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Ground Risk Model for UAVs

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Ground Risk Model for UAVs

Cover Page Footnote

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The Joint Authorities for Rulemaking on Unmanned Systems (JARUS) has promulgated a methodology that it calls a “Specific Operations Risk Assessment” (SORA) to assist regulators and operators of unmanned aerial systems (UAS) to determine how to conduct an operation safely (JARUS, 2019). SORA has been adopted as part of the official regulatory regime for UAS in Europe (European Union Aviation Safety Agency [EASA], 2022, pp. 34–196), Australia (Civil Aviation Safety Authority [CASA], 2021b), and Canada (Transport Canada, 2021). New Zealand has adopted SORA as an unofficial tool to assess applications for certification of ‘complex’ UAS operations (Civil Aviation Authority of New Zealand [CAANZ], 2022), although like the other regulators claims to be open to consider other risk assessment methodologies.

The SORA methodology ostensibly incorporates the risk management concepts associated with bow tie diagrams, with risk mitigations acting either as threat barriers to reduce the likelihood of a hazardous event occurring, or as a harm barrier to reduce the consequence of the hazardous event if it does occur (JARUS, 2017, pp. 14–18). SORA abstracts away from the bow tie diagrams to provide qualitative risk levels in the form of a “ground risk class” (GRC) and “air risk class,” intended to provide an indication of the relative level of risk from a person being struck by an unmanned aerial vehicle (UAV) and a mid-air collision respectively. These qualitative risk levels are combined into a measure of risk called the “Specific Assurance and Integrity Level” (SAIL), ranging from I to IV, which inform the selection of harm barriers called Operational Safety Objectives (OSOs) (JARUS, 2019, p. 27).

One of the difficulties of proposing an alternative risk assessment methodology is that SORA is viewed as “the most complete framework” of competing risk assessment methodologies (Cabral et al., 2018, p. 5-9). This view arises partly because SORA includes consideration of both air and ground risks, as well as recommending hazard controls (i.e. the OSOs). Although the OSOs are asserted to achieve the required level of risk reduction, there appears to be little research evidence underpinning these assertions. There is no evidence, for example, as to whether the OSOs recommended for operations at SAIL III will reduce the risk to the same risk as SAIL I. Nor is there any evidence of the effectiveness of individual OSOs. Relatedly, NASA researchers have criticized SORA on the basis that the qualitative representation of ground risk is inconsistent with the corresponding bow-tie diagrams for some scenarios, and that the corrections for harm barriers can lead to inconsistent risk assessments (Denney et al., 2018). They demonstrate that establishing a mathematical basis for SORA “tightly couples consequences and their risk factors, potentially allowing GRCs to be generated” (op. cit.). The present article also demonstrates that the qualitative classification of ground risk within SORA is inconsistent with actual risk.

This article proceeds as follows. The ensuing discussion identifies some weaknesses in the SORA methodology, specifically in relation to the GRC. Ground risk is necessarily related to population density, but the SORA guidelines have vague descriptive categorizations of population rather than precise quantitative thresholds. The interpretation of what is meant by “sparsely populated" is discussed, followed by the development of population density categories for New Zealand. A methodology for calculating ground risk is then presented. That methodology is based in part on Shelley's (2016) analysis of human harm from a falling UAV, but with a revised fatality function. Results are presented in a table format similar to SORA but referenced to the third-party fatality rate for General Aviation. Results are presented for UAV operation to a maximum height of 500 ft AGL, being a threshold height limit for air risk within the SORA methodology. Implications of the proposed ground risk methodology are discussed.

SORA Methodology and Ground Risk

As noted in the introduction, SORA assesses the overall risk of an operation of a product of both ground risk and air risk. An intrinsic ground risk is established by reference to the kinetic energy of impact and the maximum dimension of the aircraft, together with the operational scenario. Intrinsic ground risk can be modified (reduced) by application of mitigations including reducing the number of people at risk, reducing the effects of ground impact, and having an effective emergency response plan. No quantitative data or analysis is presented to validate any part of the SORA framework. The SORA guidelines claim that a "detailed mathematical model to substantiate this approach is provided in Annex F" (JARUS, 2019, p. 20), but with lack of agreement from JARUS members this Annex has never been released. The discussion that follows critique the relationship between impact energy and risk in the SORA framework, and then the implied effect of Extended Visual Line of Sight (EVLOS) and Beyond Visual Line of Sight (BVLOS) operations.

Intrinsic Ground Risk

The SORA intrinsic UAS ground risk class table summarizes risk as a natural number. Different combinations of impact energy and operational scenario can have the same ground risk number. For example, a ground risk of 3 occurs for: (a) VLOS/BVLOS over a controlled ground area with a UAV having an impact energy of at least 34 kJ but less than 1,084 kJ; (b) VLOS in a sparsely populated environment with a UAV having an impact energy of at least 700J but less than 34 kJ; and (c) BVLOS in a sparsely populated environment with a UAV having an impact energy of less than 700 J. Subsequent stages of the SORA methodology assume everything that we need to know about ground risk is encapsulated in the intrinsic ground risk number, and that the same risk treatments will apply regardless of the specific combination of mass, height, and operational scenario that resulted in that intrinsic ground risk classification.

There is a question of whether the columns in the SORA Intrinsic UAS Ground Risk Class table make logical sense, at least from the perspective of kinetic energy. Shelley (2016) quantifies the potential harm that might occur if a person was hit by a falling UAV. The fatality model adopted by Shelley has a 50% probability of fatality at an impact energy of 103 J, and an implied 99.99% probability of fatality at 210 J. In contrast, SORA's lowest risk category is for impact energy <700J, but additional risk categories adopted impact energy < 34 kJ, impact energy < 1084 kJ, and impact energy > 1084 kJ. However, once the force is such that serious injury or fatality is likely, then there is little point in adopting additional risk categories. Or, put another way, once you are dead then you can't be any more dead just because you are hit with more force. Other researchers have suggested that kinetic energy thresholds may be excessively restrictive and that other measures such as the blunt criterion or automotive vulnerability models may provide a more accurate estimate of likely harm (see, for example, Svatý et al., 2022).

The analysis in Shelley (2016) also considered the population density in the area of operation, and thus is also relevant to an assessment of whether the rows in the Intrinsic UAS Ground Risk Class make logical sense. Note that the methodologies in both Shelley and SORA focus solely on the kinetic energy of impact and do not consider alternative measures such as the blunt criterion or factors such as lacerations from spinning propellers. This limitation is also present in the current analysis.

BVLOS Operations and Intrinsic Ground Risk

The SORA framework assumes that when operating over anything other than a controlled ground area that EVLOS and BVLOS operations necessarily create a greater ground risk than VLOS operations. For most scenarios EVLOS and BVLOS operations are associated with a unit increase in the intrinsic ground risk class. It is not obvious why operating EVLOS/BVLOS rather than VLOS necessarily increases ground risk, and the SORA guidance documentation does not provide any rationale for this phenomena (Denney et al., 2018). For this to be true – resulting in a unit increment to the intrinsic ground risk – would require that the number of in-flight failures or crashes was materially higher with BVLOS than with VLOS, by at least an order of magnitude.

While we may be able to construct scenarios where a quadcopter with no propeller guards and no obstacle avoidance would have a materially higher crash rate if operated in relative close proximity to obstacles, such scenarios are not generally representative of BVLOS operations. Alternatively, perhaps it is assumed that BVLOS operations would have an order of magnitude higher in-flight failure rate due to relatively frequent crashes with manned aircraft. While this may be plausible for some operational scenarios, it cannot be assumed to apply as a general rule.

Population Density

Assessment of intrinsic ground risk requires, inter alia, determination of the ground operating environment, i.e. whether the operation will be conducted over a "gathering of people," in a "populated environment," in a "sparsely populated environment," or over a "controlled ground area." Definitions are not provided within the SORA framework for what constitutes "populated" or "sparsely populated". This lack of definitions leaves the framework open to interpretation by regulators to suit their internal agendas rather than providing a scientifically based approach to risk assessment.

Shelley (2016) considered population densities from 0.00078 to 4 people per square meter, which corresponds to densities of 780 people per square km up to 4 million people per square km. Shelley's standard range of 0.05-1.2 people per square meter likewise corresponds to populations densities of 50,000 to 1.2 million people per square km. These densities are far in excess of the densities likely in all but the most heavily populated cities – where much of the population will be sheltered inside buildings – or mass events such as concerts or sporting events. The results in Shelley's analysis cannot, therefore, be taken as representative for the range of operational scenarios within SORA.

In the United States, 14 CFR §91.119 (2022) provides that the minimum height for manned aviation over non-congested areas is 500 ft AGL "except over open water or sparsely populated areas". Similarly, 14 CFR §91.305 (2022) provides that flight tests may only be conducted "over open water, or sparsely populated areas," and 14 CFR §107.25 (2022) also makes reference to sparsely populated areas. Notwithstanding the existence and use of the term "sparsely populated", the FAA has deliberately decided not to define what is meant by that term. In 2006 the FAA noted that it considered adopting a definition of 10 people per square statute mile (FAA, 2006, p. 16258), which implies a density of 3.86 people per square km. While the FAA ultimately did not adopt that definition, it also observed that (ibid.):

> The term ‘‘unpopulated’’ would mean no people, period. The term ‘‘sparsely populated’’ suggests an area with a few scattered people where the risk to those few persons from the overflight of a suborbital rocket, even one being tested, would likely be negligible.

Thus, sparsely populated differs from unpopulated and does allow for some people to be in the relevant area.

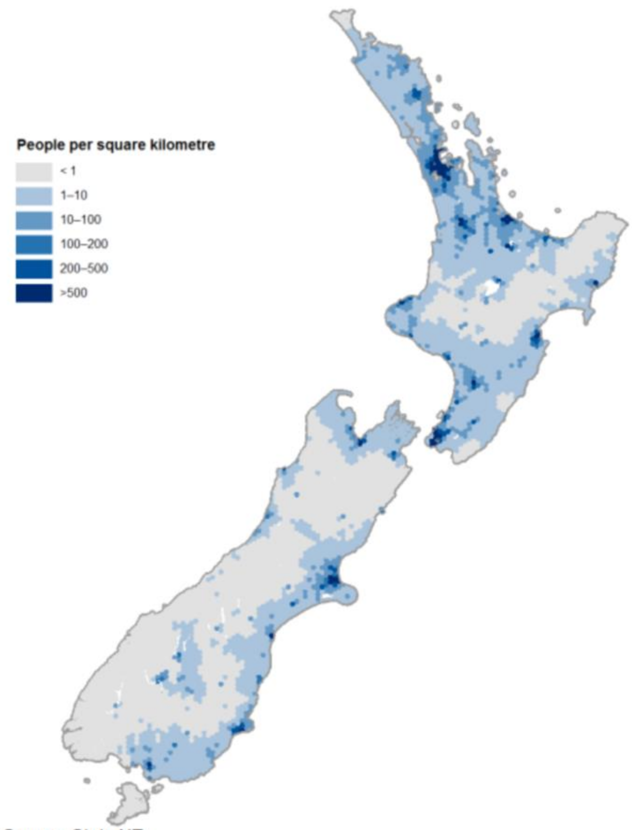
Alternative definitions of sparsely populated are available to the definition suggested by the FAA. The case *Mickalich v. United States of America* (2007) suggests that 20 people per 10 acres falls between the classifications of "congested areas" and "sparsely populated areas" in 14 CFR §91.119. One square km is 247.105 acres, so this benchmark suggests a density of 494.2 people per km^2 is greater than what might be considered sparsely populated, but less than what might be considered congested. A 2006 study of sparsely populated regions in Norway adopted a threshold of 12.5 inhabitants per km^2 (Gløersen et al., 2006). In its Notice of Proposed Amendment 2020-07, EASA proposed that an area could be considered to be "sparsely populated" for the purpose of SORA if it is classified as "thinly populated" by the European Commission (EASA, 2020, p. 10 sec. 2.2.3). A working definition of "thinly populated" is less than 100 inhabitants per km^2, although some higher densities are also possible (Dijkstra & Poelman, 2014, p. 2, sec. 2.2.1). For the purpose of UAS regulation, Australia defines sparsely populated areas as having an average population density less than 10 people per km^2 and no towns or settlements of more than 100 dwellings (CASA, 2021a, p. 6).

Figure 1 shows a map of population density published by New Zealand's official government statistician, Statistics New Zealand. While these maps show the population density across the country, the density categories are not given a descriptive name. Density categories are < 1 person per km^2, 1-10 people per km^2, 10-100 people per km^2, 100-200 people per km^2, 200-500 people per km^2, and greater than 500 people per km^2. As is evident from Figure 1, the vast majority of

New Zealand's land area meets the European Commission's definition of "thinly populated".

Figure 1

Population Density of New Zealand, as at 30 June 2017



Source: Stats NZ

The analysis that follows largely adopts the New Zealand population density categories. As shown in Table 1, an additional category of "controlled ground" is added, with no people present. The other categories adopted by New Zealand are given a descriptive title. The combination of "unpopulated" (< 1 person per km^2), "sparsely populated" (1-10 people per km^2), and "low population" (10-100 people per km^2) equate to the European Commission's definition of "thinly populated". The analysis presented here is capped at 2,000 people/km^2, and on that basis might not be appropriate to apply to mass events. The categorization of population density provided in Table 1 provides a much more granular level of detail than the standard SORA model, which in turn should allow for more nuanced risk assessments.

Table 1

Population Density Categories

Category Description	People per km^2
Controlled Ground	0
Unpopulated	< 1
Sparsely Populated	1 - 10
Low Population	10 - 100
Urban Adjacent	100 - 200
Towns	200 - 500
Dense Urban	500 - 2000

Ground Risk Methodology

Intrinsic ground risk is calculated using a model of fatality and harm caused by impact injury. The results of that analysis are presented as ground risk tables that could be used as an alternative to the Intrinsic UAS Ground Risk Class table in JARUS (2019).

Intrinsic Ground Risk

We can define intrinsic ground risk as the risk of a person being fatally or seriously injured. Determinants of this risk are the impact energy and the probability of a person being hit by a falling UAV, which in turn is a function of the population density and the size of the UAV. At the most general level, these are the same factors considered by the SORA methodology. Impact energy and the size of the UAV are the determinants of the column of the ground risk table, and population density is one of the determinants of the operational scenario (row).

To derive an alternative version of the intrinsic ground risk table we calculate the risk of a person being fatally or seriously injured for kinetic energy ranging from 0 J to 1500 kJ, and for population density ranging from 0 people per km^2 to 1000 people perkm^2, and for various dimensions of UAV. The resulting risk estimates are then stratified and assigned an ordinal risk number.

Relative Value of Fatality and Injury

To calculate ground risk we first need a method of appropriately weighting fatalities and serious injuries. If one person is killed then this is one fatality. But if there is a 10% chance of a fatality, then the risk is equivalent to 0.1 fatalities, or what we define here as 0.1 fatality-equivalents. We then need to consider the appropriate weighting of serious injuries. One option is to equally weight fatalities and serious injuries, although this arguably over-weights serious injuries. An alternative proposed by Shelley (2016) is to use a “normalized social cost” where a fatality has a value of 1 and injuries have a lesser value depending on the severity of the injury, the impact on quality of life, and the cost of treatment. In effect, the normalized social cost utilizes economic costs to calculate the fatality-equivalent value. Table 2 shows the normalized social cost estimates developed by Shelley. These are adopted as the fatality-equivalent weightings in the current analysis.

Table 2

Normalized Social Cost estimates from Shelley (2016)

Level of Injury	Normalized Social Cost	
	New Zealand	United States
Fatality	1	1
AIS 4	0.4	0.3
AIS 3	0.05	0.1
AIS 2	0.05	0.1
Minor	0.004	0.0002

Let $Risk_{FE}$ be the risk of fatal or serious injury expressed in fatality-equivalents. Implicit within Shelley's analysis, the overall risk of fatal or serious injury is given by:

$$Risk_{FE} = p(impact) \times \begin{bmatrix} p(fatality|impact) \\ +\big(1 - p(fatality|impact)\big) \times Injury_{FE} \end{bmatrix} \quad (1)$$

where $p(impact)$ is the probability of an impact, $p(fatality|impact)$ is the probability of a fatality given an impact occurs, and $Injury_{FE}$ is the fatality-equivalent cost of injury.

The probability of an impact is the product of the expected failure rate and $E[N]$, the expected number of people impacted if a failure occurs:

$$p(impact) = E[Failure\ Rate] \times E[N] \quad (2)$$

The expected failure rate can be expressed as the inverse of the mean time between failure (MTBF), which both the UAS Task Force (2015) and Shelley (2016) assume to be 100. The expected number of people impacted is:

$$E[N] = \rho \cdot \pi \cdot (r_{UAV} + r_{human})^2 \quad (3)$$

where π has its usual value, r_{UAV} is the radius of the UAV, and r_{human} is the radius of the human being.

Shelley (2016) utilizes the following logistic curve for the probability of fatality:

$$P(fatality|impact) = \frac{1}{1+e^{-k\left(E_{imp}-E_0\right)}} \quad (4)$$

where E_0 = 103 J is the impact energy associated with a 50% probability of fatality and k = 0.09 is a constant.

Oberhagemann (2012) provides the surface area of a person as viewed from above as 0.085 m^2. The same value was adopted by Shelley (2016). However, in conjunction with the estimate of 0.085 m^2, Oberhagemann also provides a stylized plan view of a human as an ellipse with major axis 0.5 m and minor axis 0.3 m which imply a cross-sectional area of 0.118 m^2. The plan view of the head is shown as a circle with diameter approximately 0.25 m, which provides a cross-sectional area of 0.049 m^2 for the head. The present analysis adopts the cross-sectional area of 0.118 m^2 to calculate the number of people impacted by a falling UAV. Relative to Shelley (2016), this assumption increases the number of people impacted by approximately 39%. However, the present analysis also assumes that a fatality only occurs if the UAV impacts the head, which is only 41% of the cross-sectional area for a person. Taken together this means that the probability of fatality is approximately 58% of the probability of fatality in Shelley (2016), but there is greater potential for injury.

For a non-fatal impact the impact energy is used to determine the injury level from Table 3. The fatality-equivalent cost of injury, $Injury_{FE}$, is then determined by the appropriate normalised social cost from Table 2.

Table 3

Relationship between Impact Energy and Skull Fracture Severity from Shelley (2016)

Outcome	Impact Energy Threshold (J)	AIS Injury Severity
No Skull Fracture		0
Minor Depressed Skull Fracture	19.8	2
Major Depressed Skull Fracture	49.5	3
Severe Life-Endangering Fracture	99	4

Finally, the calculated level of risk in fatality-equivalents is converted to an ordinal Risk Score ranging from 0 to 6 as shown in Table 4. It is assumed that the level of bystander casualties from General Aviation is an acceptable level for unmanned aircraft. Shelley (2016) demonstrates that for General Aviation in the United States the risk to members of the public is $6x10^{-7}$ fatality-equivalents per flight hour 1995 through 2014. Thus a risk of $1x10^{-8}$ or $1x10^{-7}$ is assigned a Risk Score of 1. A risk of less than $1x10^{-8}$ is assigned a Risk Score of zero. A risk of up to $1x10^{-6}$ is assigned a Risk Score of 2, a risk of up to $1 \text{ x } 10^{-5}$ is assigned a Risk Score of 3, and so on. Thus, a unit increment in the Risk Score equates to a ten-fold increase in risk.

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Table 4

Risk Score

Risk Threshold	Risk Score
0	0
1x10-8	1
1x10-7	1
1x10-6	2
1x10-5	3
1x10-4	4
1x10-3	5
1x10-2	6

Results

Intrinsic Ground Risk

Tables 10 to 17 in the appendix show the resulting risk scores. Table 10 is for a UAV of 0.1 m^2, Table 11 is for a UAV of 0.5 m^2, Table 12 is for a UAV of 1 m^2, Table 13 is for a UAV of 5 m^2, Table 14 is for a UAV of 10 m^2, Table 15 is for a UAV of 30 m^2, Table 16 is for a UAV of 50 m^2, and Table 17 is for a UAV of 80 m^2. A controlled ground risk area has a risk score of 0 for all sizes of UAV. Unpopulated areas (< 1 person per km^2) have a risk score of 0 or 1 for all sizes of UAV, indicating that the maximum ground risk is the same order of magnitude as the ground risk from General Aviation.

Sparsely populated areas (1-10 people per km^2) have a risk score of 0 for a UAV of 0.1 m^2, 0.5 m^2, or 1 m^2 for impact energy of 50 J, increasing to a risk score of 1 for all higher levels of impact energy. The risk score is always 1 for a UAV of 5 m^2 or 10 m^2. For the larger UAVs of 30 m^2, 50 m^2, and 80 m^2, the risk score is 1 for an impact energy of 50 J, increasing to a risk score of 2 for all higher levels of impact energy. The risk score of 2 indicates a ground risk ten times higher than that associated with General Aviation.

Areas of low population (10-100 people per km^2) have a risk score of 1 for a UAV of 0.1 m^2 and 0.5 m^2 for all impact energies. For a UAV of 1 m^2 the risk score is 1 up to an impact energy of 100 J, increasing to 2 for higher levels of impact energy. For a UAV of 5 m^2 or 10 m^2 the risk score is 1 at 50 J impact energy, increasing to 2 for higher levels of impact energy. For the larger UAVs of 30 m^2, 50 m^2, and 80 m^2, the risk score is 2 for an impact energy of 50 J, increasing to a risk score of 3 for all higher levels of impact energy.

Urban Adjacent areas (100-200 people per km^2) and Towns (200-500 people per km^2) have similar risk scores. For a UAV of 0.1 m^2, Urban Adjacent areas have a risk score of 1, while Towns have a risk score of 1 for an impact energy of 50 J and a risk score of 2 for all impact energies greater than 5 0J. For a UAV of 0.5 m^2 or 1 m^2, Urban Adjacent areas and Towns both have a risk score of 1 for an impact energy of 50 J and a risk score of 2 for all impact energies greater than 50 J. For larger UAV sizes there are some differences in risk score between Urban Adjacent areas and Towns. For a UAV of 5 m^2, Urban Adjacent areas have a risk score of 1 for an impact energy of 50 J

For Urban Adjacent Areas, UAVs of 10 m^2, 30 m^2, and 50 m^2 all have a risk score of 2 for impact energy of 50 J, increasing to 3 for all impact energies greater than 50 J. A UAV of 80 m^2 in an Urban Adjacent area also has a risk score of 2 for impact energy of 50 J, increasing to a risk score of 3 for 100 J, and increasing again to a risk score of 4 for impact energy of 500 J and above. For Towns, a UAV of 10 m^2 has the same risk score as for Urban Adjacent areas, being 2 for impact energy of 50 J, increasing to 3 for all impact energies greater than 50 J. A UAV of 30 m^2 in Towns has a risk score of 2 for impact energy of 50 J, increasing to a risk score of 3 for 100J , and increasing again to a risk score of 4 for impact energy of 500 J and above. UAVs of 50 m^2 and 80 m^2 in Towns have a risk score of 3 at an impact energy of 50 J, increasing to a risk score of 4 for all higher levels of impact energy.

As can be reasonably expected, Dense Urban areas (500-2000 people per km^2) have the highest level of risk. At an impact energy of 50 J, the risk score is 1 for a 0.1 m^2 UAV, 2 for a 0.5 m^2 or 1 m^2 UAV, and 3 for a UAV of 10 m^2, 30 m^2, 50 m^2, or 80 m^2. For impact energy greater than 50 J, the risk score is 2 for a 0.1 m^2 UAV, 3 for a 0.5 m^2 or 1 m^2 UAV, and 4 for a UAV of 10 m^2, 30 m^2, or 50 m^2. For a UAV of 80 m^2 the risk score is 4 for an impact energy of 100 J and 5 for an impact energy greater than 100 J.

It is apparent from Tables 10 to 17 that risk scores do not increase when impact energy increases above 500 J. Table 5 provides a summary of this "worst case" risk score by UAV Area and operational area. The risk score increases with increasing population density and increasing UAV Area, both factors which increase the probability of a person being hit by the UAV in the event of an in-flight failure. This table performs the same function as the SORA intrinsic UAS ground risk class table, with the exception that risk has been quantified and a given risk score represents the same level of risk no matter where in the table it occurs.

Table 5

Risk Score by UAV Area, Impact Energy 500 J and Above

		UAV Area							
Operational Area	People per km^2	0.1	0.5	1	5	10	30	50	80
Controlled Ground	0	0	0	0	0	0	0	0	0
Unpopulated	< 1	0	0	1	1	1	1	1	1
Sparsely Populated	1 - 10	1	1	1	1	1	2	2	2
Low Population	10 - 100	1	1	2	2	2	3	3	3
Urban Adjacent	100 - 200	1	2	2	2	3	3	3	3
Towns	200 - 500	2	2	2	3	3	4	4	4
Dense Urban	500 - 2000	2	3	3	3	4	4	4	4

Sensitivity Analysis: Normalised Social Cost

Table 5 and the risk score tables in the appendix are constructed using the normalized estimates of social cost for New Zealand. Table 6 shows the risk score when impact energy is 500 J and above, with the normalized estimates of US social cost. Comparison of Table 5 and Table 6 shows that the choice of normalized social cost does not alter the results of this analysis.

Table 6

Risk Score by UAV Area, Impact Energy 500 J and Above, Normalised US Social Cost

Operational Area	People per km^2	UAV Area 0.1	0.5	1	5	10	30	50	80
Controlled Ground	0	0	0	0	0	0	0	0	0
Unpopulated	< 1	0	0	1	1	1	1	1	1
Sparsely Populated	1 - 10	1	1	1	1	1	2	2	2
Low Population	10 - 100	1	1	2	2	2	3	3	3
Urban Adjacent	100 - 200	1	2	2	2	3	3	3	3
Towns	200 - 500	2	2	2	3	3	4	4	4
Dense Urban	500 - 2000	2	3	3	3	4	4	4	4

Sensitivity Analysis: Risk Categories

An alternative to the risk categories in Table 4 is to calculate the risk score by formula. Table 4 already exhibits a generally logarithmic progression, and this can be formalized. However, as we shall show in this sensitivity analysis, the choice of whether to truncate or round logarithmic results can alter the risk rating for a specific UAV Area / impact energy / operational area combination.

The truncated Risk Score formula is given by:

$$\text{Risk Score}_T = \begin{cases} 0 & \mid Risk_{\text{FE}} = 0 \\ max\left[\text{trunc}\left(\log_{10}\left(\frac{Risk_{\text{FE}}}{6\times10^{-7}}\right)\right), 0\right] & \mid Risk_{\text{FE}} > 0 \end{cases} \quad (5)$$

The Risk Score is set to 0 when $Risk_{FE} = 0$, as the logarithm of 0 is undefined. The resulting Risk Scores for an impact energy of 500 J and above are shown in Table 7. The truncated risk scores are very similar to those in Table 5. UAVs of area 10 m^2 and 30 m^2 have risk scores for some operational areas that are a unit increment higher in Table 7 than Table 5. However, a 1m^2 UAV over an unpopulated area and a 0.1 m^2 UAV over a sparsely populated area both have a Risk Score that is lower in in Table 7 than Table 5.

Table 7

Risk Score for Impact Energy 500 J and Above, Truncated Risk Score Formula

Operational Area	People per km²	UAV Area 0.1	0.5	1	5	10	30	50	80
Controlled Ground	0	0	0	0	0	0	0	0	0
Unpopulated	< 1	0	0	0	0	1	1	1	1
Sparsely Populated	1 - 10	0	1	1	1	2	2	2	2
Low Population	10 - 100	1	2	2	2	3	3	3	3
Urban Adjacent	100 - 200	1	2	2	3	3	3	3	3
Towns	200 - 500	2	2	2	3	3	4	4	4
Dense Urban	500 - 2000	2	3	3	4	4	4	4	4

The rounded risk score formula is given by:

$$\text{Risk Score}_R = \begin{cases} 0 & \mid Risk_{\text{FE}} = 0 \\ max\left[\text{round}\left(\log_{10}\left(\frac{Risk_{\text{FE}}}{6\times10^{-7}}\right), 0\right), 0\right] & \mid Risk_{\text{FE}} > 0 \end{cases} \quad (6)$$

As with the truncated Risk Score in equation 5, the Risk Score is set to 0 when $Risk_{FE} = 0$. The resulting Risk Scores for an impact energy of 500 J and above are shown in Table 8. Risk Scores are generally higher than those provided in Table 5, with most Risk Scores being a unit increment higher. Risk Scores for a 30 m² UAV over sparsely populated areas and areas of low population density are an increment of 2 higher than in Table 5, while a 1 m² UAV over an unpopulated area is the only scenario for which the Risk Score is lower. Risk Scores for 30 m², 5 0m², and 80 m² UAVs are generally a unit increment higher with rounding (Table 8) than with truncation (Table 7).

Table 8

Risk Score for Impact Energy 500 J and Above, Rounded Risk Score Formula

Operational Area	People per km²	UAV Area 0.1	0.5	1	5	10	30	50	80
Controlled Ground	0	0	0	0	0	0	0	0	0
Unpopulated	< 1	0	0	0	1	1	2	2	2
Sparsely Populated	1 - 10	1	1	1	2	2	3	3	3
Low Population	10 - 100	2	2	2	3	3	4	4	4
Urban Adjacent	100 - 200	2	2	3	3	3	4	4	4
Towns	200 - 500	2	3	3	4	4	4	4	4
Dense Urban	500 - 2000	3	3	4	4	4	5	5	5

Given the relative arbitrariness of assigning control actions to each risk level, neither approach to calculating the Risk Score is necessarily more correct than the other. The methodology that employs rounding will, however, often result in a higher Risk Score.

Discussion

Controlled Ground Area

Contrary to the SORA intrinsic UAS ground risk class table, the results of the present analysis demonstrate that there is no intrinsic ground risk from flight of a UAV over a controlled ground area that has no people present. This is a logical and intuitively expected outcome. This result implies that regardless of the size or mass of the UAV no special precautionary measures need to be taken to protect humans from harm. In a health and safety context, the controlled ground area has isolation controls imposed, ensuring that humans are separated from the potentially hazardous activity. As such, isolation is de facto elimination of the hazard (Young, 2017, p. 131). Further controls are only required if the means of isolation is not fully effective and a residual risk remains (ibid.). If the isolation controls are effective then no further controls are required, including airworthiness requirements for the UAV.

Comparison with Manned Aviation

The risk scores for large UAVs are at least somewhat consistent with what might be expected given the rules that apply in some jurisdictions to manned aviation. A common restriction is that experimental aircraft must not be operated over congested areas (14 CFR §91.319, 2022; CAANZ, 2021, §91.105), which correspond to the areas of higher population density in the Risk Score tables. In New Zealand, the civil aviation rules provide that for helicopters (CAANZ, 2021, §91.127(d)(3)):

> unless the helicopter is a performance Class 1 helicopter, any place used as a heliport or as a place to hover has such approach and take-off paths that an autorotative landing can be conducted without causing a hazard to any persons or property on the surface.

The requirement not to cause a hazard is very high standard and implies that the population density is sufficiently low that the pilot onboard is able to direct the helicopter to a location where there are no people who might be placed at risk.

Application of Hazard Controls

The risk rating methodology proposed in this article provides a structured basis for assessing the ability of hazard controls to reduce the risk of an unmanned aircraft operation. Consider first that a unit increase in Risk Score represents a ten-fold increase in risk. Suppose there is a hazard control that is effective in preventing 90% of inflight failures so that the MTBF increases from 100 to 1,000; the effect of this particular hazard control is a unit decrease in the Risk Score. Equivalently, the UAV could be operating over an area where 90% of the people are sheltered indoors; again there would be a unit decrease in the Risk Score. This concept can be extended to multiple controls applied to multiple independent sources of failure. Table 9 shows the risk reduction that can be obtained from the application of multiple hazard controls, each with less than perfect effectiveness. As shown in the top panel of Table 9, three independent hazard controls each with an effectiveness of 60% results in a combined failure rate of 0.064. This means that all three hazard controls will fail to be effective only 6.4% of the time; for the remaining 93.6% of the time at least one of the hazard controls will be effective and prevent a failure from occurring. An MTBF of 100 thus becomes an MTBF of 100/0.064 = 1,562. The reduction in risk level can be obtained by taking the logarithm of the combined failure rate of the controls and rounding to the nearest integer. Thus the risk reduction from the application of the three hazard controls each with an effectiveness of 60% is -1, as shown in the bottom panel of Table 9.

Table 9

Risk Reduction from Application of Hazard Controls

Control effectiveness	number of hazard controls				
	1	2	3	4	5
	combined failure rate				
90%	0.1	0.01	0.001	1E-04	1E-05
80%	0.2	0.04	0.008	0.0016	0.00032
70%	0.3	0.09	0.027	0.0081	0.00243
60%	0.4	0.16	0.064	0.0256	0.01024
50%	0.5	0.25	0.125	0.0625	0.03125
40%	0.6	0.36	0.216	0.1296	0.07776
30%	0.7	0.49	0.343	0.2401	0.16807
20%	0.8	0.64	0.512	0.4096	0.32768
	impact on risk rating				
90%	-1	-2	-3	-4	-5
80%	-1	-1	-2	-3	-3
70%	-1	-1	-2	-2	-3
60%	0	-1	-1	-2	-2
50%	0	-1	-1	-1	-2
40%	0	0	-1	-1	-1
30%	0	0	0	-1	-1
20%	0	0	0	0	0

Regulator Adoption of SORA

Notwithstanding the identified criticisms of SORA, adoption by regulatory authorities is perhaps unsurprising. In the first instance, JARUS was initially formed in 2007 by European national aviation authorities in an attempt to develop a common approach to managing risks from UAS (Dalamagkidis et al., 2012, p. 78). Civil aviation is regulated internationally according to a framework promulgated by the International Civil Aviation Organisation (ICAO), so it makes sense to adopt a common regulatory framework for UAS. Second, regulators who are constrained by capacity or capability will be better placed using SORA as a tool than having no tool at all. Third, the behavior of civil aviation regulatory agencies can be explained within the principal-agent framework of economics, where the legislature is the principal and the regulatory agency is the agent (Waterman & Meier, 1998). The regulatory agency possesses vastly more information about the specifics of the aviation sector and UAS than does the legislature. Waterman and Meier (1998) suggest that if there is broad consensus between the legislature and the agency on the appropriate goals of regulation – such as facilitating the safe integration of UAS into national airspace – then the result is that politicians will generally only intervene if there is a major problem. The SORA framework is sufficient to meet the broad regulatory objectives, even if it does not do so perfectly. The potential for political intervention in the event of a major failure then leads to the fourth reason for the adoption of the SORA methodology: blame avoidance. If a major problem does occur then bureaucratic blame avoidance can seek legitimation by appeal to the authority of the international group (Hansson, 2015; Van Leeuwen, 2007). In the event of an adverse occurrence, failure of the relevant regulator to follow what others are doing can be criticized as a failure to follow best practice, so from an institutional perspective it is always lower risk to follow the consensus of the broader group than to critically analyze and assess the methodology. The methodology presented in the current article provides a coherent and logical framework that can be used to provide alternative risk assessments while satisfying regulators' needs for legitimation.

Conclusion

This article provides a first principles calculation of ground risk that provides significantly different results to the SORA intrinsic ground risk model. For an MTBF = 100, overflight of low population density areas is consistent with the risk to third parties associated with General Aviation. As such, it is argued that this should be considered an acceptable level of risk and not require any specific additional controls.

This article has focused on the calculation of what the level of risk might be from UAS, but it has not addressed *what* "threat barriers" or "hazard controls" should be implemented for those situations where risk is higher than the generally accepted level for General Aviation. Nevertheless, it has proposed a methodology for assessing how a hazard control or group of controls should impact on the assessed risk of an operation. Furthermore, any operation which has a ground risk category of 0 or 1 should be able to proceed with no additional controls for ground risk as this is the same or lower risk as General Aviation.

Finally, the methodology presented here could form the basis of a ground risk model that can be applied by regulators. The need of regulators to seek legitimation for their approach is acknowledged, but the current SORA based approach relies on a model that is demonstrably inconsistent. The mathematical model or analysis that underpins the SORA approach has never been released, so SORA remains an opaque black box. The use of an approach published in aviation journals provides transparency and aids the process of operator acceptance.

References

14 CFR §91.119, (2022). https://www.ecfr.gov/current/title-14/chapter-I/subchapter-F/part-91/subpart-B/subject-group-ECFRe4c59b5f5506932/section-91.119

14 CFR §91.305, (2022). https://www.ecfr.gov/current/title-14/chapter-I/subchapter-F/part-91/subpart-D/section-91.305

14 CFR §91.319, (2022). https://www.ecfr.gov/current/title-14/chapter-I/subchapter-F/part-91/subpart-D/section-91.319

14 CFR §107.25, (2022). https://www.ecfr.gov/current/title-14/chapter-I/subchapter-F/part-107/subpart-B/section-107.25

CAANZ. (2021). *Civil Aviation Rules Part 91*. Civil Aviation Authority of New Zealand. https://www.aviation.govt.nz/rules/rule-part/show/91

CAANZ. (2022, September 9). Applying for a Part 102 certificate. *Civil Aviation Authority of New Zealand*. https://www.aviation.govt.nz/drones/applying-for-a-part-102-certificate/

Cabral, T., Duarte, M., Place, S., Mccarthy, P., & Caetano, J. V. (2018). *Unmanned aircraft systems risk assessment: Review of existing tools and new results*. https://doi.org/10.14339/STO-MP-IST-166-05-PDF

CASA. (2021a). *BVLOS operations in remote Australian airspace (below 400 ft AGL)* (CASA-03-5595). https://www.casa.gov.au/applicant-response-bvlos-operations-remote-australian-airspace-below-400-ft-agl

CASA. (2021b). *Standard scenario application and documents—Guidance material* (CASA-03-5597). https://www.casa.gov.au/standard-scenario-application-and-documents-guidance-material

Dalamagkidis, K., Valavanis, K. P., & Piegl, L. A. (2012). *On integrating unmanned aircraft systems into the national airspace system: Issues, challenges, operational restrictions, certification, and recommendations*. Springer.

Denney, E., Pai, G., & Johnson, M. (2018). *Towards a rigorous basis for specific operations risk assessment of UAS*. 37th AIAA/IEEE Digital Avionics Systems Conference (DASC 2018), London. http://dx.doi.org/10.1109/DASC.2018.8569475

Dijkstra, L., & Poelman, H. (2014). *A harmonized definition of cities and rural areas: The new degree of urbanization* (Regional Working Paper WP 01/2014). European Commission. https://eclass.hua.gr/modules/document/file.php/GEO244/Documentation_texts-graphics-papers/EC.Regional%26Urban_PolicyDG_DIJKSTRA%26POELMAN_2014_01_new_urban_wp.pdf

EASA. (2020). *Notice of Proposed Amendment 2020-07: Unmanned aircraft system beyond visual line operations over populated areas or assemblies of people in the 'specific' category* (RMT.0730). European Union Aviation Safety Agency. https://www.easa.europa.eu/sites/default/files/dfu/NPA%202020-07.pdf

EASA. (2022). *Easy access rules for unmanned aircraft systems*. European Union Aviation Safety Agency. https://www.easa.europa.eu/en/document-

library/easy-access-rules/easy-access-rules-unmanned-aircraft-systems-regulations-eu
Federal Aviation Administration. (2006). Experimental permits for reusable suborbital rockets. *Federal Register*, *71*(62), 16251–16273.
Gløersen, E., Dubois, A., Copus, A., & Schürmann, C. (2006). *Northern peripheral, sparsely populated regions in the European Union and in Norway* (Report 2006:2). Nordregio. https://www.diva-portal.org/smash/get/diva2:700429/FULLTEXT01.pdf
Hansson, S. (2015). Discursive strategies of blame avoidance in government: A framework for analysis. *Discourse & Society*, *26*(3), 297–322. https://doi.org/10.1177/0957926514564736
JARUS. (2017). *JARUS guidelines on Specific Operations Risk Assessment (SORA)* (1.0). Joint Authorities for Rulemaking on Unmanned Systems. http://jarus-rpas.org/sites/jarus-rpas.org/files/ jar_doc_06_jarus_sora_v1.0.pdf
JARUS. (2019). *JARUS guidelines on Specific Operations Risk Assessment (SORA)* (2.0). Joint Authorities for Rulemaking on Unmanned Systems. http://jarus-rpas.org/sites/jarus-rpas.org/files/jar_doc_06_jarus_sora_v2.0.pdf
Mickalich v. United States of America, No. 05-72276 (United States District Court Eastern District of Michigan 5 April 2007). https://www.govinfo.gov/app/details/USCOURTS-mied-2_05-cv-72276/context
Oberhagemann, D. (2012). *Static and dynamic crowd densities at major public events* (Technical Report vfdb TB 13-01). Vereinigung zur FÄrderung des Deutschen Brandschutzes e. V. (vfdb), German Fire Protection Association, Technical-scientific advisory board (TWB), Department 13. https://www.vfdb.de/media/doc/sonstiges/forschung/eva/tb_13_01_crowd_densities.pdf
Shelley, A. V. (2016). A model of human harm from a falling unmanned aircraft: Implications for UAS regulation. *International Journal of Aviation, Aeronautics, and Aerospace*, *3*(3), 1–42. https://doi.org/10.15394/ijaaa.2016.1120
Svatý, Z., Nouzovský, L., Mičunek, T., & Frydrýn, M. (2022). Evaluation of the drone-human collision consequences. *Heliyon*, *8*(11), e11677. https://doi.org/10.1016/j.heliyon.2022.e11677
Transport Canada. (2021). *Advisory Circular (AC) No. 903-001: Remotely piloted aircraft systems operational risk assessment*. https://tc.canada.ca/en/aviation/reference-centre/advisory-circulars/advisory-circular-ac-no-903-001
UAS Task Force. (2015). *Task force recommendations final report*. Unmanned aircraft systems (UAS) registration task force (RTF) aviation rulemaking committee (ARC). https://downloads.regulations.gov/FAA-2015-7396-5594/attachment_1.pdf

Van Leeuwen, T. (2007). Legitimation in discourse and communication. *Discourse & Communication*, *1*(1), 91–112. https://doi.org/10.1177/1750481307071986

Waterman, R. W., & Meier, K. J. (1998). Principal-agent models: An expansion? *Journal of Public Administration Research and Theory*, *8*(2), 173–202. https://doi.org/10.1093/oxfordjournals.jpart.a024377

Young, S. A. (2017). *Efficacy and understanding of the safety hierarchy of controls* [PhD Thesis, Federation University Australia]. https://researchonline.federation.edu.au/vital/access/services/Download/vital:13343/SOURCE1?view=true

Appendix

Risk Tables

Table 10

Risk Score, UAV Area = 0.1m²

Operational Area	People per km²	Impact Energy					
		50J	100J	500 J	700J	5 kJ	50 kJ
Controlled Ground	0	0	0	0	0	0	0
Unpopulated	< 1	0	0	0	0	0	0
Sparsely Populated	1 - 10	0	1	1	1	1	1
Low Population	10 - 100	1	1	1	1	1	1
Urban Adjacent	100 - 200	1	1	1	1	1	1
Towns	200 - 500	1	2	2	2	2	2
Dense Urban	500 - 2000	1	2	2	2	2	2

Table 11

Risk Score, UAV Area = 0.5m²

Operational Area	People per km²	Impact Energy					
		50J	100J	500 J	700J	5 kJ	50 kJ
Controlled Ground	0	0	0	0	0	0	0
Unpopulated	< 1	0	0	0	0	0	0
Sparsely Populated	1 - 10	0	1	1	1	1	1
Low Population	10 - 100	1	1	1	1	1	1
Urban Adjacent	100 - 200	1	2	2	2	2	2
Towns	200 - 500	1	2	2	2	2	2
Dense Urban	500 - 2000	2	3	3	3	3	3

Table 12

Risk Score, UAV Area = 1m²

Operational Area	People per km^2	Impact Energy					
		50J	100J	500 J	700J	5 kJ	50 kJ
Controlled Ground	0	0	0	0	0	0	0
Unpopulated	< 1	0	0	1	1	1	1
Sparsely Populated	1 - 10	0	1	1	1	1	1
Low Population	10 - 100	1	1	2	2	2	2
Urban Adjacent	100 - 200	1	2	2	2	2	2
Towns	200 - 500	1	2	2	2	2	2
Dense Urban	500 - 2000	2	3	3	3	3	3

Table 13

Risk Score, UAV Area = 5m²

Operational Area	People per km^2	Impact Energy					
		50J	100J	500 J	700J	5 kJ	50 kJ
Controlled Ground	0	0	0	0	0	0	0
Unpopulated	< 1	0	1	1	1	1	1
Sparsely Populated	1 - 10	1	1	1	1	1	1
Low Population	10 - 100	1	2	2	2	2	2
Urban Adjacent	100 - 200	1	2	2	2	2	2
Towns	200 - 500	2	3	3	3	3	3
Dense Urban	500 - 2000	2	3	3	3	3	3

Table 14

Risk Score, UAV Area = 10m²

Operational Area	People per km²	Impact Energy 50J	100J	500 J	700J	5 kJ	50 kJ
Controlled Ground	0	0	0	0	0	0	0
Unpopulated	< 1	0	1	1	1	1	1
Sparsely Populated	1 - 10	1	1	1	1	1	1
Low Population	10 - 100	1	2	2	2	2	2
Urban Adjacent	100 - 200	2	3	3	3	3	3
Towns	200 - 500	2	3	3	3	3	3
Dense Urban	500 - 2000	3	4	4	4	4	4

Table 15

Risk Score, UAV Area = 30m²

Operational Area	People per km²	Impact Energy 50J	100J	500 J	700J	5 kJ	50 kJ
Controlled Ground	0	0	0	0	0	0	0
Unpopulated	< 1	1	1	1	1	1	1
Sparsely Populated	1 - 10	1	2	2	2	2	2
Low Population	10 - 100	2	3	3	3	3	3
Urban Adjacent	100 - 200	2	3	3	3	3	3
Towns	200 - 500	2	3	4	4	4	4
Dense Urban	500 - 2000	3	4	4	4	4	4

Table 16

Risk Score, UAV Area = 50m²

Operational Area	People per km^2	Impact Energy					
		50J	100J	500 J	700J	5 kJ	50 kJ
Controlled Ground	0	0	0	0	0	0	0
Unpopulated	< 1	1	1	1	1	1	1
Sparsely Populated	1 - 10	1	2	2	2	2	2
Low Population	10 - 100	2	3	3	3	3	3
Urban Adjacent	100 - 200	2	3	3	3	3	3
Towns	200 - 500	3	4	4	4	4	4
Dense Urban	500 - 2000	3	4	4	4	4	4

Table 17

Risk Score, UAV Area = 80m²

Operational Area	People per km^2	Impact Energy					
		50J	100J	500 J	700J	5 kJ	50 kJ
Controlled Ground	0	0	0	0	0	0	0
Unpopulated	< 1	1	1	1	1	1	1
Sparsely Populated	1 - 10	1	2	2	2	2	2
Low Population	10 - 100	2	3	3	3	3	3
Urban Adjacent	100 - 200	2	3	4	4	4	4
Towns	200 - 500	3	4	4	4	4	4
Dense Urban	500 - 2000	3	4	5	5	5	5

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