidents and fatalities. The purpose of choosing Air Carrier data, or flights operating under FAR Part 121 was to test the ground model using much larger aircraft than those used in the GA calibration process to determine if the model would hold up for larger, heavier airframes with better reliability records. Information on Air Carrier accidents under FAR Part 121 was available with sufficient information to derive bystander deaths. This information was used as input into the simple ground model and the model using the terminal effects described throughout this document.

In this particular case, the simple model under-predicted fatality results by over 79% while the full event tree proposed in this paper differed from actual fatality data by only approximately 3%. Once again, the event tree model was able to predict the casualties to less than 10% accuracy when compared to real-world mishap data.

4.2. *Sensitivity analysis*

In order to determine which factors had the most impact on the variability of the casualty rate response variable in the model, a sensitivity analysis was conducted. All of the potential input variables were varied along reasonable ranges, based on data related to the ground environment or current UAS trends. Fig. 7 shows the major factors contributing to the variability of the ground casualty rate in the form of a tornado plot or regression coefficients. Clearly, the UAS weight, population density, and vehicle failure rate have the most impact on casualties. The weight plays a major role because, in this model, it contributes to impact area and kinetic energy to determine shelter penetration.

4.3. *UAS safety assessment*

The ultimate goal of devising this framework is to provide a means to accurately assess the risk posed by UAS operations given information about the UAS, its failure rate, and the operating environment. To demonstrate the application of this framework, an example is provided for a 4.4 lb air vehicle. The FAA law passed in February, 2012 mandated that the FAA enter into agreements with government agencies to allow for the use of 4.4 pound air vehicles for public safety purposes, presumably law enforcement, under certain provisions [47].

One possible application for the model is to determine the allowable safe operating environments for a particular type of vehicle. To demonstrate this application, the 4.4 lb vehicle above was assumed to have system failure rates commensurate with current small UAS. In the simulation to assess these operations, the overall population density was allowed to vary according to a

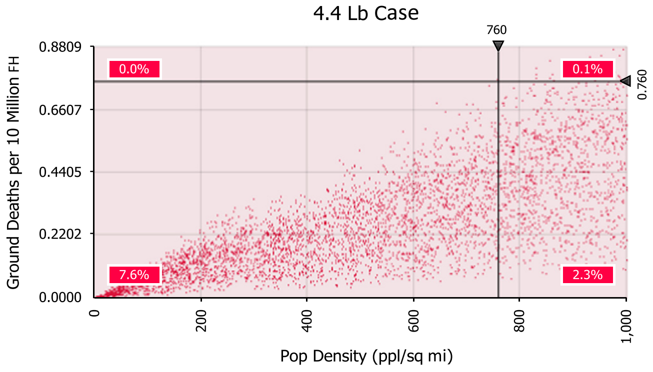

Fig. 8. Scatterplot for 4.4 Lb Case.

Table 10
Summary of 4.4 Lb unmitigated ground risk simulation.

Variable	Value	Units
Target third-party rate for initial study	0.760	Fatalities/10 million FH
Population density required for 100% confidence in not exceeding target	760	People/mile^2
Number of counties nationwide	3143	#
Number of counties with fewer than 760 people/mile^2	2967	
Counties with fewer than 760 people/mile^2	94.4	%
U.S. land mass with fewer than 760 people/mile^2	97.7	
Number of people living in areas with greater than 760 people/mile^2	129 million	#

uniform distribution in order to assess safety across a broad range of operating environments.

The results of the simulation appear in the scatterplot in Fig. 8. This figure shows the data in terms of ground deaths per 10 million FH. A line on the vertical axis is included at 0.76 deaths/10 million FH to correspond to the historical third-party death rate discussed previously. The assumption is that the UAS should be no more dangerous to people on the ground than manned aircraft were for the period in question. To be extremely conservative and ensure no cases exceed this value, one can limit the acceptable cases to those cases which incur a lower casualty rate than manned aircraft data, which corresponds to operations in areas with less than 760 people per square mile.

From the U.S. Census data by county, there are 3143 counties in the country. Of these, 2967 have a population density lower than 760 people per square mile and these counties account for over 97% of the land mass of the country [45]. This means that with no mitigation measures in place, an air vehicle weighing 4.4 pounds could operate with current reliability levels over 97% of the country or all but 176 counties and still pose less risk to bystanders than GA aircraft have. A summary of the results described above for the 4.4 lb air vehicle simulations with no risk mitigation measures in place appears in Table 10.

5. Conclusions

The framework outlined in this paper demonstrates a way to link UAS failure rates to public safety. It uses an accepted reliability tool in the form of event trees to describe the sequence of events that could occur in the event of UAS failures. Where gaps in knowledge exist concerning the effects of those failures on the public, data from existing and related studies is used. The utility of this framework was already demonstrated with the experiment above to assess the risk posed by a 4.4 lb air vehicle. In addition, this framework can be used to set failure rate standards useful for certification purposes for UAS based on size and operating environment.

Table 11
Population density values by category.

Information	People/mile^2	% of Landmass	Source
Remote	10	46	U.S. census data and ArcGIS online designations [45,48]
Rural	100	37.6	
Suburban	1000	14.4	
Urban	10,000	1.9	
Metropolitan	25,000	<1	
Metropolitan city center	71,564	0.0005	

Table 12
UAS categories by weight.

Group	Weight (lbs)	Source
Group 1 (Micro)	<1	N/A
Group 2 (Mini)	1.1–4.4	FAA law [47]
Group 3 (Small)	4.5–55	FAA law, DoD, EASA drafts [47,49,50]
Group 4 (Tactical)	56–351	ICAT study, EASA drafts [12,51]
Group 5 (Medium)	352–1320	DoD [49]
Group 6 (Large)	1321–10,000	Based on predator C [52]
Group 7 (Heavy)	10,001–25,000	Based on Global Hawk [52]

In order to delineate population density values on the ground it is useful to link them to something that UAS users can view graphically and understand when planning flight operations. Different Geographic Information System (GIS) packages can display map overlays with population density values. The values were obtained from U.S. Census data and cross-referenced to classifications found in the ArcGIS software package. Tables 11 and 12.

Based on the analysis used to build the casualty prediction model, the best way to delineate UAS into categories is based on vehicle weight. Since the DoD is currently the largest user of UAS and most UAS will likely be derivatives of these systems in the future, the DoD group system is a likely starting point for a category system. The groups below also combined aspects of the classification system described in different sources to ensure a wider basis of vehicles was covered.

To develop failure rate requirements for UAS, the following procedure was conducted. For each combination of UAS weight and population density in Table 13, a simulation was conducted using the ground risk model. The software was used to determine the maximum system failure rate for each combination that would ensure that the vehicle in question would not exceed 7.6×10^{-8} deaths per FH, the historical bystander fatality rate for manned aviation. The values throughout Table 13 are those maximum system failure rates. The green cases represent failure rates that meet or are below current UAS failure rates, based on the historical data cited throughout this paper. In other words, those systems should be able to meet the required TLS with no mitigation necessary. The yellow boxes represent a required improvement in the system failure rate of one order of magnitude, compared to the same historical rates. It is possible that since historical UAS failure rates in question are largely based on Department of Defense (DoD) usage in combat situations that an improvement of one order of magnitude could be seen by civilian UAS operators. When UAS missions are conducted by DoD in combat situations, it is likely that additional risks are taken with respect to weather, maintenance, and operating conditions that would not be necessary for civilian operators. The magenta boxes indicate combinations that would require two or more orders of magnitude

Table 13
Maximum system failure rates (per FH) to meet ground TLS.

Group	Remote	Rural	Suburban	Urban	Metro	City center
Group 1 (Micro)	1.20×10^{0}	1.20×10^{-1}	1.50×10^{-2}	1.50×10^{-3}	6.01×10^{-3}	2.10×10^{-4}
Group 2 (Mini)	2.73×10^{-1}	2.73×10^{-2}	3.42×10^{-3}	3.42×10^{-4}	1.37×10^{-4}	4.77×10^{-5}
Group 3 (Small)	7.31×10^{-3}	7.31×10^{-4}	9.14×10^{-5}	9.14×10^{-6}	3.66×10^{-6}	1.28×10^{-6}
Group 4 (Tactical)	1.15×10^{-3}	1.15×10^{-4}	1.43×10^{-5}	1.43×10^{-6}	5.73×10^{-7}	2.00×10^{-7}
Group 5 (Medium)	3.05×10^{-4}	3.05×10^{-5}	3.81×10^{-6}	3.81×10^{-7}	1.52×10^{-7}	5.32×10^{-8}
Group 6 (Large)	4.02×10^{-5}	4.02×10^{-6}	5.03×10^{-7}	5.03×10^{-8}	2.01×10^{-8}	7.03×10^{-9}
Group 7 (Heavy)	1.61×10^{-5}	1.61×10^{-6}	2.01×10^{-7}	2.01×10^{-8}	8.04×10^{-9}	2.81×10^{-9}

improvement in system failure rate. This level of improvement is unlikely without significant changes in UAS design and operations in these boxes would require risk mitigation measures and/or significant improvements in failure rates to achieve the TLS.

Based on the desire of many stakeholders in the UAS community, the economic advantages of UAS integration and the requirements in the 2012 FAA Modernization bill, UAS integration is a compelling a vital goal for this country. However, based on the very nature of unmanned aircraft, there is a presently not a quantifiable link between system reliability and public safety. In order to establish that link, a methodology such as the one described in this paper is necessary. Developing a methodology to link UAS reliability and safety allows officials to set system reliability requirements and operating requirements that are meaningful and linked to public safety. Only then will the United States be able to realize the full potential of UAS operating in the NAS, while maintaining the outstanding public safety record that aviation already enjoys in this country.

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