A45-Shielded UAS Operations: Detect and Avoid (DAA): Task 2 Shielding Classes, Risk Assessments, and Listing of Mitigations Report

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16. Abstract

The demand for Beyond Visual Line Of Sight (BVLOS) operations using Uncrewed Aircraft Systems (UASs) is high owing to the numerous associated benefits. One approach that can enable small UAS (sUAS) BVLOS operations is shielded operations, wherein a sUAS is operated near objects such as buildings, powerlines, etc. This Alliance for System Safety through University Research Excellence (ASSURE) project (A45) has numerous associated tasks. Herein, the focus is on Safety Risk Assessment (SRA) for shielded operations (to evaluate shielding benefits).

The team developed shielding classes that define the type of shielded operation and the environment for three hazard categories: air, ground, and infrastructure. Doing so for the air risk category involved understanding low-altitude Crewed Aircraft (CA) operations, analysis of applicable regulations to identify drivers for low-altitude CA operations, and identification of other factors that drive low-altitude CA operations. The result is a classification system that provides information about the type of shielded operation and associated environmental characteristics.

The SRA utilized the well-established approach of defining risk as a combination of severity and likelihood. Severity scales were developed/modified based upon previous work (air and ground risk) or created (infrastructure risk) leveraging the experience of the team. A Probabilistic Risk Analysis (PRA) framework is developed that illustrates the likelihood of events associated with interactions with CA (well clear violation, near mid-air collision, mid-air collision). This framework illustrates how risk ratios combine when sequential events occur and illustrates how shielding and combinations of shielding and DAA reduce air risk.

Estimates of shielding benefits and CA traffic density are used to evaluate shielded operational risk, with the highest shielding without DAA producing a 1D (yellow) risk. Requirements for DAA systems to produce 1E (yellow) risk are examined, as are means for reducing DAA requirements.

Analysis of survey data indicates that how near operators fly to obstacles depends upon the operator and the obstacle, with some avoiding certain obstacles at relatively large distances (>200 ft) and others regularly flying close (<25 ft) to obstacles. A limited analysis of cooperative aircraft data supports these results, showing that agricultural applicators can fly very close to powerlines (within 31 ft). Thus, it appears as if the benefits of shielding can be limited depending on the types of low altitude CA operations that might be encountered.

A conservative risk estimate for ground collisions in a rural environment is 1D (yellow). This can be reduced using mitigations identified herein. No estimate for infrastructure risk is provided, though it is noted that a collision of an sUAS with a powerline did result in a power outage of ~3 hrs (severity of 2).

Hazard causes and mitigations are provided. Moreover, future work and opportunities, including regulatory/policy opportunities, are discussed.

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TABLE OF ACRONYMS

Acronym	Meaning
2D	Two Dimensional
ADS-B	Automatic Dependent Surveillance-Broadcast
AGL	Above Ground Level
ARC	Aviation Rulemaking Committee
ASSURE	Alliance for System Safety of UAS Through Research Excellence
ATC	Air Traffic Control
ATO	Air Traffic Organization
ATS	Air Traffic Services
AVS	Office of Aviation Safety
BVLOS	Beyond Visual Line Of Sight
C2	Command and Control
CA	Crewed Aircraft
CFR	Code of Federal Regulations
CONOPS	Concept Of Operations
DAA	Detect And Avoid
EMI	ElectroMagnetic Interference
EMS	Emergency Medical Services
FAA	Federal Aviation Administration
FTP	Flight Test Plan
FHWA	Federal Highway Administration
GPS	Global Positioning System
HAA	Helicopter Air Ambulance
HTAWS	Helicopter Terrain Awareness and Warning System
IFR	Instrument Flight Rules
IMC	Instrument Meteorological Conditions
INS	Inertial Navigation System
JARUS	Joint Authorities for Rulemaking of Unmanned Systems
IR	InfraRed
LIDAR	Light Detection And Ranging
LTE	Long Term Evolution
MAC	Mid-Air Collision
MCA	Minimum Crossing Altitude
MEA	Minimum En Route Altitude
MOCA	Minimum Obstruction Clearance Altitude
MSL	Mean Sea Level
NAAA	National Agricultural Aviation Association
NAS	National Airspace System
NASEM	National Academies of Sciences, Engineering, and Medicine
NEMSPA	National EMS Pilots Association
NMAC	Near Mid-Air Collision
NS	No Shielding
NVIS	Night Vision Imaging System
P2P	Point to Point
PDF	Probability Density Function
PRA	Probabilistic Risk Analysis
SAA	Sense And Avoid
SF	Shielding Factor
SL	Shielding Level
SME	Subject Matter Expert
SMR	Strategic Mitigation Ratio

SO	Shielding Object
SRA	Safety Risk Assessment
sUAS	Small Uncrewed Aircraft System
UA	Uncrewed Aircraft
UAS	Uncrewed Aircraft System
UASFM	UAS Facility Map
UND	University of North Dakota
U.S.	United States
U.S.C.	United States Code
VFR	Visual Flight Rules
VOR	Very High Frequency Omni-Directional Range
VMC	Visual Meteorological Conditions
WAAS	Wide Area Augmentation System
WCV	Well Clear Violation

EXECUTIVE SUMMARY

The demand for Beyond Visual Line Of Sight (BVLOS) operations using Uncrewed Aircraft Systems (UASs) is high owing to the numerous associated benefits. One approach that can enable small UAS (sUAS) BVLOS operations is shielded operations, wherein a sUAS is operated near objects such as buildings, powerlines, etc. For the purposes of this effort, operation near such objects is assumed to produce a safety benefit relative to encounters with Crewed Aircraft (CA) since CA will generally maintain separation from such objects.

This Alliance for System Safety through University Research Excellence (ASSURE) project (A45) has numerous associated tasks. Herein, the focus is on Safety Risk Assessment (SRA) for shielded operations. Well-defined processes are used, with effort divided into two primary tasks:

- Development of a set of shielding classes, which can be used to support an SRA
- Hazard analysis (SRA)

The team developed shielding classes that define the type of shielded operation and the environment for three hazard categories: air, ground, and infrastructure. Doing so for the air risk category involved understanding low-altitude CA operations, analysis of applicable regulations to identify drivers for low-altitude CA operations, and identification of other factors, in addition to regulations, that drive low-altitude CA operations. The result is a classification system that provides information about the type of shielded operation and environmental characteristics (air, ground, and infrastructure) associated with the operation.

The SRA utilized the well-established approach of defining risk as a combination of severity and likelihood. Severity scales were developed/modified based upon previous work (air and ground risk) or created (infrastructure risk) leveraging the experience of the A45 team. A Probabilistic Risk Analysis (PRA) framework is developed that illustrates the likelihood of events associated with interactions with CA [well clear violation, Near Mid-Air Collision (NMAC), Mid-Air Collision (MAC)]. This framework illustrates how risk ratios combine when sequential events occur (e.g., well clear violation, NMAC, and MAC). This framework is also used to illustrate how shielding and combinations of shielding and DAA reduce air risk.

Estimates of shielding benefits and CA traffic density are used to evaluate shielded operational risk, with the highest shielding without DAA producing a 1D (yellow) risk. Requirements for DAA systems to produce 1E (yellow) risk are examined, as are means for reducing DAA requirements. A survey of operators indicated that how near they fly to obstacles depends upon the operator and the obstacle, with some avoiding certain obstacles at relatively large distances (>200 ft) and others regularly flying close (<25 ft) to obstacles (e.g., agricultural applicators near powerlines). A limited analysis of cooperative aircraft data from agricultural applicators support this finding (passing within 31 ft). Thus, it appears as if the benefits of shielding can be limited depending on the types of low altitude CA operations that might be encountered.

A conservative risk estimate for ground collisions in a rural environment is 1D (yellow). This can be reduced using mitigations identified herein. No estimate for infrastructure risk is provided, though it is noted that a collision of an sUAS with a powerline did result in a power outage of ~3 hrs (severity of 2).

Hazard causes and mitigations are provided. Moreover, future work and opportunities, including regulatory/policy opportunities, are discussed.

1 INTRODUCTION

The demand for Beyond Visual Line Of Sight (BVLOS) operations using Uncrewed Aircraft Systems (UASs) is high.[1] Such operations produce numerous benefits, including humanitarian and economic (e.g., UAS BVLOS Aviation Rulemaking Committee (ARC) 2022). Humanitarian benefits include improving health outcomes (including saving lives), while economic benefits include reduced costs and increased efficiency associated with numerous use cases (inspection, package delivery, etc.). These benefits have resulted in increased pursuit of BVLOS capabilities, with much of the focus being upon small UAS (sUAS) owing to reduced risks (air and ground collision risks) associated with such aircraft.

One approach that can enable sUAS BVLOS operations is shielded operations, wherein a sUAS is operated near objects such as buildings, powerlines, etc. Operation near such objects is assumed to produce a safety benefit relative to encounters with Crewed Aircraft (CA) since CA will generally maintain separation from such objects for both safety reasons and because of regulatory requirements. Shielded operations have the potential for enabling safe sUAS BVLOS operations. While the amount of low-altitude airspace that could be accessed using shielding is relatively small, such operations could be used, in addition to serving directly-related use cases such as powerline inspection, to serve as a network (e.g., powerline networks) that enables operations to reach stakeholders' customers.[2]

The Alliance for System Safety of UAS Through Research Excellence (ASSURE) project A45-Shielded UAS Operations: Detect and Avoid (DAA) (A45) involves numerous tasks associated with shielded operations. Herein, the focus is on Safety Risk Assessment (SRA) associated with each defined Concept Of Operations (CONOPS). Processes follow those defined by the Federal Aviation Administration (FAA), including U.S. Department of Transportation (2017a, 2019) and FAA Air Traffic Organization (2019).

2 TASKS

Tasks in A45 include:

0. Project Management:

   Management of the overall project, including project kick-off, the project research task plan, technical interchange meetings, program management reviews, leadership briefings, and project close out.
1. Literature Review and Risk Identification

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[1] It is noted that the term Uncrewed Aircraft (UA) is used to indicate aircraft that do not have humans onboard. Thus, the term refers to the physical location of the crew (UA do have a crew). UA are contrasted with Crewed Aircraft (CA) that do have humans onboard.

[2] An estimate of impacted airspace can be produced using the electric power transmission grid, which involves large transmission lines and not smaller distribution lines. This grid consists of approximately 120,000 miles of lines in the contiguous United States (https://en.wikipedia.org/wiki/North_American_power_transmission_grid#Description). Assuming operations within 100 ft on either side of these lines, based upon UAS BVLOS ARC (2022), and assuming no width for the lines, this results in an impacted area of 4545.45 mi^2. Dividing by the area of the contiguous United States, 3,119,884.69 mi^2 (https://en.wikipedia.org/wiki/Contiguous_United_States), produces an impact on ~0.15% of contiguous United States airspace. This estimate is low, of course, as it does not include smaller distribution lines or other types of objects (buildings, towers, tree lines, etc.).

A comprehensive literature review of shielding research, including terminology, shielding benefits, and identification of risks associated with shielded operations.

2. Shielding Classes, Risk Assessments, and Listing of Mitigations
    a. Shielding Classes/Categories
    b. Hazard Analysis

    Identification/creation of shielding classes/categories and completion of a hazard analysis in which risks and risk mitigations are identified.
3. Analysis of DAA Requirements and Obstacle Avoidance Requirements

    Development of a simulation environment that will allow assessment of risks and potential solutions identified in Tasks 1 and 2. Numerical simulations will be performed to analyze the competing shielding requirements to manage risks with flight near obstacles and to manage risks with CA. Risks evaluated include those associated with the type of operation, UAS characteristics, type of obstacle, and type of intruder.
4. Flight Test Plans

    Development of Flight Test Plans (FTPs) for the most promising types of shielded operations. Operations are based upon industry needs, need to evaluate performance based on previous findings, and the viability of performing such tests.
5. Tests and Reports

    Tests and demonstrations conducted using the developed FTPs from Task 4 and documentation of the approach and outcomes. Reports will interpret the significance of tests and outcomes and the degree to which results refine and validate previous shielding recommendations.
6. Standards Development

    Participation in relevant standards development efforts. Results from A45 will be used to enhance those efforts by providing relevant research results.
7. Final Briefing and Final Report

    Summarization of all of the previous papers and reports (excluding meeting notes) into a final report package for the overall project.
8. Peer Review

    A peer review of the final report.

The focus herein is on Task 2. Task 2a involves creation of classes/categories of shielded operations whereas the Task 2b foci are evaluation of risk and identification of mitigations. Task 2b includes consideration of numerous factors, including:

- Prioritization for managing simultaneous risks
- Type of UAS
- Phase of flight
- Layered mitigations
- Obstacle avoidance capabilities
- Global Positioning System (GPS) and obstacle map validation approaches
- ElectroMagnetic Interference (EMI) mitigations
- DAA
    - Capabilities
    - Concepts that include safe states
    - Filtering of non-relevant tracks (e.g., ground vehicles, birds, etc.)

- Bird strike hazards

3 TASK 2A: SHIELDING CLASSES/CATEGORIES

3.1 Low-Altitude CA Operations

Because obstacles that can be utilized for shielding exist at low Above Ground Level (AGL) altitudes, low-altitude CA operations are considered herein. Weinert and Barrera (2000) aggregated information from a broad set of sources to conduct an extensive review of low-altitude manned aircraft operations. While additional information regarding low-altitude manned aircraft operations can be gleaned from other sources (e.g., Xue et al. 2018; Weinert et al. 2019; Underhill and Weinert 2021), Weinert and Barrera (2000) represents the most comprehensive review available and is the focus here.

A summary of the information provided by Weinert and Barrera (2000) is provided in Table 1. The set of 12 operations provided by Weinert and Barrera (2000) has been supplemented by the A45 team, as indicated in the comments. In this table, specific Code of Federal Regulations (CFR) sections are provided for some operations. It is noted that it is possible that not all low-altitude operations are captured in Table 1 (e.g., hot air balloons). Gliders, sailplanes, and powered parachutes are generally considered to be ultralights. Additional information regarding operations listed in Table 1 is provided in the following sections.

3.1.1 Spraying and Dusting

As indicated in Table 1, Spraying and Dusting flights are executed at very low altitudes (2-20 ft AGL), indicating that relative to these operations the ground does not provide shielding benefits. Detailed information regarding flight characteristics (climb/descent angles, turn rates, spraying speeds, spraying altitudes, cruise speeds, cruise altitudes, etc.) derived from flight log data are provided by Ryker et al. (2020), results from which are partially summarized by Sugumar et al. (2021). It is noted that these data have not been used to determine flight occurrence characteristics such as location-driven, seasonal, and diurnal (day/night) patterns. These are considered in Section 3.2.1.2 of this report. In addition, Ryker et al. (2022) determined that during non-mission-specific legs (not dispensing or conducting aerial work operations related to agriculture, horticulture, or forest preservation) such aircraft commonly operate above 500 ft AGL, although some are below 500 ft AGL.

It is noted that under 14 CFR Part 137, which governs Spraying and Dusting, firefighting with fixed-wing aircraft is allowed (U.S. Department of Transportation 2017b). This use case is quite a bit different from agricultural operations, and can result in operations under 14 CFR Part 137 in locations where agricultural operations would not otherwise occur (e.g., non-agricultural lands such as forests, semi-arid regions, etc.).

3.1.2 Insect and Fish Release

Both of these operations occur at relatively low altitudes. The speeds at which these occur are consistent with general aviation single-engine aircraft speeds (e.g., Underhill and Weinert 2021).

3.1.3 Helicopter Air Ambulance (HAA)

As with other types of low-altitude manned aircraft operations, data regarding HAA operations is lacking. This includes the number of flight hours per year. Estimates vary from 100,000-300,000 for the years 1991-2003 to 900,000 from 1993-2003 and 1,600,000 in 2004 (Weinert and Barrera

2020). Speeds are not provided in Weinert and Barrera (2020). However, Underhill and Weinert (2021) found that rotorcraft tend to be flown at lower speeds relative to fixed-wing aircraft at low altitudes (with similar accelerations, vertical rates, and turn rates). They also found that they tend to fly lower than fixed-wing aircraft, though they likely had a limited sample in their data set.

Table 1. Summary of low-altitude CA operations. Adapted from Weinert and Barrera (2020).

Operation	Flight Altitudes (ft AGL)	Speeds (kts)	14 CFR Part	Comments
Spraying and Dusting	2-20	50-120	137	Firefighting with fixed-wing allowed (U.S. Department of Transportation 2017b).
Insect Release	300-2500	78-88*	91, 135	Uncertainty regarding 14 CFR part (depending on who executes flights).
Fish Release	150-300	70	91, 135	Uncertainty regarding 14 CFR part (depending on who executes flights).
Helicopter Air Ambulance	0 and up	Not Provided	135 (135.271, Subpart L)	
Infrastructure Inspection (Rotary Wing)	0 and up	0-100	91	A45 added
Infrastructure Inspection (Fixed Wing)			91	A45 added
Infrastructure Work (Rotary Wing)	Infrastructure height	~0	91	A45 added; Example is work on powerlines.
Helicopter Air Tours	400-3300	Not Provided	91 (91.147), 119, 121, 135, 136	Aircraft models can be used to obtain airspeeds.
Helicopter Offshore Operations	500 and up	Not Provided	135 (135.181)	Aircraft models can be used to obtain airspeeds.
Helicopter News Gathering	500-3280	0-140	119, 135	
Helicopter Public Safety	300-3280	0-140	119, 135	
Helicopter External-Load Operations	0 and up		133	A45 added (firefighting, wire pulling, etc.).
Training	200 and up	Not Provided	121, 129, 135, 137, 141	Aircraft models can be used to obtain airspeeds.
Animal Sciences	30-4590**	19-175***	91, 135	
Earth Sciences	100-2130	27-120	91, 135	
Plant Sciences	<500-32,000	11-200	91	
Recreational Flying			91	A45 added
Ultralight Vehicles	<=12,500	≤ 55	103	A45 added; Supplemental oxygen required for flight > 30 minutes above 12,500 ft; Been flown above 12,500 ft.

*Average speeds based on operational guidance.
**Many operations are reported to occur below 500 ft AGL.
***175 kt flights at altitudes 1200-2000 ft AGL. Highest speed for altitudes < 700 ft AGL is 108 kts.

3.1.4 Infrastructure Inspection with Rotary- and Fixed-Wing Aircraft

The A45 team added these operations, as inspection (e.g., powerline inspection) with CA is expected to occur relatively close to the relevant infrastructure. To identify possible stand-off distances, the A45 team explored literature regarding powerline inspection. When conducted using CA, these inspections are almost invariably conducted using helicopters (e.g., Yang et al. 2020). Information regarding stand-off distances and speeds is difficult to acquire. However, sources of these include:

1. Whitworth et al. (2001), who refer to operations that are relatively near to powerlines being within 30-50 m (~100-165 ft) of them. They also simulated powerline inspection using a 20 m (~65 ft) horizontal and vertical offset at a flight speed of 10 m s^{-1} (~20 kts).
2. Williams et al. (2001), who describe helicopter inspections occurring within 10-15 m (~33-50 ft) of powerlines and at 15 m AGL.
3. Ma and Chen (2004), who describe:
   a. A detailed inspection technique used in the past wherein trained inspectors onboard helicopters inspect using binoculars and cameras while recording data in a log book. This is typically conducted while hovering.
   b. Evolving, at that time, helicopter-based approaches:
      i. Utilization of video surveillance, with flight speeds of 50-60 mph (~43-52 kts) and stand-off distances of 30-50 m (~100-165 ft).
      ii. Utilization of image-based surveillance, with a flight speed of 55 mph (~48 kts) and a stand-off distance of 300 ft.
      iii. A video and still image analysis system that provides detail such as identification of broken insulators at speeds of 70-90 mph (~61-78 kts).
4. West and Segerstrom (2000), who describe flights with speeds of 50-70 kts and operated 50-75 m (~165-250 ft) above the powerlines.

Examples of Infrastructure Inspection using fixed-wing CA are harder to find. Frost (2010) indicated that at that time the operational practice for pipeline inspections was operation of light aircraft flown at ~500 ft AGL and 100 kts. Frost indicated that these operations typically used a single pilot but sometimes utilized an observer and that detection of issues relied upon the vision of the pilot and/or observer. St. Pierre (1999) describes oil pipeline monitoring and wildlife surveys in the North Slope of Alaska using a Twin Otter CA. Their example pipeline images indicate that they were collected at ~1,000 ft distance and were overhead (or nearly so), indicating flight above 500 ft AGL. Their example wildlife image was captured at 500 ft AGL. Powell et al. (1998) provide more detail regarding the flight characteristics of these operations, and indicated that flights were typically conducted at altitudes of 500-1000 ft AGL.

While information regarding use of fixed-wing CA for powerline inspections is difficult to find, evidence that they are used for this purpose is present (e.g., NASA 2022). As indicated by Matikainen et al. (2016), fixed-wing CA have commonly been used to monitor vegetation encroachment while rotary-wing CA have commonly been used for inspecting powerline components.

3.1.5 Infrastructure Work (Rotary Wing)

Rotary-wing aircraft are used to work on powerlines, including maintenance and external load operations (14 CFR Part 133) such as wire pulling, marker ball installation/removal, etc. (IEEE

ESMOL Subcommittee15.07 2006). A key requirement for aspects of this work is being at the same potential as the part on which work is conducted. Helicopters generally hover or move very slowly for this type of operation and separation distances relative to the infrastructure can be minimal (zero).

3.1.6 Helicopter Air Tours

In addition to the 14 CFR §91.147 regulations, local rulesets can also govern these operations. Nationwide data regarding flight hours are hard to find. However, some local statistics are available (e.g., New York). The altitude range provided in Table 1 is based upon company websites and a few informal phone surveys. It is expected that some air tours may operate below the 400 ft lower limit listed in Table 1. Flight characteristics are likely to be similar to those identified by Underhill and Weinert (2021), with lower and slower flight relative to fixed-wing aircraft and similar accelerations, vertical rates, and turn rates.

3.1.7 Helicopter Offshore Operations

These operations involve transport of passengers or supplies. Data regarding these operations are limited. Such operations are commonly compared to HAA operations, though differences have been noted.

3.1.8 Helicopter News Gathering and Public Safety

Information regarding these use cases was difficult for Weinert and Barrera (2020) to identify. Consequently, the information is drawn from publications that describe specific operations and does not represent a large and rigorous data set. Reported speeds for such operations reach a relatively high value (140 kts), though these operations are likely conducted at relatively lower speeds such as those identified by Underhill and Weinert (2021), as lower speeds would commonly enhance mission effectiveness for these use cases. From the limited information available, Weinert and Barrera (2020) concluded that operational altitudes are ≥ 500 ft AGL. However, according to Center for Criminal Justice Operations and Management (1971), police operations are conducted as low as 300 ft AGL and, thus, this is the lowest altitude listed in Table 1. It is quite possible that police operations are conducted at lower altitudes, though information regarding such operations is hard to find. Very little information regarding flight hours is provided, and what is provided would not easily be extensible to the National Airspace System (NAS) (though reasonable assumptions could be made to estimate flight hours in major cities).

3.1.9 Helicopter External Load Operations

FAA (2022) provides a description of external load operations. From that context, an external load is something attached to an aircraft that is not located inside the aircraft. As indicated by FAA (2022), external load operations involve numerous missions (e.g., placing an air conditioner on a building as part of construction). External load operations can also include firefighting and work with powerlines such as wire pulling, marker ball installation/removal, etc. (IEEE ESMOL Subcommittee15.07 2006).

3.1.10 Training

While Weinert and Barrera (2020) indicated that training operations are generally above 500 ft, they can occur at lower altitudes. Examples from University of North Dakota (UND) flight operations are provided in Figure 1. As indicated in Figure 1, some training operations reach altitudes as low as ~200 ft AGL. These altitudes are likely associated with practicing emergency engine-out procedures with associated selection of a landing point prior to recovery and ground reference maneuvers.

The aircraft used for training are generally single-engine fixed-wing aircraft, for which characteristics are known (Underhill and Weinert 2021). While information regarding flight hours is limited in Weinert and Barrera (2020), Part 141 schools do track flight hours and, thus, such information could be established.

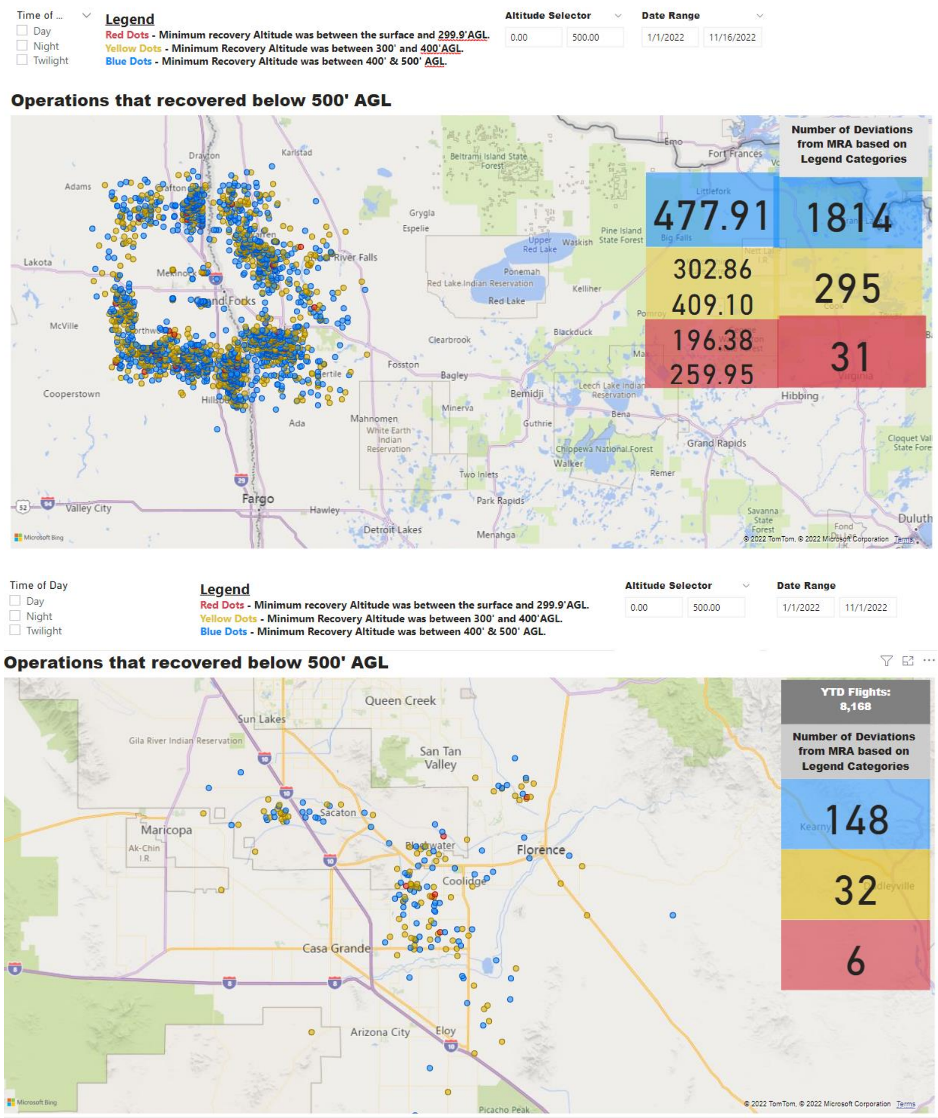

Figure 1. Minimum altitudes associated with training exercises that reached altitudes below 500 ft AGL from 1 January – 16 November 2022 near Grand Forks, ND (top), and from 1 January – 1 November 2022 near Phoenix, AZ (bottom). Colored boxes (blue, yellow, red) indicate altitudes (left column for Grand Forks) and number of occurrences (right column for Grand Forks and only column for Phoenix) during the relevant time period. Altiude information in colored boxes is minimum altitude for that category (top) and average altitude

for that category (bottom), with the blue category for Grand Forks showing only average altitude. Figures courtesy of Brian Willis, UND Flight Operations.

3.1.11 Animal, Earth, and Plant Sciences

For these operations, flight altitudes can be < 500 ft AGL. In addition, speeds can reach fairly high values, though most of the reported values are near the peak for general aviation single-engine aircraft speeds (Underhill and Weinert 2021). Moreover, the reported values do not exceed values observed by Underhill and Weinert (2021). For some of these missions, helicopters are used at low altitudes (e.g., animal sciences). In addition, many Animal Sciences flights (wildlife searches) are typically conducted at low altitudes, while mapping of animal habitats involves flights at a wider range of higher altitudes.

Weinert and Barrera (2020) conclude that Earth Sciences missions commonly are not conducted at low altitudes, although some do occur at altitudes down to ~100 ft AGL. These missions are conducted with a variety of aircraft (helicopters and single- and multi-engine fixed-wing aircraft).

Plant Sciences flights can extend to low altitudes (< 500 ft AGL) and can utilize multiple aircraft types (fixed- and rotary-wing aircraft). Speeds for such operations cover a broad range. Very little information regarding flight hours is provided.

3.1.12 Recreational Flying

The A45 team added this use case. It captures activities such as people sightseeing at low altitudes and gatherings where takeoff and landing might use uncommon surfaces (e.g., driveways). Such activities are permitted under CFR §91.119, which is discussed in detail in Section 3.2.

3.1.13 Ultralight Vehicles

Weinert and Barrera (2020) do not include Ultralight Vehicles in their analysis but do provide characteristics from Markowski (1982). From Markowski (1982), these vehicles are generalized as having cruise speeds of ~43 kts, stall speeds down to 22 kts, and vertical rates of 500 ft min^{-1}. Ultralight Vehicles operations are governed by 14 CFR Part 103. They may not be operated in Class A, B, C, D, or within the lateral boundaries of the surface area of Class E airspace designated for an airport unless prior authorization from the Air Traffic Control (ATC) facility having jurisdiction over that airspace is obtained. Thus, ultralight flights are generally confined to Class G and E airspace. They also may not be operated over congested areas. Because ultralight pilots are not certified, it is difficult to find information regarding the number of active pilots and flight hours. It is noted that these are referred to as vehicles because the FAA considers them as vehicles, which means that they do not have an airworthiness certification.

3.2 Shielding Classes

The principal types of hazard outcomes associated with shielded operations are:

- Collision with CA (air risk)
- Collision with people or property (ground risk)
- Collision with infrastructure

The definition of infrastructure used herein follows that provided by Dictionary (2022). It is considered to be facilities and systems serving the public (e.g., energy production and distribution systems, transportation systems, etc.). Property, in contrast, is associated with private entities (companies, individuals, etc.). The definition of critical infrastructure is from title 42 of the United States Code (U.S.C.) (U.S. House of Representatives 2010, p. 6028): '…"critical infrastructure" means systems and assets, whether physical or virtual, so vital to the United States that the incapacity or destruction of such systems and assets would have a debilitating impact on security, national economic security, national public health or safety, or any combination of those matters.'

These three categories (air, ground, and infrastructure) are broad. The ground risk outcome is primarily focused on collisions with people. Collisions with property could be considered, but do not play a significant role herein.

Given these three primary hazard outcomes, shielding classes can be defined according to how they impact outcomes (e.g., likelihood). Because collision with CA is expected to be the outcome that is most impactful, most likely, and hardest to mitigate, air risk is considered to be the top tier category. The secondary tier is ground risk, and the tertiary tier is infrastructure risk. A fourth tier indicates type of shielding operation.

3.2.1 Air Risk Category

Collision with CA is expected to be the outcome that is most impactful, most likely, and hardest to mitigate. Thus, air risk is the top tier category for shielding classes.

Air risk depends upon numerous factors. One critical component is regulations that dictate low-altitude operations. The following provides information regarding such regulations.

3.2.1.1 Regulatory Analysis

CFR Part 91 (General Operating and Flight Rules; e-CFR 2022a) provides guidance regarding low-altitude operations. 14 CFR §91.119 (Minimum safe altitudes: General; e-CFR 2022a) states: "Except when necessary for takeoff or landing, no person may operate an aircraft below the following altitudes:

- (a) ***Anywhere.*** An altitude allowing, if a power unit fails, an emergency landing without undue hazard to persons or property on the surface.
- (b) ***Over congested areas.*** Over any congested area of a city, town, or settlement, or over any open air assembly of persons, an altitude of 1,000 feet above the highest obstacle within a horizontal radius of 2,000 feet of the aircraft.
- (c) ***Over other than congested areas.*** An altitude of 500 feet above the surface, except over open water or sparsely populated areas. In those cases, the aircraft may not be operated closer than 500 feet to any person, vessel, vehicle, or structure.
- (d) ***Helicopters, powered parachutes, and weight-shift-control aircraft.*** If the operation is conducted without hazard to persons or property on the surface -
  - (1) A helicopter may be operated at less than the minimums prescribed in paragraph (b) or (c) of this section, provided each person operating the helicopter complies with any routes or altitudes specifically prescribed for helicopters by the FAA; and
  - (2) A powered parachute or weight-shift-control aircraft may be operated at less than the minimums prescribed in paragraph (c) of this section."

Clause (a) is very permissive. Discussions among the A45 team indicate that pilots generally maintain altitudes of at least 500 ft above the surface, but that recreational flying (Table 1) does occur and fits under clause (a). Recreational flying includes low-altitude sight-seeing (non-commercial) and gatherings wherein pilots land on and launch from surfaces that are not dedicated for aircraft operations (driveways, etc.). Clause (c) drives a significant segregation of CA traffic, with many CA not operating below 500 ft above the surface except during takeoff and landing.

Other sections of Part 91 impact minimum altitudes. A very important restriction applies under Instrument Flight Rules (IFR), as opposed to Visual Flight Rules (VFR). 14 CFR §91.155 (Basic VFR weather minimums; e-CFR 2022a) provides conditions under which aircraft may not be flown under VFR. Table 2 provides these conditions. As shown in Table 2, for VFR visibility is required to be:

- At least 3 statute miles in class B, C, D, and E airspace below 10,000 ft Mean Sea Level (MSL).
- At least 1 statute mile in class G airspace below 1200 ft AGL for other-than-helicopter aircraft and helicopters operating at night more than ½ mile from runway or helipad of intended landing.
- At least ½ statute mile in class G airspace below 1200 ft AGL for helicopters operating during the day and helicopters operating at night within ½ mile of a runway or helipad of intended landing.

If these visibilities are not met (or if cloud clearance conditions are not met) and special VFR operations are not authorized, Instrument Meteorological Conditions (IMC) exist and IFR is required. IFR altitude requirements are provided by 14 CFR §91.177 (Minimum altitudes for IFR operations; e-CFR 2022a):

> "(a) ***Operation of aircraft at minimum altitudes.*** Except when necessary for takeoff or landing, or unless otherwise authorized by the FAA, no person may operate an aircraft under IFR below -
>
> (1) The applicable minimum altitudes prescribed in parts 95 and 97 of this chapter. However, if both a MEA and a MOCA are prescribed for a particular route or route segment, a person may operate an aircraft below the MEA down to, but not below, the MOCA, provided the applicable navigation signals are available. For aircraft using VOR for navigation, this applies only when the aircraft is within 22 nautical miles of that VOR (based on the reasonable estimate by the pilot operating the aircraft of that distance); or
>
> (2) If no applicable minimum altitude is prescribed in parts 95 and 97 of this chapter, then -
>
> (i) In the case of operations over an area designated as a mountainous area in part 95 of this chapter, an altitude of 2,000 feet above the highest obstacle within a horizontal distance of 4 nautical miles from the course to be flown; or
>
> (ii) In any other case, an altitude of 1,000 feet above the highest obstacle within a horizontal distance of 4 nautical miles from the course to be flown.
>
> (b) ***Climb.*** Climb to a higher minimum IFR altitude shall begin immediately after passing the point beyond which that minimum altitude applies, except that when ground obstructions intervene, the point beyond which that higher minimum altitude applies shall be crossed at or above the applicable MCA."[3]

14 CFR Part 95 (IFR Altitudes, e-CFR 2022b) prescribes altitudes governing operation of aircraft under IFR on Air Traffic Services (ATS) routes and 14 CFR Part 97 (Standard Instrument

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[3] The acronyms in this quote are Minimum En Route Altitude (MEA), Minimum Obstruction Clearance Altitude (MOCA), Very High Frequency Omni-Directional Range (VOR), and Minimum Crossing Altitude (MCA).

Procedures; e-CFR 2022c) prescribes IFR procedures and weather minima at civil airports. Thus, under IMC, IFR operations away from defined routes and civil airports are prescribed to be ≥ 1000 feet above the highest nearby (within 4 nautical miles) obstacle. IMC, therefore, are permissive of low-altitude Uncrewed Aircraft (UA) operations (shielded or not).

Table 2. 14 CFR Part 91 conditions under which aircraft may not be operated under VFR.

Airspace	Condition	Visibility (<; statute miles)	Maximum Distance From Clouds (<; ft)
A		N/A	N/A
B		3	Clear of clouds
C		3	500 ft below 1000 ft above 2000 ft horizontal
D		3	500 ft below 1000 ft above 2000 ft horizontal
E	< 10,000 ft Mean Sea Level (MSL)	3	500 ft below 1000 ft above 2000 ft horizontal
E	≥ 10,000 ft MSL	5	1000 ft below 1000 ft above 1 statute mile
G	• 1200 ft or less above surface • Aircraft other than helicopters • Day	1	Clear of clouds
G	• 1200 ft or less above surface • Aircraft other than helicopters • Night	3	500 ft below 1000 ft above 2000 ft horizontal
G	• 1200 ft or less above surface • Airplane, powered parachute, or weight-shift controlled aircraft • Night • Operating in an airport traffic pattern within ½ mile of runway	1	Clear of clouds
G	• 1200 ft or less above surface • Helicopters • Day	½	Clear of clouds
G	• 1200 ft or less above surface • Helicopters • Night	1	Clear of clouds
G	• 1200 ft or less above surface • Helicopters • Night • Operating within ½ mile of runway or helipad of intended landing	½	Clear of clouds
G	• More than 1200 ft above surface but less than 10,000 ft MSL • Day	1	500 ft below 1000 ft above 2000 ft horizontal
G	• More than 1200 ft above surface but less than 10,000 ft MSL • Night	3	500 ft below 1000 ft above 2000 ft horizontal
G	More than 1200 ft above the surface and at or above 10,000 ft MSL	5	1000 ft below 1000 ft above 1 statute mile horizontal

Special VFR operations (14 CFR §91.157; e-CFR 2022a) can be conducted with ATC clearance (i.e., in controlled airspace). Under these operations, an other-than-helicopter aircraft operation requires at least 1 mile of visibility. No minimum is provided for helicopter operations under these conditions.

14 CFR Part 135 (Operating Requirements: Commuter and On Demand Operations and Rules Governing Persons On Board Such Aircraft; e-CFR 2022d) provides guidance regarding some low-altitude operations depicted in Table 1. 14 CFR §135.203 (VFR: Minimum altitudes; e-CFR 2022d) states:

"Except when necessary for takeoff and landing, no person may operate under VFR -

(a) An airplane -

(1) During the day, below 500 feet above the surface or less than 500 feet horizontally from any obstacle; or

(2) At night, at an altitude less than 1,000 feet above the highest obstacle within a horizontal distance of 5 miles from the course intended to be flown or, in designated mountainous terrain, less than 2,000 feet above the highest obstacle within a horizontal distance of 5 miles from the course intended to be flown; or

(b) A helicopter over a congested area at an altitude less than 300 feet above the surface."

Thus, for VFR commuter and on demand operations away from takeoff and landing locations, fixed-wing aircraft are restricted to 500/1000 ft AGL and above during the day/night while helicopters are not restricted over non-congested areas but are restricted to 300 ft AGL and above over congested areas.

Specifics regarding HAA operations are provided in Subpart L of 14 CFR Part 135 (e-CFR 2022d). Relative to 14 CFR Part 91, requirements are higher for VFR operations, as indicated in Table 3. For VFR in Class G airspace, visibility has to be at least 2 miles during the day and 3 miles at night in a non-mountainous local flying area. Under Part 91 (Table 2), visibility minimums are ½/1 miles for helicopters operating during the day/night, with the exception of ½ mile at night within ½ mile of a runway or helipad of intended landing.

14 CFR §135.615 delineates vertical clearance for obstacles for the enroute phase of HAA flights. For daytime flights the vertical clearance is 300 ft; for nighttime flights the vertical clearance is 500 ft.

Table 3. Weather minimums for HAA operations under VFR in Class G airspace.

Location	Day		Night		Night Using an Approved Night Vision Imaging System (NVIS) or Helicopter Terrain Awareness and Warning System (HTAWS)	
	Ceiling (ft)	Flight Visibility (statute miles)	Ceiling (ft)	Flight Visibility (statute miles)	Ceiling (ft)	Flight Visibility (statute miles)
Nonmountainous local flying area	800	2	1000	3	800	3
Nonmountainous non-local flying area	800	3	1000	5	1000	3
Mountainous local flying area	800	3	1500	3	1000	3
Mountainous non-local flying area	1000	3	1500	5	1000	5

14 CFR Part 137 (Agricultural Aircraft Operations; e-CFR 2022e) provides guidance regarding the Spraying and Dusting operation type in Table 1. Low altitudes like those listed in Table 1 are allowed in both other-than-congested areas (§135.49) and, with approval, congested areas (§135.51), and are allowed when (§135.29):

- Dispensing
- Conducting non-dispensing aerial work operations related to agriculture, horticulture, or forest preservation.

Otherwise (labeled non-mission-specific herein), spraying and dusting aircraft altitudes are dictated by 14 CFR Part 91 (e-CFR 2022a), with aircraft expected to operate at altitudes of 500 ft and above AGL during non-mission-specific legs. Ryker et al. (2022) determined that during non-mission-specific legs such aircraft commonly operate above 500 ft AGL, although some are below 500 ft AGL. These could result from aircraft operating below 500 ft AGL [e.g., under clause (a) of 14 CFR §91.119], uncertainty in data/analysis, or both.

The A45 team added Helicopter External-Load Operations to the set of operations identified by Weinert and Barrera (2000). These are governed by 14 CFR Part 133 (Rotorcraft External-Load Operations; e-CFR 2022f). An example of such an operation is dispensing of water to fight fires. Under 14 CFR Part 133, such operations can deviate from Part 133 rules as needed in emergencies involving the safety of persons or property. In non-emergency situations, these operations can be conducted over congested areas if executed without producing hazards to persons or property on the surface (§133.33). In addition, away from densely populated areas, congested airways, and busy airports where passenger transport operations are conducted, such operations can be conducted below 500 ft AGL (§133.33). Part 133 IFR operations can only be conducted if approved by the Administrator (§133.33).

Ultralight vehicle operations are regulated by 14 CFR Part 103 (Ultralight Vehicles; e-CFR 2022g). Important restrictions on ultralight operations include:

- Daytime only operations (§103.11)
- Operations during twilight periods 30 minutes before official sunrise and 30 minutes after official sunset or, in Alaska, civil twilight, if certain conditions are met (§103.11)
- No operations over congested areas of cities, towns, settlements, or open-air assemblies (§103.15)
- No operations in Class A, B, C, or D airspace, or within the lateral boundaries of the surface area of Class E airspace designated for an airport unless prior authorization from ATC is provided (§103.17)
- Operation only by visual reference with the surface (§103.21)

Visibility and cloud clearance requirements for ultralight operations are provided in Table 4. These correspond with the values provided for Part 91 VFR (Table 2).

Table 4. Visibility and cloud clearance requirements for ultralight operations.

Airspace	Condition	Visibility (<; statute miles)	Maximum Distance From Clouds (<; ft)
A		N/A	N/A
B		3	Clear of clouds
C		3	500 ft below 1000 ft above 2000 ft horizontal
D		3	500 ft below 1000 ft above 2000 ft horizontal
E	< 10,000 ft Mean Sea Level (MSL)	3	500 ft below 1000 ft above 2000 ft horizontal
	≥ 10,000 ft MSL	5	1000 ft below 1000 ft above 1 statute mile
G	1200 ft or less above surface	1	Clear of clouds
	More than 1200 ft above surface but less than 10,000 ft MSL	1	500 ft below 1000 ft above 2000 ft horizontal
	More than 1200 ft above surface and at or above 10,000 ft MSL	5	1000 ft below 1000 ft above 1 statute mile horizontal

A summary of regulations regarding low-altitude CA operations is provided in Table 5. Table 5 is organized such that CFR §91.119 forms the basis/foundation and is, thus, located at the bottom of the table. Other operations modify that basis and are organized above the 91.119 line.

Table 5. Summary of low-altitude CA regulations.

CFR Part:	Conditions:	Operations Not Generally Allowed	Exceptions Allowing Operations			
137 – Agricultural Aircraft Operations	Aircraft used in agricultural operations	When not dispensing ≤ 500 ft	Dispensing in other than congested areas	Non-dispensing work related to ag., horticulture, or forest preservation in other than congested areas	With approval in congested areas	
135 – Operating Requirements: Commuter and On Demand Operations and Rules Governing Persons On Board Such Aircraft	1. Commuter & on-demand operations 2. VFR	1. Daytime (≤ 500 ft) 2. Nighttime (≤ 1000 ft non-mountainous; ≤ 2000 ft mountainous)	Takeoff and landing	Helicopter not ≤ 300 ft over congested areas	Enroute phase for Helicopter Air Ambulance (HAA) over obstacles not ≤ 300/500 ft (day/night)	
133 – Rotorcraft External-Load Operations	External-load operations	Without Administrator permission	Permission and away from densely populated areas, congested airways, and busy airports	Permission and over congested areas without hazards to persons or property at surface	Emergencies involving the safety of persons or property	
103 – Ultralight Vehicles	Aircraft meets definition of ultralight vehicle	1. At night 2. Over congested areas 3. In Class A, B, C, or D 4. In lateral boundaries of surface area of Class E for airport 5. Non-VFR conditions	Allowed during daytime, non-congested areas, outside of A, B, C, D, and E (designated for airport), in VFR conditions			
91.177 – Minimum Altitudes for IFR Operations & 95 – IFR Altitudes & 97 – Standard Instrument Procedures	IMC (requiring IFR)	Away from defined routes and civil airports (≤ 1000 ft non-mountainous; ≤ 2000 ft mountainous)	Takeoff and landing	Otherwise authorized by the FAA	If allowed by Part 95 or 97: IFR on Air Traffic Services (ATS) routes and near civil airports	Climbing to a higher altitude just beyond the point where a minimum altitude applied
91.157 – Special VFR Weather Minimums	1. Not airport where special VFR operations are prohibited (91 App. D §3) 2. Below 10,000 ft MSL within airspace contained by the upward extension of lateral boundaries of controlled airspace designated to the surface for an airport	Anywhere	Fixed wing: 1. ATC clearance 2. Clear of clouds 3. Vis. ≥ 1 statute mile 4. Sunrise to sunset if not Part 61 compliant & aircraft 91.205 equipped	Helicopter: 1. ATC clearance 2. Clear of clouds		
91.119 – Minimum Safe Altitudes: General	General operations	1. Congested areas (≤ 1000 ft) 2. Other than congested areas (≤ 500 ft)	Takeoff and landing	Anywhere an emergency landing can be executed without undue hazard to persons or property on the surface	Helicopters (without hazards to persons or property on the surface and complying with prescribed routes and altitudes)	Powered parachutes and weight-shift-control aircraft in other than congested areas (without hazards to persons or property on the surface)

From these regulations, three factors that clearly impact low-altitude operations are:

- Airspace class
- IMC vs. Visual Meteorological Conditions (VMC)
- Congested vs. other-than congested area.
- Daytime vs. nighttime

Other drivers that impact low-altitude CA traffic levels are discussed in the subsequent section.

3.2.1.2 Other Factors

The A45 team explored other factors that impact low-altitude CA traffic levels and, thus air risk. Additional factors beyond those identified in the previous section that impact CA traffic levels are driven by whether there is a reason for the operation (operation need), as opposed to whether an operation is permitted (operation permission). A challenge with this, of course, is that one cannot completely rule out any operation based upon there being no reason for it, since technically it is allowed.

Operation need is driven by multiple factors that, for simplicity, are summarized as humanitarian and economic. Humanitarian needs include operations that improve health outcomes (e.g., locating a lost hiker, delivering medicine, eliminating a dangerous CA operation, etc.) that do not necessarily produce immediate economic benefit. Economic needs involve financial benefit through reduced costs/increased efficiency, etc. An operation can involve both—improving health outcomes, for instance, commonly has downstream economic impacts.

A complete analysis of all factors that may affect CA traffic levels for operations listed in Table 1 is beyond the scope of this effort. Subsequently, leading factors, as identified by the A45 team, are discussed.

3.2.1.2.1 Location Factors

Location, beyond airspace class and congested versus other-than congested areas, could influence the likelihood of CA operations. The following, non-exhaustive list provides some possible influences that should be validated if and when such data are available:

1. Spraying and Dusting operations are not expected where agriculture, horticulture, or forest preservation activities would not be conducted, including cities, arid regions, etc. A caveat is firefighting activities conducted under CFR Part 137, which could occur in additional areas.
2. Release of sterile insects to control pests, as described by Weinert and Barrera (2020), is not expected in areas where insects are unlikely to cause negative impacts, which could include arid regions.
3. Fish Release would occur over bodies of water. Thus, operations away from bodies of water would have little chance of interacting with this type of CA operation.
4. HAA operations could occur practically anywhere the need for an ambulance exists. The likelihood of encountering such a service may often be reduced in locations of very low population density because the number of people that would potentially require that service is small. Alternatively, in remote areas the only option may be an HAA.
5. By definition, Infrastructure Inspection (rotary- and fixed-wing) operations are more likely around some obstacles that can be used for shielded sUAS operations. These include

powerlines, power poles, etc. Encountering such operations may be less likely when flying near obstacles that do not require inspection (e.g., tree rows). However, low-altitude operations do occur near trees (e.g., tree harvesting, logging operations, and surveillance).

6. Infrastructure Work operations occur near infrastructure for which rotary-wing aircraft can be utilized (e.g., powerlines)
7. Helicopter Air Tours are generally flown at altitudes above 400 ft AGL (Weinert and Barrera 2020). Operations away from air tour bases and associated attractions would minimize the likelihood of encountering such operations.
8. By definition, Helicopter Offshore Operations serve offshore needs. The odds of encountering such operations are minimal inland from coastal bases.
9. Helicopter News Gathering is generally conducted in larger cities by news organizations. The likelihood of encountering these types of flights is lower away from larger cities.
10. Helicopter External-Load Operations flights support a wide variety of operations/use cases (infrastructure, construction, firefighting, etc.). Given this, it is not easy to define areas where these operations are less likely, although areas of low population density would seemingly reduce encounter likelihood.
11. Training flights will be concentrated near CFR Part 141 training schools. Such schools commonly have defined training areas, avoidance of which would minimize interaction with such operations.
12. Animal, Earth, and Plant Sciences flights could be avoided by identifying potential flight drivers (e.g., Earth science areas of interest, plants of scientific interest, etc.).
13. Recreational Flying is a type of operation for which characteristics (locations, timing, number of flights/flight hours) are unknown.
14. Ultralight Vehicles are restricted by airspace class and are not allowed over congested areas, the two location-based factors that have already been identified. Other location factors are not immediately apparent, although it seems unlikely that such vehicles would be flown near obstacles owing to associated increased risk.

From these, an additional location factor that could be considered is agricultural/horticultural/forest areas versus non. This factor would reduce the likelihood of encountering spraying and dusting operations, which involve dynamic flight characteristics (Ryker et al. 2022) that could be challenging for DAA systems. For this analysis, this factor is not considered, although it may be incorporated in the future. Other additional location factors beyond airspace class and congested versus other-than-congested areas are hard to identify owing to the varied types of low-altitude operations.

3.2.1.2.2 Temporal Factors

Temporal factors beyond daytime/nighttime may impact low-altitude CA density. The predominate factor identified by the A45 team is growing vs. non-growing season. This factor strongly impacts Spraying and Dusting operations as outside of the growing season there is no economic driver for these operations. A caveat is firefighting operations conducted under CFR Part 137, which are not necessarily driven by the growing season. In addition, other types of operations may preferentially occur in the non-growing season, including Christmas tree harvesting, transport of persons for sport (hunting), etc.

Struttmann and Zawada (2019) conducted a survey of CFR Part 137 certificate holders. This survey is an excellent source of information regarding those who conduct Spraying and Dusting. While it does not provide information regarding the duration of the application season (for any locations in the United States (U.S.)), it does regularly refer to the application season, which underscores the importance of the growing season to these operations. Results from Struttman and Zawada (2019) could be leveraged to establish an initial estimate of flight hours and geographical distribution of operations across the U.S., as information relating to these (e.g., total acres treated, percentage of operations by state, etc.), though incomplete owing to collection via a survey, is provided. Results also provide additional insights, including:

1. Approximately 16% of the aircraft used for Spraying and Dusting are helicopters, with the rest being fixed-wing aircraft.
2. A significant percentage of the respondents (31%) indicated that they intend to use Automatic Dependent Surveillance-Broadcast (ADS-B) in or out in the next 3 years.
3. A small percentage of operators, 4%, indicated that they use UAS in their operations.
4. Of those that use UAS, 74% use them for remote sensing or imaging and 26% use them for applying material.
5. Operators do fly at night, with 7% conducting such operations. These operations occurred predominantly (74%) in the far west region of the U.S. Such operations are enabled through use of lights, night vision goggles, or both.
6. Most operators treat corn, small grains, and soybeans. Information from the survey and predominate local crop types could be used to estimate relative operational levels as a function of location.
7. The percentage of operators that encountered specified obstacles during 2017 are:
    a. 59% for unmarked communications towers.
    b. 52% for wind turbines and/or unmarked meteorological towers
8. UAS were encountered, while conducting aerial applications, by 15% of operators. Most encounters occurred in the Midwest, followed by the South.
9. A slight minority (41%) have a policy regarding working near wind turbines. Of those that have a policy, most charge extra (43%), many refuse to do the application (26%), some apply only by helicopter (11%), and the rest have other policies. This indicates that wind turbines result in decreased activity, but by no means guarantee that operations are not occurring.
10. Operators identified powerlines, communication towers, and meteorological towers (in that order) as presenting the greatest risks to them. UAS were ranked as presenting roughly half the risk of powerlines, as the 12^{th} most significant risk, behind risks such as birds and adverse weather.
11. While some operators conducted flights on more than 200 days yr^{-1}, most operated less than 200 days yr^{-1}, with the peak in responses in the 101-200 days yr^{-1} category. This further underscores the importance of growing season.

While the exact duration of the non-growing season is not available from surveys such as Struttmann and Zawada (2019), it can be estimated as the period from first fall freeze to last spring freeze. Such data are readily available, with an example shown in Figure 2. Such an estimate may be conservative, as A45 team experience indicates that Spraying and Dusting using aircraft is not common pre-emergence or very late in crop lifecycles.

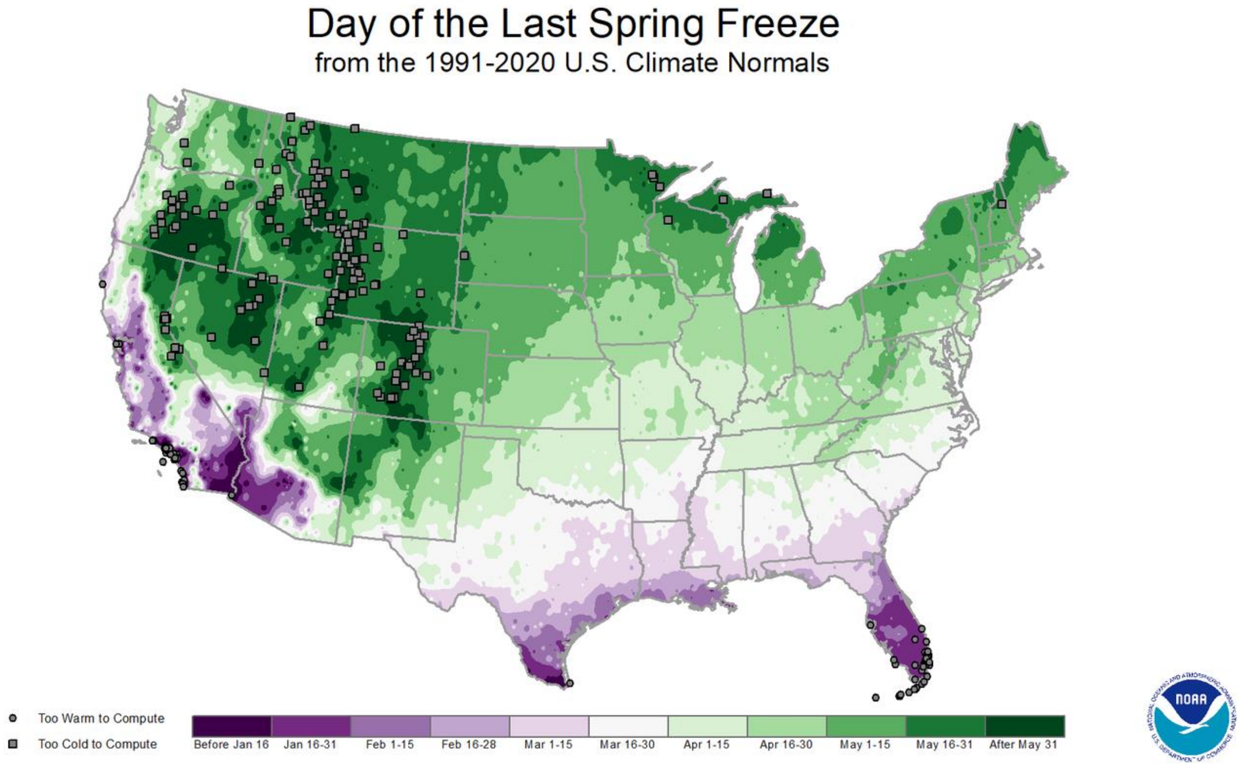

Figure 2. Day of last spring freeze for the contiguous United States. From National Centers for Environmental Information (2022).

It is noted that growing vs. non-growing season also likely impacts Insect Release and Fish Release. Both are likely less common, at least in some parts of the U.S., during the "cold" season. Fish release, in particular, is almost certain to not occur when bodies of water are ice covered.

3.2.1.3 Analysis

A quantitative analysis approach comprised of an airspace characterization would be the preferred means by which to characterize CA traffic. Such an analysis can be accomplished using radar data (e.g., Theisen et al. 2010). In addition, with assumptions regarding the percentage of cooperative vs. non-cooperative traffic, studies such as Weinert et al. (2020a) can be used to estimate CA activity. Such quantitative approaches have limitations. Radar-based approaches generally do not provide enough information to separate out different types of operations, although they can provide some information such as fixed vs. rotary wing operations (Theisen et al. 2010). Estimates based upon cooperative data include uncertainty regarding the fraction of cooperative vs. non-cooperative aircraft. It is noted that ground-based radars are being utilized to enable DAA for low-altitude UA operations. They can, thus, be used for airspace characterization. Their reach is limited, however, as under normal atmospheric propagation conditions radar beams gain altitude with range, reaching an altitude of 400 ft AGL at a range of ~45 km. Given the inherent variability in CA traffic with location, time of day, day of week, and time of year (e.g., Theisen et al. 2010, Struttmann and Zawada 2019), generalization of airspace characterizations to different locations and dates/times can involve significant uncertainty. Uncertainties/error bounds could be estimated, however, through analysis of airspace characterization data sets.

In the case where data do not enable quantitative airspace characterization, a qualitative approach can be applied. The approach outlined herein utilizes the factors regarding low-altitude CA traffic identified above (labeled as groups):

- Airspace Class (B, C, D, E, and G): Airspace class impacts low-altitude traffic, including restriction of operations (e.g., 14 CFR Part 103) and definition of VMC vs. IMC (e.g., 14 CFR §91.155).
- Population Density (congested vs. other-than congested area): This is used in relevant sections of 14 CFR, including minimum altitudes (§91.119; §135.203) and restriction of ultralight operations (§103.15).
- Time of Day (day vs. night): This affects definition of VMC/IMC (e.g., 14 CFR §91.155), altitude of operations (e.g., 14 CFR §135.203), and whether operations are allowed (§103.11).
- Season (non-growing vs. growing): This impacts the likelihood of encountering aircraft associated with certain types of operations (e.g., Spraying and Dusting).
- Meteorological Condition (IMC vs. VMC): Away from defined routes and civil airports, low-altitude CA operations are not allowed under IMC conditions (14 CFR Part 95).

Other factors (e.g., agricultural/horticultural/forest areas versus non) could easily be utilized with this approach if desired. It is noted that other qualitative approaches could be developed—the one illustrated here is a specific instantiation of a broader set of possible qualitative approaches.

In this approach, Subject Matter Expert (SME) input is used to estimate relative traffic levels for each member of each of the above groups using the qualitative column of Table C2 from U.S. Department of Transportation (2019), shown in Table 6. In this application, the purpose is to label CA operations as routine, occurring often, etc., using the associated Likert scale. Thus, these values do not map to NAS-wide impacts, which is how Table 6 is generally utilized. Numeric values were assigned to the letter classifications to enable averaging of SME input, with the values being:

A: 5
B: 4
C: 3
D: 2
E: 1

An additional category having the numeric value of 0 was added to account for operations that are not allowed by regulations or, in the SME's opinion, would not occur because there is no reason for the operation.

Table 6. Table C2 from U.S. Department of Transportation (2019).

	Qualitative	Quantitative – Time/Calendar-based Occurrences Domain-wide/System-wide
Frequent A	Expected to occur routinely	Expected to occur more than 100 times per year (or more than approximately 10 times a month)
Probable B	Expected to occur often	Expected to occur between 10 and 100 times per year (or approximately 1-10 times a month)
Remote C	Expected to occur infrequently	Expected to occur one time every 1 month to 1 year
Extremely Remote D	Expected to occur rarely	Expected to occur one time every 1 to 10 years
Extremely Improbable E	Unlikely to occur, but not impossible	Expected to occur less than one time every 10 years

An example SME input is shown in Table 7. It is noted that the example in Table 7 does not have all of the operations listed in Table 1, as it is missing Infrastructure Work, Helicopter External-Load Operations, and Recreational Flying. These operations were added to Table 1 after this analysis was completed. As the intent is to illustrate how such an analysis could be completed, the impact of omitting these operations is minimal.

The first step in developing a ranking of CA activity is averaging of individual SME inputs for each operation and group value (each numeric cell in Table 7). Empty cells are treated as missing or “no input”, and “N/A” values are also not used in this computation. For the example shown herein, averages are provided in Table 8.

The next step is looping across all combinations of group values and computing Likert scores for each combination. Each combination combines five elements, one from each group, producing a total of 80 combinations. The score for each combination is given by the minimum of the values. For example, for Spraying and Dusting the set {class G, Other than Congested Area, Day, Growing Season, VMC} has values {4.50, 4.75, 4.75, 4.75, 4.00} (Table 8), which produces the resulting value of 4.00. The minimum value is utilized because CA traffic levels are expected to be driven by the most restrictive condition that affects them.

The final step is averaging of values across use cases for each of the 80 combinations of group elements. It is noted that in the example shown here, use cases were treated equally in that each received an equal weight in the averaging step. One could easily weight different use cases more heavily according to expected importance for an operational area.

Table 7. Example SME input for CA activity levels. Groups and associated values are colored to provide quick visual group identification. Values are shaded to indicate higher relative activity levels, with low activity (1) having light green shading and high activity (5) having darker-green shading. A value of "N/A" indicates that the group is not expected to impact that use case.

SME 1	Class B	Class C	Class D	Class G	Class E	Congested Area	Other than Congested Area	Day	Night	Non-Growing Season	Growing Season	IMC	VMC
Spraying and Dusting	1	2	3	4	4	1	4	4	1	0	4	0	4
Insect Release	1	1	1	1	1	1	1	1	1	0	1	0	1
Fish Release	1	1	1	1	1	1	1	1	1	0	1	0	1
Helicopter Air Ambulance	4	4	4	2	2	4	2	4	4	N/A	N/A	0	4
Infrastructure Inspection (Rotary Wing)	2	3	3	3	3	3	3	3	2	N/A	N/A	0	3
Infrastructure Inspection (Fixed Wing)	2	3	3	3	3	3	3	3	2	N/A	N/A	0	3
Helicopter Air Tours	1	1	3	3	3	3	3	3	3	N/A	N/A	0	3
Helicopter Offshore Operations	2	2	3	3	3	3	3	3	3	N/A	N/A	0	3
Helicopter News Gathering	2	2	3	3	3	3	3	3	3	N/A	N/A	0	3
Helicopter Public Safety	1	1	1	1	1	3	3	3	3	N/A	N/A	0	3
Training	0	0	0	3	3	0	3	3	0	N/A	N/A	0	3
Animal/Earth/Plant Sciences	0	0	0	3	3	0	3	3	0	3	3	0	3
Ultralight Vehicles	1	1	1	4	4	0	4	4	0	1	4	0	4

Table 8. As in Table 7, but average of SME inputs for CA activity levels.

	Class B	Class C	Class D	Class G	Class E	Congested Area	Other than Congested Area	Day	Night	Non-Growing Season	Growing Season	IMC	VMC
Spraying and Dusting	1	2.5	3.75	4.5	4.25	1.75	4.75	4.75	0.5	1	4.75	0	4
Insect Release	1.5	2	2	3	1.75	2.5	3	3.75	1.25	1	1.75	0	1
Fish Release	1	1.75	1.75	3.5	2.25	1.5	3.75	3.75	0.75	1	1.5	0	1
Helicopter Air Ambulance	4.5	4.5	4.25	3.25	4	4.5	3.75	4.5	4.5	N/A	N/A	0	4
Infrastructure Inspection (Rotary Wing)	2.25	2.75	3.25	4	3	3	3.75	4	1	N/A	N/A	0	3
Infrastructure Inspection (Fixed Wing)	1.5	2.5	3	4	3	3	3.75	4	1	N/A	N/A	0	3
Helicopter Air Tours	3	2.5	3.5	4	4	4	4	4.25	3.75	N/A	N/A	0	3
Helicopter Offshore Operations	3	2	2	3.75	3.75	2.25	3.75	4	4	N/A	N/A	0	3
Helicopter News Gathering	4.25	4.25	3.75	3.75	3.5	4.25	4	4.25	4.25	N/A	N/A	0	3
Helicopter Public Safety	4	4	3.75	3.25	3	4.25	4	4.25	4.25	N/A	N/A	0	3
Training	3	3	3.25	4.25	3.75	3	4.25	4.25	3	N/A	N/A	0	3
Animal/Earth/Plant Sciences	0.66	1.33	1.33	3.66	2.33	1.33	3.66	4.33	0.66	2.33	3	0	3
Ultralight Vehicles	0.5	0.5	3.25	4.5	4	0	3.75	4.5	0	1.75	3	0	4

3.2.1.4 Results

Results are provided in Table 9. A subset of group combinations is shown in Table 9 because the rest of the values, which include IMC as a group element/value, are zero.

As indicated in Table 9, important delineators include VMC, which results in values being non-zero, and daytime, which is a group value that is present for all group combinations having scores > 1.97. Thus, three air-risk-driven classes (A) are apparent for this example:

- A1. IMC conditions
- A2. VMC conditions at night
- A3. VMC conditions during the daytime

One could add a fourth class for values > 2.5, which is VMC during the daytime and during the growing season.

It is noted that results shown in this example are driven by the experiences of the SMEs, which depend upon numerous factors (employment, flight experience, location, etc.). Thus, execution of this methodology using a different set of SMEs, especially SMEs with different employment experiences in different locations, would likely produce a different stratification of results. Given this, however, IMC and daytime/nighttime, because of their basis in regulation, are likely to arise as delineators in perceived risk/CA activity.

It is also noted that this type of approach is similar to that of Joint Authorities for Rulemaking of Unmanned Systems (2019). As such, it is limited by its qualitative nature.

Table 9. Scores for group combinations. Values for combinations including IMC are 0, and thus only one combination including IMC is shown.

Airspace Class	Congested (CD) vs Non-Congested (NDC)	Day (D) or Night (N)	Growing Season (GS) vs Non-Growing Season (NGS)	VMC or IMC	Score
C	NCD	N	GS	IMC	0
C	NCD	N	NGS	VMC	1.704615385
C	NCD	N	GS	VMC	1.704615385
C	CD	N	NGS	VMC	1.723846154
C	CD	N	GS	VMC	1.723846154
G	CD	N	NGS	VMC	1.723846154
G	CD	N	GS	VMC	1.723846154
D	NCD	N	NGS	VMC	1.743076923
D	NCD	N	GS	VMC	1.743076923
D	CD	N	NGS	VMC	1.762307692
D	CD	N	GS	VMC	1.762307692
B	CD	N	NGS	VMC	1.781538462
B	CD	N	GS	VMC	1.781538462
G	NCD	N	NGS	VMC	1.781538462
G	NCD	N	GS	VMC	1.781538462
E	CD	N	NGS	VMC	1.781538462
E	CD	N	GS	VMC	1.781538462
B	NCD	N	NGS	VMC	1.82
B	NCD	N	GS	VMC	1.82
E	NCD	N	NGS	VMC	1.82
E	NCD	N	GS	VMC	1.82
B	CD	D	NGS	VMC	1.973846154
B	CD	D	GS	VMC	1.973846154
B	NCD	D	NGS	VMC	2.050769231
B	NCD	D	GS	VMC	2.050769231
C	CD	D	NGS	VMC	2.083076923
C	NCD	D	NGS	VMC	2.102307692
C	CD	D	GS	VMC	2.140769231
G	CD	D	NGS	VMC	2.140769231
D	CD	D	NGS	VMC	2.179230769
G	CD	D	GS	VMC	2.198461538
E	CD	D	NGS	VMC	2.198461538
C	NCD	D	GS	VMC	2.217692308
D	CD	D	GS	VMC	2.236923077
E	CD	D	GS	VMC	2.256153846
D	NCD	D	NGS	VMC	2.294615385
G	NCD	D	NGS	VMC	2.41
E	NCD	D	NGS	VMC	2.448461538
D	NCD	D	GS	VMC	2.602307692
E	NCD	D	GS	VMC	2.775384615
G	NCD	D	GS	VMC	2.788461538

3.2.2 Ground Risk Category

Ground risk has been defined in multiple ways, depending on what is considered to be significant from a collision perspective. The Joint Authorities for Rulemaking of Unmanned Systems (2019) (JARUS) defined ground risk as involving collisions with persons. U.S. Department of Transportation (2019) states that collisions with persons or a moving vehicle are potential outcomes that must be considered. Herein, the focus is on collisions with people, although this approach could easily be modified to consider other types of collisions.

The severity of collisions with people depend upon multiple factors, including, but not limited to, kinetic energy of the UA at the time of collision, where on a person's body the collision occurs, and how sheltered the person is from the collision (a direct collision is expected to cause more serious injuries than a collision that occurs after, for instance, a UA travels through the windshield of a car) (Arterburn et al. 2017; Breunig et al. 2018; Primatesta et al. 2020). Likelihood of collision with people depends upon factors including, but not limited to, the likelihood of a UA crash, shelter factor, time of day, weather, and whether an outdoor event is occurring (e.g., Breunig et al. 2018; Primatesta et al. 2020).[4]

Given these dependencies, the JARUS defined ground risk classes that include UA characteristics (maximum dimension or kinetic energy), type of UAS operation (BVLOS vs. line of sight), population density, and exposure (gathering of people). As the intent here is to define classes driven by the environment (and not characteristics of the UA or operation), the focus is on population density and exposure.

While a stratified set of classes having numerous levels could be developed, the approach here is to utilize only a few levels for simplicity. One natural division is urban vs. rural. The definition of urban is somewhat complicated, with factors utilized by the U.S. Census Bureau including (National Archives and Records Administration 2022):

- Housing density
- Percentage of impervious (ground) surface
- Population density
- Distance between nearby urban areas (areas joined if gaps are small)
- Number of housing units
- Number of commuter destinations
- Status as an active airport

Population density is an important factor used by the U.S. Census Bureau, and their delineation of 500 persons mi^{-2} is used herein to divide between rural and urban areas for evaluating ground risk. While this may not include areas such as industrial areas that are considered urban by the U.S. Census Bureau, it serves the purpose of providing categories for UAS ground risk. The interested reader is directed to U.S. Census Bureau (2022) for significant resources regarding urban and rural classification, including maps delineating characteristics of U.S. urban and rural areas.

Thus, ground risk classes (G), as defined by the A45 team, are:

G1. Controlled area with no third-party persons present

[4] The latter three factors affect the number of people who are outside and, thus, have more exposure to (less shelter from) a UA crash.

G2. Rural area (< 500 persons mi^{-2})
G3. Urban area (≥ 500 persons mi^{-2})
G4. Gathering of people outside (un-sheltered)

It is noted that a third-party is someone who is not part of the UAS operation. More granularity is possible by expanding the categories by population density, according to number of persons taking part in an outside gathering, according to shielding factor differences, etc. This is a potential area for future work.

3.2.3 Infrastructure Risk Category

Of the categories associated with operational environment (air, ground, and infrastructure), infrastructure risk is the most nebulous (e.g., Joint Authorities for Rulemaking of Unmanned Systems 2019). Smith (2015), for example, highlights potential threats associated with bad actors (e.g., terrorists), but does not stratify potential targets. Joint Authorities for Rulemaking of Unmanned Systems (2019) and U.S. Department of Transportation (2019) identify damage to critical infrastructure as something to be considered, but do not delineate associated risk classes. Cybersecurity & Infrastructure Agency (2022) discusses critical infrastructure risks associated with UAS, but also does not discuss risk classes. Risk classes for infrastructure may not be published because doing so could provide enabling information to bad actors.

Given the relative lack of information regarding infrastructure classes, the A45 team proposes the following set of infrastructure (I) classes:

I1. Non-infrastructure and non-property (e.g., tree rows)
I2. Property
I3. Infrastructure
I4. Critical infrastructure

As with ground risk, further granularity can be provided by further dividing these classes (e.g., according to degree of property damage, importance of infrastructure, etc.).

3.2.4 Type of Shielded Operation Category

The type of shielded operation category is different from the other categories in that, while it does provide information regarding operating environment, it does not necessarily relate directly to environmentally-driven risk. This category identifies characteristics regarding the Shielding Object (SO), with the following SO classes:

SO-LL: Long Linear shielding objects, such as powerlines
SO-R: Rectangular shielding objects, such as buildings (rectangular in both horizontal and vertical planes)
SO-NV: Narrow Vertical shielding objects, such as towers, wind turbines, etc.

These are driven by geometric characteristics of the shielding objects. Conceivably, other classes could be defined for objects such as guy wires and bridges, though these can likely be placed in these existing classes (e.g., SO-LL).

The SO classes likely impact characteristics of UAS used for associated operations. For operations associated with the SO-LL class, for example, a fixed-wing UA might be preferred. Operations associated with the SO-R and SO-NV classes, on the other hand, may be more likely to be executed using a rotary-wing UA. In addition, these classes likely dictate CA flight patterns, as one might expect flight patterns around an SO-NV shielding object to be different from those around an SO-

R shielding object. Confirmation of this expectation is beyond the scope of this project. This is a potential future work topic.

3.2.5 Aggregated Shielding Classes

Aggregated shielding classes can be formed from the defined classes for each category. Since the type of shielded operation is different from the others, it is recommended that it be visually separated from other categories. A proposed format for communicating the aggregated shielding class is SO-X | AN-GN-IN, where X represents of the SO classes and N indicates a number (Table 10). A specific example is SO-LL | A3-G2-I3, which indicates a Long Linear shielding object with flights in VMC conditions during the daytime in a rural area near infrastructure.

Table 10. Suggested format for communicating aggregated shielding classes. The table is divided according to shielding object, air risk, ground risk, and infrastructure risk categories. Emboldened characters are provided in a shielding class specification whereas italics provide descriptions of classes.

Shielding Object			Air Risk			Ground Risk			Infrastructure Risk		
Label	**Class**	*Description*	**Label**	**Class**	*Description*	**Label**	**Class**	*Description*	**Label**	**Class**	*Description*
	LL	*Long Linear objects such as powerlines*		**1**	*Instrument meteorological conditions*		**1**	*Controlled area with no third-party persons present*		**1**	*Non-infrastructure and non-property (e.g., tree rows)*
SO-	**R**	*Rectangular objects such as buildings*	**| A**	**2**	*Visual meteorological conditions at night*	**-G**	**2**	*Rural Area (< 500 persons mi^{-2})*	**-I**	**2**	*Property*
	NV	*Narrow Vertical objects such as towers, wind turbines, etc.*		**3**	*Visual meteorological conditions during the day*		**3**	*Urban Area (> 500 persons mi^{-2})*		**3**	*Infrastructure*
							4	*Gathering of un-sheltered people*		**4**	*Critical infrastructure*

4 TASK 2B: HAZARD ANALYSIS

4.1 Background

Numerous assumptions, many of which are driven by previous work, apply for all evaluated CONOPS. These are described in the following sections.

4.1.1 Assumptions

Operations are assumed to occur at or below 400 ft and to be conducted using a group 1 or 2 UAS [DoD (Department of Defense) 2011]. Base aircraft configuration, unless otherwise noted, excludes alternative navigation systems [Inertial Navigation System (INS), altitude measurement system, etc.], DAA systems, obstacle avoidance systems, and collision avoidance systems. These are assumed to not be part of the base aircraft configuration so that their value/risk benefit can be evaluated through the risk assessment performed herein.

Unless otherwise noted, UAS operations are assumed to be within the closest (best) shielding level. Shielding levels are defined as:

- Shielding Level (SL) 1 (SL1): Within 50 ft (horizontally or vertically) of shielding object
- SL2: Within 100 ft (horizontally or vertically) of shielding object
- SL3: Within 200 ft (horizontally or vertically) of shielding object
- No Shielding (NS): Beyond 200 ft (horizontally or vertically) of shielding object

These levels are primarily based upon SME input from the A45 team (from their experiences when operating in the field). They do align with the recommendation from UAS BVLOS ARC (2022), that defined a Shielded Operation to be within 100 ft horizontally or vertically of a structure. It is noted that UAS BVLOS ARC (2022) did not provide analysis supporting the 100 ft dimensions for Shielded Area, which is its definition for the volume of airspace 100 ft vertically and horizontally around an obstacle. UAS BVLOS ARC (2022) indicates that existing regulations (14 CFR §91.119; e-CFR 2022a) prohibit a significant portion of aircraft from operating at low altitudes except for takeoff and landing and states that, with the exception of a helicopter landing or taking off from a building, no crewed aircraft should be within 100 ft for the vast majority of low altitude operations. It is noted that while regulations do prohibit a significant portion of aircraft from operating at low altitudes, as indicated in Section 3.2.1.1, many operations are permitted as discussed in Section 3.1 and summarized in Table 1.

As information regarding low-altitude CA flight characteristics relative to obstacles becomes available, definitions for shielding levels will be updated. The A45 team is pursuing such information through both analysis of flight data and a survey, both of which are described in subsequent sections.

4.1.2 Well clear

A definition for well clear is needed for two reasons. The first is evaluation of the likelihood of loss of well clear when performing shielded operations without a DAA system. The second is the same but with a DAA system, which then provides information regarding the benefit of that mitigation.

The sUAS well clear definition recommended by Weinert et al. (2018), with horizontal separation of 2000 ft and vertical separation of 250 ft, is applied herein. This recommendation is based upon unmitigated collision risk in operational volumes that are not impacted by obstacles (i.e., aircraft flight patterns are not constrained by the presence of obstacles). With this definition, the unmitigated probability of a Near Mid-Air Collison (NMAC) given a Well Clear Violation (WCV), $P_{(NMAC|WCV)}$, is estimated at 0.1, while the unmitigated probability of a Mid-Air Collision (MAC) given an NMAC, $P_{(MAC|NMAC)}$, is estimated at 0.01 (Weinert et al. 2018). An NMAC is defined as simultaneous loss of 500 ft horizontal and 100 ft vertical separation. This results in the probability of a MAC given a WCV, $P_{(MAC|WCV)}$, being 0.001.[5]

For shielded operations, other definitions of well clear could be applied. The first utilizes a shielding object wherein the UA is maneuvered such that the shielding object is between it and the CA. Because the CA cannot be flown through the object to reach the UA, the UA is well clear of the CA.

Another possible definition for well clear leverages the impact of a shielding object on CA flight. Near a shielding object, CA flight is constrained in that certain flight characteristics would not be realized owing to them producing a collision risk with the shielding object. These constraints could be used to enable well clear status near a shielding object without requiring the aircraft to adhere to the Weinert et al. (2018) recommendation. A crop duster that interacts with a power line, for instance, likely climbs or descends in a perpendicular orientation relative to that power line.[6] The lack of horizontal motion along the power-line could enable a UA to be "well-clear" of such a CA even if it is within 2000 ft of the CA. Such an approach to defining well clear for shielded operations would require comprehensive data regarding how aircraft flown for various low-altitude operations interact with shielding objects.

4.1.3 NMAC

An NMAC is defined as simultaneous loss of 500 ft horizontal and 100 ft vertical separation. This definition is from RTCA (2008).

4.2 Concept Of Operations (CONOPS)

In this analysis, the intent is to develop methods that could be applied to any CONOPS. CONOPS that have been emphasized recently within the community are described in the following sections.

4.2.1 Linear Infrastructure

Significant effort has been directed at using UA to perform tasks associated with linear infrastructure, such as powerlines and pipelines. While these tasks can be varied, the focus is generally on inspection.[7] The desire, generally, is to fly BVLOS over significant distances to capture data related to infrastructure (e.g., Bruggeman et al. 2011; Matikainen et al. 2016). Commonly, the information sought relates to identification of failures or potential failures, including encroachment of vegetation (Matikainen et al. 2016). Given that optical sensors are commonly used for inspections, many operations occur during the daytime. However, InfraRed (IR) and Light Detection And Ranging (LIDAR) data are also used, and thus nighttime operations are likely (Matikainen et al. 2016).

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[5] A justification of how these probabilities are combined (multiplied) is provided in a later section.

[6] Crop dusters may also fly parallel to power lines. The characteristics of such flight legs (e.g., height, horizontal distances from lines, etc.) are not known and are a topic of future study.

[7] A Google Scholar search on 29 December 2022 using the words "infrastructure inspection drones" produced ~8,700 results since the year 2021.

4.2.2 Package Delivery

Package delivery has also received significant attention.[8] Much of the focus for the use case is in urban and suburban environments (Benarbia and Kyamakya 2022). Thus, shielding using buildings or other infrastructure such as powerlines could benefit this use case. Rural environments do not provide as many shielding opportunities (i.e., as many buildings), though shielding using existing buildings, tree rows, powerlines, etc., could be helpful. Deliveries could be conducted during both during the day and at night, although noise considerations may result in daytime deliveries being much more common.

4.3 Methodology

An SRA that could be applied to the CONOPS discussed above and other CONOPS as needed is developed following processes delineated by U.S. Department of Transportation (2017a, 2019) and FAA Air Traffic Organization (2019). The following sections provide details regarding determination of severity, likelihood, and risk.

4.3.1 Overarching Approach

4.3.1.1 Severity

Severities are based upon previous efforts (e.g., Askelson et al. 2017; Theisen et al. 2020), desired consistency with severity definitions in Appendix C of U.S. Department of Transportation (2019), and A45 team efforts. Figure 3 provides the severity tables used herein for air, ground, and infrastructure risk.

For air risk, levels 3 and 4 were determined in a previous, unpublished research effort wherein data from Figure 5 of Weinert et al. (2018), which provides unmitigated NMAC likelihood for sUAS interacting with CA, were digitized and fit using various Two-Dimensional (2D) functions. From this, unmitigated NMAC risk was estimated to double, relative to an initial horizontal and vertical separation of 2000 ft and 250 ft, respectively, for an initial horizontal and vertical separation of 1500 ft and 187.5 ft, respectively. This second initial separation represents a 25% well-clear intrusion (in both dimensions). Thus, doubling of unmitigated NMAC risk is considered to be significant and a viable delineator between severities 3 and 4 for air risk.

It is noted that a MAC is assigned a severity level of 1 (Catastrophic). This is consistent with the approach of Askelson et al. (2017) and Table 3.3. of FAA Air Traffic Organization (2019), both of which consider a MAC as catastrophic. Table C1 of U.S. Department of Transportation (2019) indicates that a severity of 1 (Catastrophic) is defined as "Multiple fatalities (or fatality to all on board) usually with the loss of aircraft/vehicle". Table 3.3 of FAA Air Traffic Organization (2019) indicates that "An effect categorized as catastrophic is one that results in a fatality or fatal injury". Thus, a common theme is that a fatality must occur, with U.S. Department of Transportation (2019) requiring multiple fatalities for a severity level of 1 (Catastrophic) and FAA Air Traffic Organization (2019) indicating that at least one fatality must result. A MAC between a UA and CA is not guaranteed to produce a fatality (e.g., Oliveras et al. 2017). The likelihood of a fatality, given a MAC, is not known. Thus, Askelson et al. (2017) were conservative and assumed a fatality could occur in such a situation, which also appears to be the approach in Table 3.3 of FAA Air Traffic Organization (2019). A better approach, if information regarding the likelihood of at least

[8] A Google Scholar search on 29 December 2022 using the words "drone package delivery" produced ~11,200 results since the year 2021.

one fatality given a UA/CA MAC were available, would be to define air risk severity category 1 (Catastrophic) as a UA/CA MAC that results in at least one fatality. Because such an estimate is not available, the conservative approach of Askelson et al. (2017) is utilized herein.

Ground risk severity categories are aligned with Table 3.3. of FAA Air Traffic Organization (2019), with impacts being for persons not directly related to the UAS operation. For categories 1 and 2, these ground risk severity categories are more conservative than those provided in Table C1 of U.S. Department of Transportation (2019), which defines severity categories as:

1. Multiple fatalities (or fatality to all on board) usually with the loss of aircraft/vehicle
2. Multiple serious injuries; fatal injury to a relatively small number of persons (one or two); or a hull loss without fatalities
3. Physical distress or injuries to persons
4. Physical discomfort to persons
5. Negligible safety effect

Category 5 in Figure 3 is less conservative than that used in Table C1 of U.S. Department of Transportation (2019) while categories 3 and 4 in Figure 3 represent a more specific breakdown of category 3 in Table C1 of U.S. Department of Transportation (2019). It is noted that FAA Air Traffic Organization (2019) defines a serious injury to be one that:

- Requires hospitalization for more than 48 hours, commencing within seven days from the date the injury was received;
- Results in the fracture of any bone, except for simple fractures of fingers, toes, or nose;
- Causes sever hemorrhages, nerve, muscle, or tendon damage;
- Involves any internal organ; or
- Involves second- or third-degree burns, or any burns affecting more than 5% of the body's surface.

A non-serious injury would, thus, be something that causes bodily damage that is neither serious nor fatal.

Infrastructure collision risk severity is not elucidated by either FAA Air Traffic Organization (2019) or U.S. Department of Transportation (2019). Severity definitions in Figure 3 are from A45 team discussions. The original approach to severity utilized damage to infrastructure (≤ $500 or no collision for category 5 and > $500 for category 4) and damage to critical infrastructure (any damage for category 3, partial system failure for category 4, and damage with associated fatalities for category 5). This approach was eschewed in favor of that shown in Figure 3, which is based upon associated cost of damage (categories 4 and 5) and length of system disruption (categories 1-3). The change in approach resulted from challenges with the original approach such as properly identifying fatalities associated with infrastructure damage. Infrastructure outage periods, on the other hand, are relatively easy to identify. It is noted that the infrastructure severity scale shown in Figure 3 does not delineate between infrastructure and critical infrastructure. Conceivably, the same severity scale could be used for both.

A45 Air Risk:

Minimal 5	Minor 4	Major 3	Hazardous 2	Catastrophic 1
Well Clear maintained by either AC maneuvering*	Well Clear Violation by less than or equal to 25%	Well Clear violated by more than 25%	Near midair collision w/ less than 500 ft. horizontal and 100 ft. vertical (NMAC)	Midair collision (MAC)

A45 Ground Risk:

Minimal 5	Minor 4	Major 3	Hazardous 2	Catastrophic 1
Discomfort to those on the ground (not directly related to the UAS operation)	Non-serious injury to three or fewer people on the ground	Non-serious injury to more than three people on the ground	Serious injury to persons other than the UAS crew	Fatality or fatal injury to persons other than the UAS crew

A45 Inf. Collision Risk:

Minimal 5	Minor 4	Major 3	Hazardous 2	Catastrophic 1
Damage to infrastructure less than $500 or no collision	Damage to infrastructure greater than $500	Damage to infrastructure resulting in system disruption for less than 1 hour	Damage to infrastructure resulting in system disruption for 1 to 24 hours	Damage to infrastructure resulting in system disruption for more than 24 hours

Figure 3. Severity tables: Air risk (top), ground risk (middle), and infrastructure collision risk (bottom).

4.3.1.2 Likelihood

Likelihood is formulated as occurrence per (UA) flight hour and is NAS-wide following FAA Air Traffic Organization (2019). Occurrence rates for likelihood follow Table 3.5 of FAA Air Traffic Organization (2019), which is shown in Table 11. This approach to likelihoods is used because it automatically scales to the volume of UA operations given its inherent utilization of (UA) flight hours. The approach in U.S. Department of Transportation (2019) utilizes the number of occurrences per calendar period (e.g., per month, year, etc.). This approach is a little more challenging when scaling given the inherent need to estimate the total number or hours of operations. It is noted that Table 11, given its Air Traffic Organization (ATO) origin, is designed for flight near airports and in controlled airspace.

Table 11. Likelihood categories and associated occurrence rates from FAA Air Traffic Organization (2019).

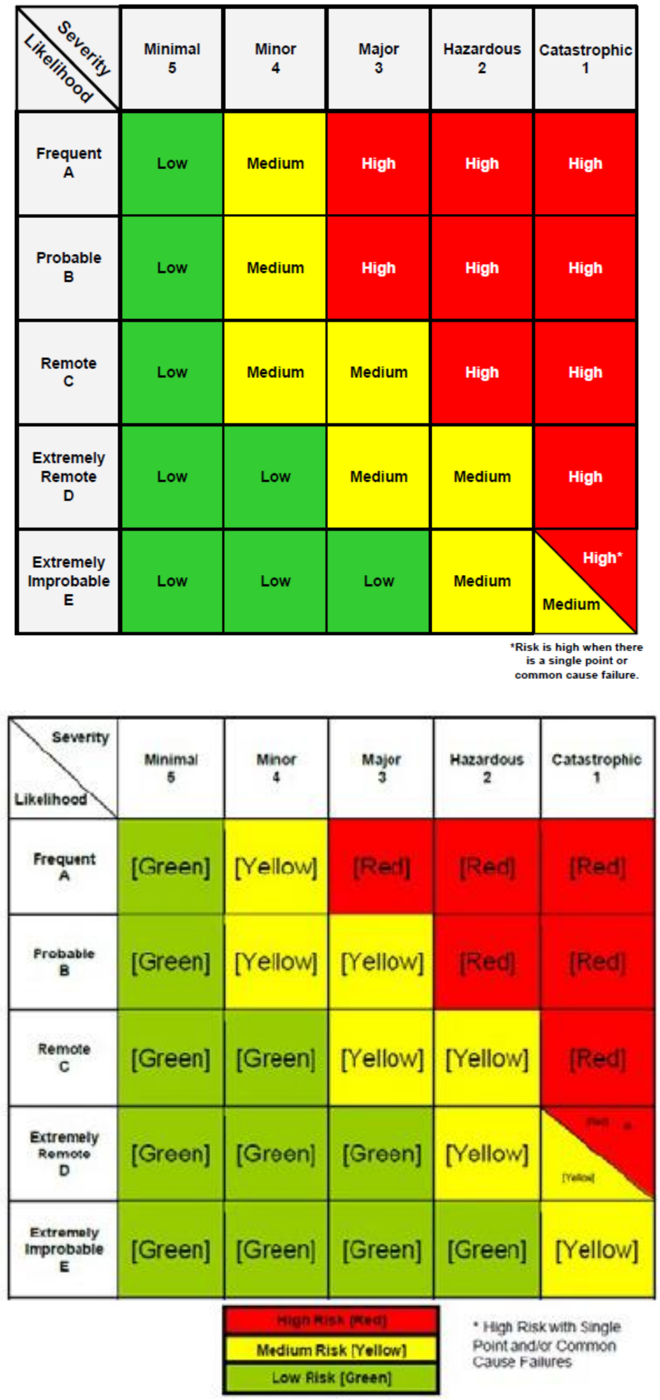
	Operations: Expected Occurrence Rate (per operation / flight hour / operational hour[3])
	Quantitative (ATC / Flight Procedures / Systems Engineering)
Frequent A	(Probability) ≥ 1 per 1000
Probable B	1 per 1000 > (Probability) ≥ 1 per 100,000
Remote C	1 per 100,000 > (Probability) ≥ 1 per 10,000,000
Extremely Remote D	1 per 10,000,000 > (Probability) ≥ 1 per 1,000,000,000
Extremely Improbable E	1 per 1,000,000,000 > (Probability) ≥ 1 per 10^{14}

4.3.1.3 Risk

Herein risk, also referred to as safety risk, is defined as the composite of severity and likelihood (FAA Air Traffic Organization 2019, p. 38; U.S. Department of Transportation 2019, p. B-2). Risk is expressed using a risk matrix, two of which are shown in Figure 4. As indicated by U.S. Department of Transportation (2017a), the top risk matrix in Figure 4 applies to the Commercial Operations/Large Transport Category while the bottom risk matrix in Figure 4 applies to General Aviation Operations/Small Aircraft and Rotorcraft. However, the choice of risk matrix is not solely driven by these categories. As indicated by FAA Air Traffic Organization (2019), the top matrix in Figure 4 is used when the ATO accepts the risk associated with an operation. Otherwise, either of the matrices shown in Figure 4 is used. As indicated by U.S. Department of Transportation (2019, p. 3-3), the Office of Aviation Safety (AVS) is responsible for a "UAS operation:

i. That occurs at or below UAS Facility Map (UASFM) altitudes, wholly within UASFM altitudes, or at or below 400 feet above ground level (AGL) in Class G airspace; and,
ii. Do not create a new requirement(s) for air traffic service provisions through the operation or through mitigations for the operation."

It is assumed herein that AVS is responsible and, thus, that the bottom risk matrix in Figure 4 applies. If this is not the case, switching to the other (top) risk matrix is trivial.



Likelihood \ Severity	Minimal 5	Minor 4	Major 3	Hazardous 2	Catastrophic 1
Frequent A	Low	Medium	High	High	High
Probable B	Low	Medium	High	High	High
Remote C	Low	Medium	Medium	High	High
Extremely Remote D	Low	Low	Medium	Medium	High
Extremely Improbable E	Low	Low	Low	Medium	High* / Medium

*Risk is high when there is a single point or common cause failure.

Likelihood \ Severity	Minimal 5	Minor 4	Major 3	Hazardous 2	Catastrophic 1
Frequent A	[Green]	[Yellow]	[Red]	[Red]	[Red]
Probable B	[Green]	[Yellow]	[Yellow]	[Red]	[Red]
Remote C	[Green]	[Green]	[Yellow]	[Yellow]	[Red]
Extremely Remote D	[Green]	[Green]	[Green]	[Yellow]	[Red] * / [Yellow]
Extremely Improbable E	[Green]	[Green]	[Green]	[Green]	[Yellow]

High Risk [Red]
Medium Risk [Yellow]
Low Risk [Green]

* High Risk with Single Point and/or Common Cause Failures

Figure 4. Risk matrices from FAA Air Traffic Organization (2019) (top) and U.S. Department of Transportation (2019) (bottom). Split cells are high risk (red) when outcomes are driven by single point and/or common cause failures.

4.3.1.4 Quantification of Risk

As discussed in FAA Air Traffic Organization (2019), use of a qualitative, SME-based approach to likelihood estimation is recommended only if data are not available for implementing a quantitative approach. Herein, some types of data are available and some types of data are not. Thus, the approach is a mixed, quantitative/qualitative approach. For severities, levels are generally chosen based upon SME input regarding the worst credible outcome. This outcome is defined as the most unfavorable, yet believable and possible, outcome (FAA Air Traffic Organization 2019). If an outcome is determined to occur once every > 10^{14} hrs, then it is deemed to not be credible following FAA Air Traffic Organization (2019, p. 49). The following sections provide details regarding risk estimation, with the emphasis on likelihood estimation.

4.3.2 Air Risk

4.3.2.1 Probability/Likelihood of Events

The National Academies of Sciences, Engineering, and Medicine (NASEM) published a report that recommended, among other things, development of a Probabilistic Risk Analysis (PRA) process for evaluating risk associated with UAS operations (NASEM 2018). Following that recommendation, Weber et al. (2020) developed a PRA framework for application to UAS operations. This framework is rooted in probability theory, which provides a proven and well-defined foundation. Moreover, it is driven by the law of total probability, which in this context can be expressed as

$$P(O)=\sum_{i=1}^{k}P(C_i)P(O\,|\,C_i)\,, \tag{1}$$

where P is probability, O indicates an outcome (e.g., MAC), k is the total number of outcome causes, C_i represents the i^th^ outcome cause, and | indicates probability given a condition/event (Mendenhall et al. 1990, p. 64).

Because a MAC is generally considered to be the credible worst outcome for shielded operations. O in this case is a MAC. For convenience, (1) is split according to nominal and failure conditions, producing

$$P_{MAC}\left(D_{MAC}\right)=F_{nom}P_{MAC|nom}\left(D_{MAC|nom}\right)+\sum_{i=1}^{N_{fail}}F_{fail_i}P_{MAC|\,fail_i}\left(D_{MAC|\,fail_i}\right), \tag{2}$$

where the nomenclature has been changed such that subscripts on P symbols indicate outcomes/events, symbols in parentheses next to P symbols indicate dependence of P on those variables, D is a general symbol indicating a set of dependency variables, F_{nom} is the fraction of time in which the system is in a nominal state (no failures), N_{fail} is the number of failure modes, and F_{fail_i} is the fraction of time in which the system is in the i^{th} failure mode. To get to a MAC, one first needs an encounter (Enc) with a CA, a WCV, and an NMAC. Thus, $P(MAC) = P(Enc \cap WCV \cap NMAC \cap MAC)$, where the symbol $\cap$ indicates intersection or "and". From the multiplicative law of probability (Mendenhall et al. 1990, p. 52), this can be expressed, using the original nomenclature, as

$$P(Enc \cap WCV \cap NMAC \cap MAC) = P(Enc)P(WCV \mid Enc)P(NMAC \mid Enc \cap WCV)P(MAC \mid Enc \cap WCV \cap NMAC). \tag{3}$$

Because an NMAC only occurs if a WCV occurred which can only occur if there was an encounter, $P(NMAC| Enc \cap WCV)$ can be written as $P(NMAC|WCV)$. In addition, a MAC can only occur if an NMAC occurred which can only happen if a WCV and an encounter occurred, which means that $P(MAC| Enc \cap WCV \cap NMAC)$ can be expressed as $P(MAC|NMAC)$. Thus, the likelihood of a MAC can generally be expressed as

$$P(MAC) = P(Enc)P(WCV \mid Enc)P(NMAC \mid WCV)P(MAC \mid NMAC). \tag{4}$$

Inserting (4) into the MAC terms on the rhs of (2) and re-arranging with the assumption that nominal and failure modes experience the same encounter rate/probability produces

$$\bar{P}_{MAC}(D_{MAC}) = \bar{P}_{Enc}(D_{Enc}) \times \left\{ \begin{array}{l} F_{\text{nom}}\left[P_{\text{WCV|Enc}}\left(D_{\text{WCV|Enc}}\right)P_{\text{NMAC|WCV}}\left(D_{\text{NMAC|WCV}}\right)P_{\text{MAC|NMAC}}\left(D_{\text{MAC|NMAC}}\right)\right] \\ +\sum_{i=1}^{N_{fail}} F^i\left[P^i_{\text{WCV|Enc}}\left(D^i_{\text{WCV|Enc}}\right)P^i_{\text{NMAC|WCV}}\left(D^i_{\text{NMAC|WCV}}\right)P^i_{\text{MAC|NMAC}}\left(D^i_{\text{MAC|NMAC}}\right)\right] \end{array} \right\}, \tag{5}$$

where it is assumed that encounter rates are expressed in units of time^{-1} (e.g., per flight hour) with $\bar{P}$ indicating units of time^{-1}, superscript i indicates the ith failure mode, and non-superscript terms associated with F_{nom} are for nominal conditions. The relation (5) is general in that the failure conditions could include multiple failures occurring at once and the nominal conditions apply for whatever set of equipage that applies (e.g., DAA system). Equation (5) provides the rate of MACs in units of time^{-1} (e.g., per flight hour). If one desires the likelihood of a MAC given an encounter, (5) is expressed without the encounter rate as

$$P_{MAC|Enc}\left(D_{MAC|Enc}\right) = \left\{ \begin{array}{l} F_{\text{nom}}\left[P_{\text{WCV|Enc}}\left(D_{\text{WCV|Enc}}\right)P_{\text{NMAC|WCV}}\left(D_{\text{NMAC|WCV}}\right)P_{\text{MAC|NMAC}}\left(D_{\text{MAC|NMAC}}\right)\right] \\ +\sum_{i=1}^{N_{fail}} F^i\left[P^i_{\text{WCV|Enc}}\left(D^i_{\text{WCV|Enc}}\right)P^i_{\text{NMAC|WCV}}\left(D^i_{\text{NMAC|WCV}}\right)P^i_{\text{MAC|NMAC}}\left(D^i_{\text{MAC|NMAC}}\right)\right] \end{array} \right\}. \tag{6}$$

Equations (5) and (6) are interpreted from the standpoint of the likelihood of a MAC given that an encounter occurs. They do not provide guidance regarding probabilities if applied assuming one specific type of encounter, as the outcome in that case is either a MAC or not (1 or 0). Thus, (5) and (6) provide the likelihood of a MAC or of a MAC given that an encounter occurs based upon what occurs given the characteristics of ownship (the UA in this case) and of the set of encounters it may experience, with a distribution of intruder sizes, speeds, encounter geometries, changes in direction (horizontally and vertically), and changes in speeds (horizontally and vertically). For any one encounter a MAC may result. However, for the distribution encounter properties, the likelihood of a MAC is generally much less than 1.

The first step in application of (5) and (6) is definition of an encounter, which is needed to evaluate $P_{WCV|Enc}$. For illustration, horizontal maneuvers are assumed and, thus, only the horizontal components of defined boundaries (e.g., well clear) are considered. For this effort, an encounter is defined to occur when a CA is within an annulus from the well clear boundary (2000 ft) to a circle defined by intruder speed multiplied by 75 s plus the horizontal well clear radius. The 75 s value is the time associated with the early threshold for the hazard zone (essentially, well clear volume) as defined in RTCA (2017). Given an assumed intruder speed of 120 kts, the area of this annulus, A_{Enc}, is 32.85 mi^2.[9] Assuming that CA populate the area inside the well clear volume A_{WC} (0.45076 mi^2) at the same airspace density ρ_{CA} as they occupy the area in the encounter annulus A_{Enc} and that the aircraft that exist inside the well clear area came from the encounter annulus, the number of aircraft inside the well clear area is given by a fraction f times the number of aircraft inside the annulus computed from $\rho_{CA}A_{WC} = f\,\rho_{CA}A_{Enc}$, which produces $f = A_{WC}/A_{Enc}$.[10] This fraction is $P_{WCV|Enc}$ when no system that enables DAA is present, labeled herein as $P_{WCV|Enc}(B)$, where B indicates the base configuration of the UA. For the definition of encounter used herein, $P_{WCV|Enc}(B)$ = 0.0137. It is noted that this fraction is arbitrary because it depends upon the definition of encounter. If one uses a larger encounter area, this fraction decreases, which aligns with the "Big Sky" expectation. Once aircraft encounter rates are computed, however, the arbitrary nature disappears because use of different areas for defining an encounter is accounted for when computing P_{Enc} since $P_{Enc} = \rho_{CA}A_{Enc}$. This results in $P_{WCV}(B) = \rho_{CA}A_{WC}$, as expected.

For a system in its nominal state with a base configuration (no DAA, collision avoidance system, etc.), $P_{MAC|Enc}(EQ_B) = P_{WCV|Enc}(EQ_B) \times P_{NMAC|WCV}(EQ_B) \times P_{MAC|NMAC}(EQ_B)$, where EQ indicates EQuippage and subscript B indicates Base (i.e., base equipage). From Weinert et al. (2018), $P_{NMAC|WCV}(EQ_B) = 0.1$ and $P_{MAC|NMAC}(EQ_B) = 0.01$. Thus, the "Big Sky" probability of a MAC given an encounter as defined herein is (0.0137)(0.1)(0.01) = 0.0000137.

When a system that enables sensing and avoiding of CA is present, the probabilities $P_{WCV|Enc}$, $P_{NMAC|WCV}$, and $P_{MAC|NMAC}$ are affected.[11] For each type of event (well clear, NMAC, and MAC), this can be approached by apportioning the trajectories according to those that would have caused the outcome if ownship did not maneuver owing, for instance, to the presence of a DAA system, and those that would not have caused that outcome. For any of these events, the likelihood of occurrence with a system $P_E(S)$ can be expressed as

$$P_E\left(EQ_{SAA}\right) = \frac{N_{E\_ENS} + N_{E\_NNS}}{N_{ENS} + N_{NNS}}, \tag{7}$$

where EQ_{SAA} indicates equipage with a Sense And Avoid (SAA) system, N_{E_ENS} is the number of events that occur with a system (e.g., DAA system) for the trajectories for which the events would occur with no system, N_{E_NNS} is the number of events that occur with a system for the trajectories for which no events would occur with no system, N_{ENS} is the number of trajectories for which the event would occur with no system, and N_{NNS} is the number of trajectories for which no events occur with no system. In (7), N_{E_NNS} is the number of events induced by the system.

The probability of an event can also be expressed in terms of risk ratio, which is defined to be the ratio between the probability of an event with a system $P_E(EQ_{SAA})$ and the probability of an event without a system $P_E(EQ_B)$ (ICAO 2006, ASTM 2020). Thus,

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[9] As with Weinert et al. (2018), ownship speed is considered to be inconsequential relative to intruder speed. This is the basis of the spatial, rather than temporal, definition of well clear in Weinert et al. (2018).
[10] It is noted that airspace density is expected to have units per area and time interval (e.g., $mi^{-2}\,hr^{-1}$).
[11] The term "sense and avoid" is used generically to indicate systems that enable DAA, avoidance of NMACs, and avoidance of MACs. The term DAA is commonly used to indicate systems used for the purpose of maintaining well clear status.

$$P_E\left(EQ_{SAA}\right) = RR_E\left(SAA\right) P_E\left(EQ_B\right), \tag{8}$$

where $RR_E(SAA)$ is the risk ratio for the event for the particular SAA system being considered. Thus, risk ratio provides a very clean relation between the two probabilities.

Risk ratio can be related to N_{E_ENS}, N_{E_NNS}, N_{ENS}, and N_{NNS}. To do so, N_{E_ENS} and N_{E_NNS} are expressed as

$$\begin{aligned} N_{E\_ENS} &= f_{E\_ENS} N_{ENS} \\ N_{E\_NNS} &= f_{E\_NNS} N_{NNS}, \end{aligned} \tag{9}$$

where f_{E_ENS} is the fraction of those trajectories that result in events with no system that have events with the system and f_{E_NNS} is the fraction of those trajectories that result in no events with no system that have events with the system. Inserting these into (7) produces

$$P_E\left(EQ_{SAA}\right) = \frac{f_{E\_ENS} N_{ENS}}{N_{ENS} + N_{NNS}} + \frac{f_{E\_NNS} N_{NNS}}{N_{ENS} + N_{NNS}} = f_{E\_ENS} P_E\left(EQ_B\right) + f_{E\_NNS}\left(\frac{N_{NNS}}{N_{ENS} + N_{NNS}}\right). \tag{10}$$

Dividing by $P_E(EQ_B)$ produces

$$RR_E\left(SAA\right) = f_{E\_ENS} + f_{E\_NNS}\left(\frac{N_{NNS}}{N_{ENS} + N_{NNS}}\right)\left(\frac{N_{ENS} + N_{NNS}}{N_{ENS}}\right) = f_{E\_ENS} + f_{E\_NNS}\left(\frac{N_{NNS}}{N_{ENS}}\right). \tag{11}$$

Substituting for f_{E_NNS} provides the final result

$$RR_E\left(SAA\right) = f_{E\_ENS} + \frac{N_{E\_NNS}}{N_{ENS}}. \tag{12}$$

Thus, *if the number of induced events is small compared to the number of events that occur with no system, the risk ratio is given by the fraction of those trajectories that result in events with no system that have events with the system*.

Given (8) and that with a system in a nominal state $P_{MAC|Enc}(EQ_{SAA}) = P_{WCV|Enc}(EQ_{SAA}) \times P_{NMAC|WCV}(EQ_{SAA}) \times P_{MAC|NMAC}(EQ_{SAA})$,

$$\begin{aligned} &P_{MAC|Enc}\left(EQ_{SAA}\right) = P_{WCV|Enc}\left(EQ_{SAA}\right) P_{NMAC|WCV}\left(EQ_{SAA}\right) P_{MAC|NMAC}\left(EQ_{SAA}\right) \\ &= \left[RR_{WCV|Enc}\left(SAA\right) P_{WCV|Enc}\left(EQ_B\right)\right]\left[RR_{NMAC|WCV}\left(SAA\right) P_{NMAC|WCV}\left(EQ_B\right)\right]\left[RR_{MAC|NMAC}\left(SAA\right) P_{MAC|NMAC}\left(EQ_B\right)\right] \\ &= \left[RR_{WCV|Enc}\left(SAA\right) RR_{NMAC|WCV}\left(SAA\right) RR_{MAC|NMAC}\left(SAA\right)\right]\left[P_{WCV|Enc}\left(EQ_B\right) P_{NMAC|WCV}\left(EQ_B\right) P_{MAC|NMAC}\left(EQ_B\right)\right], \end{aligned} \tag{13}$$

which clearly illustrates the impact of the system (the product of risk ratios) on the probability of a MAC. If one is interested in an event earlier in the chain (e.g., WCV or NMAC), then the set of risk ratios associated with that event indicate the impact of the system. Moreover, combinations of risk ratios denote the risk ratio for the combined event—e.g., $RR_{NMAC|Enc}(SAA) = RR_{WCV|Enc}(SAA) RR_{NMAC|WCV}(SAA)$.

The impact of shielding can be incorporated using the risk ratio concept. With this approach,

$$P_E\left(EV_{SH}, EQ_B\right) = SF_E\left(ST, D\right) P_E\left(EV_{NSH}, EQ_B\right), \tag{14}$$

where EV_{SH} indicates an EnVironment with SHielding, $SF_E(ST,D)$ is the Shielding Factor (SF) for the event in question for the Shielding Type (powerlines, building, etc.) and for a specified distance (D) from the shielding object, and EV_{NSH} indicates a Non-SHielded environment. Following (13) for a system with a base configuration in a shielded environment,

$$P_{MAC|Enc}\left(EV_{SH},EQ_B\right)=P_{WCV|Enc}(EV_{SH},EQ_B)P_{NMAC|WCV}(EV_{SH},EQ_B)P_{MAC|NMAC}(EV_{SH},EQ_B)$$
$$=\left[SF_{WCV|Enc}\left(ST,D\right)SF_{NMAC|WCV}\left(ST,D\right)SF_{MAC|NMAC}\left(ST,D\right)\right]\times \quad (15)$$
$$\left[P_{WCV|Enc}(EV_{NSH},EQ_B)P_{NMAC|WCV}(EV_{NSH},EQ_B)P_{MAC|NMAC}(EV_{NSH},EQ_B)\right].$$

Combining the impacts of shielding and SAA can be accomplished by considering the shielded environment to be the "background" environment for an SAA system

$$P_E\left(EV_{SH},EQ_{SAA}\right)=RR_E\left(ST,SAA\right)P_E\left(EV_{SH},EQ_B\right), \quad (16)$$

where $RR_E(ST,SAA)$ is the risk ratio for an event in a defined shielding type for a SAA system. This is an application of (8) with the shielded environment as the background environment for the SAA system. From (14), $P_E(EV_{SH},EQ_B) = SF_E(\underline{ST},D)P_E(EV_{NSH},EQ_B)$. Thus, for a shielded environment with a SAA system

$$P_E\left(EV_{SH},EQ_{SAA}\right)=RR_E\left(ST,SAA\right)SF_E\left(ST,D\right)P_E\left(EV_{NSH},EQ_B\right). \quad (17)$$

Multiplying these together for WCV|Enc, NMAC|WCV, and MAC|NMAC produces

$$P_{MAC|Enc}\left(EV_{SH},EQ_{SAA}\right)=\left[SF_{WCV|Enc}\left(ST,D\right)SF_{NMAC|WCV}\left(ST,D\right)SF_{MAC|NMAC}\left(ST,D\right)\right]\times$$
$$\left[RR_{WCV|Enc}\left(ST,SAA\right)RR_{NMAC|WCV}\left(ST,SAA\right)RR_{MAC|NMAC}\left(ST,SAA\right)\right]\times \quad (18)$$
$$\left[P_{WCV|Enc}(EV_{NSH},EQ_B)P_{NMAC|WCV}(EV_{NSH},EQ_B)P_{MAC|NMAC}(EV_{NSH},EQ_B)\right].$$

This shows the combined benefits of shielding, the first bracketed term on the rhs of (18), and of SAA, the second bracketed term on the rhs of (18).

4.3.2.2 Aircraft Encounter Rate

Relations like (13), (15), and (18) illustrate the benefits of SAA and shielding. A risk matrix based upon these relations, however, has not been developed. Thus, at this point establishment of risk, which depends upon occurrence per flight hour, requires some sort of estimation of CA encounter rate. Quantification of this is tremendously challenging given the lack of data regarding low-altitude CA operations. This lack of data not only presents estimation challenges, it also results in significant uncertainties in estimates. An approach to estimating uncertainties is discussed in a later section.

The following is one possible approach to estimating low altitude CA airspace density. It is assuredly limited by inherent uncertainties. Alternative approaches should be explored. It is noted that given the many required assumptions, the following can be considered as a framework that can be applied to estimate encounter rate once data become available.

The starting point is the data provided in Table IV of Weinert et al. (2020a), which provides the number of CA flight hours for aircraft at altitudes from 50-5000 ft AGL from cooperative CA data, $H_{flgt\_CA\_5000ft}$, collected using the OpenSky Network (Schäfer et al. 2014). Data from 2019 are utilized herein as those data are from all of 2019 and provide the highest airspace density. Weinert et al. (2020a) collected the data each Monday. The data coverage area is shown in Figure 5. This area is not completely covered by the OpenSky Network. A visualization of coverage for 31 December 2019 is provided in Figure 6. The colors in Figure 6, which was generated using a tool provided at the OpenSky Network website, are relative, with the darkest reds indicating the lowest coverage altitudes. From Figure 6, it is apparent that nearly all of the data processed by Weinert et al. (2020a) came from the contiguous U.S. Areas from outside of the contiguous U.S. would approximately fill in the hole near the middle of the contiguous U.S. Given this and assuming that the darkest shade of red indicates coverage from 50-500 ft AGL, the A45 team estimates that the 50-500 ft AGL coverage for the Weinert et al. (2020a) data set, C_{Area_500ft}, was ~0.01.

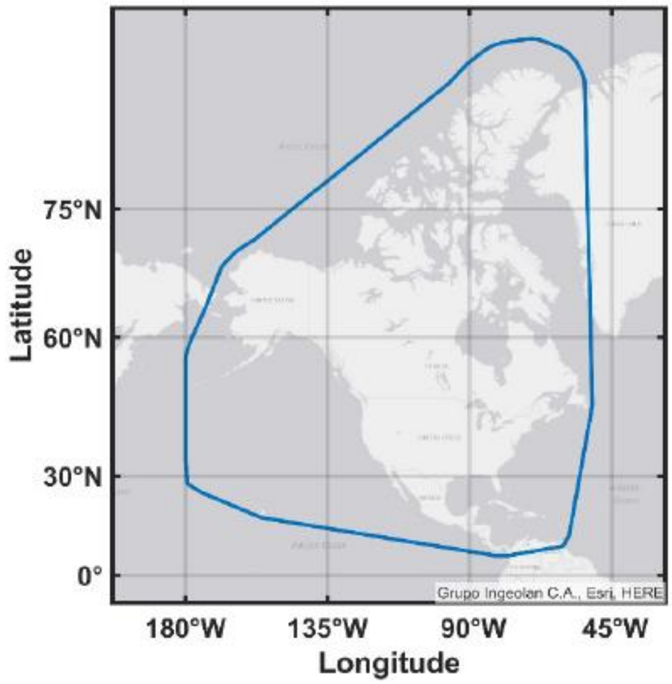

Figure 5. Coverage area for data used to estimate CA airspace density. From Weinert et al. (2020a).

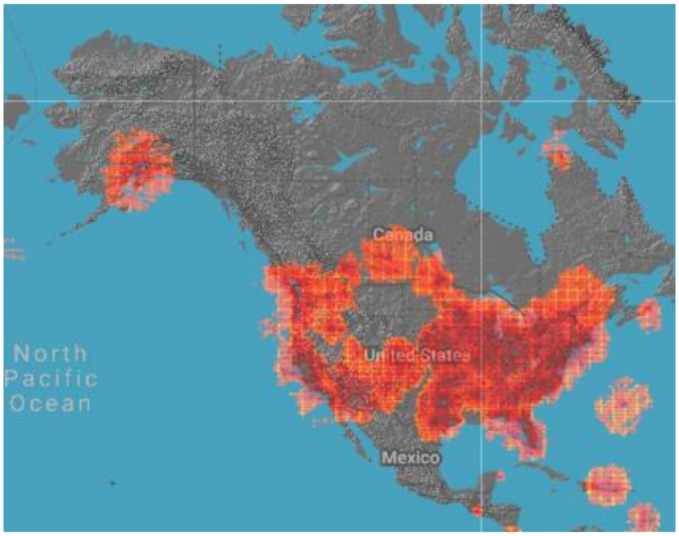

Figure 6. OpenSky Network coverage for 31 December 2019. Colors are relative, with the darkest reds indicating the lowest coverage altitudes.

The Weinert et al. (2020a) data are for altitudes rom 50-5000 ft AGL. To estimate airspace density for ≤ 500 ft AGL, Figures 2-4 of Weinert et al. (2020b) are used. These were generated using a subset of the data utilized by Weinert et al. (2020a), being drawn from the U.S., Puerto Rico, and the U.S. Virgin Islands. Figures 2-4 of Weinert et al. (2020b) provide altitude and airspace distributions for fixed-wing multi-engine aircraft, fixed-wing single-engine aircraft, and rotorcraft. The plot for fixed-wing single-engine aircraft is provided in Figure 7. Based upon these plots and focusing on the "Other" airspace class (Class E and G for low-altitude aircraft), the A45 team estimated that rotorcraft were ~10% of overall traffic from 50-5000 ft AGL. In addition, the percentage of traffic below 500 ft AGL relative to that below 5000 ft AGL is estimated to be 10% for fixed-wing and multi-wing aircraft and 25% for rotorcraft. Weighting the fixed wing aircraft by 0.9 and the rotorcraft by 0.1 produces a percentage of traffic below 500 ft AGL (relative to that below 5000 ft AGL), $P_{traff\_500/5000\text{ft}}$ of 0.12. It is noted that these estimates could be improved by using a tool that extracts values from plots such as PlotDigitizer (2023). Given the approximate nature of the estimation method for airspace density used herein, these estimates were not revised in this manner. This is a potential future effort topic.

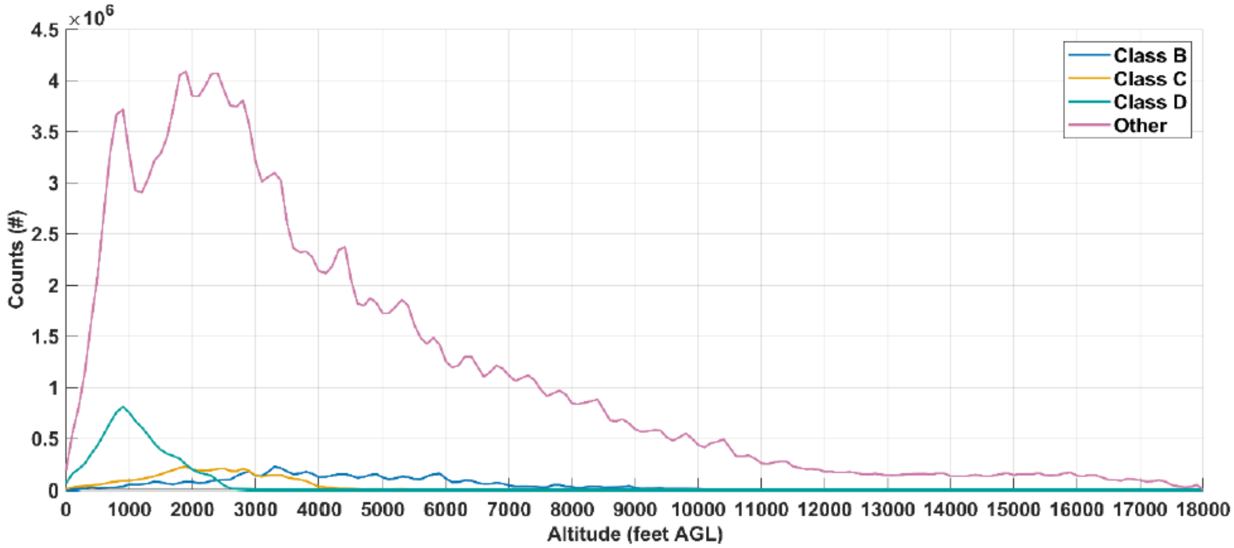

Figure 7. Altitude and airspace distributions for fixed-wing single-engine aircraft observed below 18,000 ft AGL. From Weinert et al. (2020b).

Division of $H_{flgt\_CA\_5000ft}$ by the number of sample hours, H_{smpl}, which is also provided by Weinert et al. (2020a), provides the number of aircraft flying for an hour for altitudes of 50-5000 ft AGL. Multiplication of this by $P_{traff\_500/5000ft}$ provides the number of aircraft flying for an hour at altitudes below 500 ft for the area sampled, which is expanded to the area of the contiguous U.S. by dividing by the coverage factor C_{Area_500ft}. This is converted into an airspace density by dividing by the area of the contiguous U.S. (A_{Cont_US}), which is 3,119,884.69 mi^2. Dividing by this number treats all of the low altitudes in the contiguous U.S. as if it is Class G airspace. At this point, one has the airspace density for cooperative aircraft. To get the airspace density for all aircraft, this quantity is divided by the assumed percentage of cooperative aircraft P_{coop}. The computation is, thus,

$$\rho_{CA} = \left(\frac{H_{flght\_CA\_5000\,ft}}{H_{smpl}}\right) P_{traff\_500/5000\,ft} \left(\frac{1}{C_{Area\_500\,ft}}\right)\left(\frac{1}{A_{Cont\_US}}\right)\left(\frac{1}{P_{coop}}\right). \qquad (19)$$

For the 2019 data from Weinert et al. (2020a), as assumed P_{coop}=0.5, and the other values assumed0020herein, $\rho_{CA} = 1.084794\times10^{-3}$ hr^{-1} mi^{-2}.

It is noted that the coverage area associated with cooperative receivers located at the ground, which are what are used with the OpenSky Network, increases with height. This results in more aircraft being detected with increasing height for a constant aircraft airspace density. This effect can be ameliorated by formulating an aircraft density from aircraft counts $N(h)$ as $N(h)/A(h)$, where $A(h) = \pi\left[\sqrt{2h(4/3)a}\right]^2$, a is the Earth's radius, the quantity in the brackets is the equation for the radio horizon assuming average low-altitude propagation conditions (Bean and Dutton 1966, p. 59), and it is assumed that no obstructions (hills, buildings, etc.) are present. Integration of this aircraft density from the surface to 500 ft and the surface to 5000 ft, followed by division, produces the desired $P_{traff\_500/5000ft}$. This correction was not applied herein and is a potential future effort topic.

4.3.2.3 Background Risk Estimate

Within the well clear area (0.450756 mi^2), ρ_{CA} = 1.084794×10^{-3} hr^{-1} mi^{-2} corresponds to 4.88978×10^{-4} hr^{-1}. For these encountered aircraft and without an SAA system, 10% will reach NMAC and 1% of those that reach NMAC will reach a MAC. Thus, the collision rate without an SAA system is 4.88978×10^{-7} hr^{-1}, or an occurrence every 2,045,081 hrs. Consequently, the default air risk without an SAA system and without shielding is estimated to be 1C (cf. Table 11). This indicates that collision with a CA is credible.

4.3.2.4 Impact of Shielding

4.3.2.4.1 Literature Review

The A45 team examined literature in an attempt to find information regarding SFs. Very little information was found beyond:

- Some information regarding inspections (as close at ~30 ft as discussed in Section 3.1.4)
- Information provided by the National Agricultural Aviation Association (NAAA) in a letter to the FAA in which the NAAA indicated that aerial applicators would fly within 50 ft of a powerline 100% of the time and within 20 ft of a powerline 95% of the time (NAAA 2019). It is not known how many respondents provided input for these estimates.
- The discussion in UAS BVLOS ARC (2022) that defined a Shielded Operation to be within 100 ft horizontally or vertically of a structure (Section 4.1.1)
- The definition of shielded operation used by the Civil Aviation Authority of New Zealand, which is, away from airports, within 100 m of, and below the top of, a natural or man-mane object (Civil Aviation Authority of New Zealand 2023). Within 4 km of an airport, their definition adds the requirement of a physical barrier capable of stopping a UA between a UA and the airport.
- The Lester and Weinert (2019) recommendation that shielded operations enable UA to be well clear of CA when they are within 50 ft vertically and 250 ft horizontally of natural or man-made obstacles. They also indicated that UA must remain 2000 ft horizontally from the movement and non-movement areas of airports (runways, taxiways, and ramps), helipads, and low-altitude helicopter routes.
- Evaluation of stand-off distances between ADS-B equipped aircraft and obstacles. Obstacles were identified from the FAA Digital Obstacle File (FAA 2023) and the Federal Highway Administration (FHWA) National Bridge Inventory (FHWA 2023), and ADS-B data were obtained from the OpenSky Network. This dataset is expected to be published soon and is expected to be helpful with estimating SFs (Andrew Weinert 2021, personal communication).

The dataset being developed by Andrew Weinert (2021, personal communication) is expected to be helpful for estimating SFs. This is especially true if aircraft associated with low-altitude operations can be identified, thus enabling evaluation of SFs for those types of operations. Given the lack of information regarding SFs, the A45 team used several approaches to estimate them, as discussed in the following sections.

4.3.2.4.2 Qualitative (SME) Estimate

The first approach utilized by the A45 team to estimate the shielding factor SF for the four shielding levels outlined in Section 4.1.1 (SL1, SL2, SL3, and NS) was estimation through SME input. Input from 7 SMEs from the A45 team was used for low altitude traffic associated with operations from Table 1, with the Infrastructure Work and Helicopter External-Load Operations use cases excluded because SME input was acquired before these use cases were added to the list. The impact of excluding these use cases is expected to be minimal.

Input and results are shown in Table 12. SMEs provided percentages of overall low-altitude operations associated with specific operations for the ranges of expected percentages. Thus, for any type of operation, they indicated the expected maximum and minimum percentages of overall low-altitude traffic for that operation. The low and high values were averaged across SMEs and then averaged together for each operation to produce the Average column in Table 12. This Average column was then normalized such that the values add to 100% (Normalized column). SMEs also provided likelihoods that aircraft associated with the types of operations would be flown within the distances associated with SL1-SL3 (50, 100, and 200 ft) of linear infrastructure. Those SME inputs were averaged across the SMEs. Linear infrastructure (SO-LL) was chosen as that is an important type of shielding. Shielding Factors for other objects (e.g., SO-R or SO-NV) could be estimated using the same methodology.

Once the normalized percentages and SFs were determined, the overall SF was determined for SO-LL for all of the types of operations. The overall SF was computed by weighting the individual SFs by the normalized percentages. This produced the shielding factors shown in Table 13. Table 13 also provides the number of hours between each CA collision occurrence and associated air risk for each shielding factor. From the definition of shielding factor [e.g., (14)] and considering rates of collisions per unit time as in (5), the number of hours between each collision in Table 13 is given by the background collision rate of 1 every 2,045,081 hrs divided by the shielding factor for each shielding level.

As shown in Table 13, based upon SME input operating within SL1 reduces the CA air risk from 1C (red) to 1D (yellow). Thus, shielding is estimated to have a significant impact on air risk.

It is noted that the estimated occurrence rate of 1 every 14,969,025 hrs is approximately three times higher than an estimate for a shielded Class G airspace (outside 3 nm of public airports) referenced by UAS BVLOS ARC (2022, p. 37). The UAS BVLOS ARC estimate is an occurrence every 45,454,545 hrs, which still corresponds to a 1D (extremely remote) risk.

Table 12. Averages of percentages of overall low-altitude operations associated with specific operations and shielding factors for low-altitude operations derived from SME input.

	Percentage of low-alt. traffic (LOW)	Percentage of low-alt. traffic (HIGH)	Average	Normalized	Prob. flying within 50 ft of linear infrastructure	Prob. flying within 100 ft of linear infrastructure	Prob. flying within 200 ft of linear infrastructure
Spraying and Dusting	1.428571	45.71429	23.57	15.80	0.4	0.657143	0.857143
Insect Release	0	2.428571	1.214	0.81	0	0.15	0.314286
Fish Release	0	2.428571	1.214	0.81	0.014286	0.028571	0.121429
Helicopter Air Ambulance	3.142857	24.28571	13.71	9.20	0.157143	0.421429	0.707143
Infrastructure Inspection (Rotary Wing)	5.428571	27.57143	16.5	11.06	0.228571	0.607143	0.885714
Infrastructure Inspection (Fixed Wing)	5.714286	27.57143	16.64	11.16	0.114286	0.321429	0.635714
Helicopter Air Tours	2.285714	13.57143	7.929	5.32	0.014286	0.085714	0.178571
Helicopter Offshore Operations	4	11.14286	7.571	5.08	0	0.071429	0.164286
Helicopter News Gathering	4.142857	13.28571	8.714	5.84	0.014286	0.071429	0.192857
Helicopter Public Safety	5.714286	17.14286	11.43	7.66	0.135714	0.278571	0.492857
Training (fixed wing)	2.571429	17.14286	9.857	6.61	0	0.007143	0.071429
Training (rotary wing)	1.571429	12.85714	7.214	4.84	0.057143	0.15	0.264286
Animal/Earth/Plant Sciences	0	3.571429	1.786	1.20	0.028571	0.114286	0.285714
Recreational Flying	3.571429	18.57143	11.07	7.42	0.021429	0.078571	0.242857
Ultralight Vehicles	4	17.42857	10.71	7.18	0.057143	0.157143	0.3
Sum or weighted value:			**149.1**	**100**	**0.1366209**	**0.3070232**	**0.5003421**

Table 13. Shielding levels and associated air risk based upon SME inputs.

Shielding Level	Shielding Distance (ft)	Shielding Factor (SME-Based)	Number of Hours Between Occurrences	Risk
SL1	≤ 50	0.1366209	14,969,025	1D
SL2	≤ 100	0.3070232	6,660,999	1C
SL3	≤ 200	0.5003421	4,087,366	1C
NS	> 200	1.0	2,045,081	1C

4.3.2.4.3 Survey

4.3.2.4.3.1 Shielding Factor Estimation

The A45 team developed a survey to acquire information regarding likelihoods that, as part of low-altitude CA operations, aircraft are flown within specified distances of shielding objects (Appendix A). Six additional questions (questions 31-36) were added to assist the ASSURE project A54-Propose UAS Right-of-Way Rules for Unmanned Aircraft Systems (UAS) Operations and Safety Recommendations (A54). To help recruit respondents, the A45 team met with personnel from the NAAA, the National EMS (Emergency Medical Services) Pilots Association (NEMSPA), and a major energy utility company. Personnel from the NAAA and NEMSPA provided feedback regarding questions that resulted modifications. All communicated with their members/contacts to ensure that potential respondents were aware of the survey.

SFs consistent with the definition provided in Section 4.3.2.1—in the effective form of a risk ratio as in (14)—were derived from the frequency vs. distance questions (questions 6, 8, 10, 12, 14, 16, 18, 20, 22, and 25). Response options for given distance ranges are qualitative, based upon recommendations from discussions with the NAA and NEMSPA. Values were quantified according to Table 14. It is noted that this qualitative to quantitative mapping is inherently subjective. One could argue, for instance, that 25% is too high for something that occurs “Rarely”. Regardless, this generally captures SFs to the degree that respondents accurately report them. Future work associated with analysis of actual aircraft tracks, as described in subsequent sections, will provide more accurate estimates of SFs.

Table 14. Qualitative-to-quantitative mapping used for analysis of SFs from survey data.

Distance Range (ft)	Mean Distance (ft)	Qualitative Frequency	Quantitative Frequency (%)
≤ 25	12.5	Never	0
26-50	37.5	Rarely	25
51-100	75.0	Sometimes	50
101-200	150.0	Often	75
201-500	350.0	Always	100

One of the challenges encountered is that respondents answered frequency vs. distance questions in different ways. Examples for the three types of responses, labeled Cumulative Frequency (C), Probability Density Function (PDF)-Normalized (PN), and PDF-Unnormalized (PU), are provided in Table 15. The expectation was that respondents would provide C type responses (i.e., if one always passes within 25 ft of an obstacle one would, by default, always pass within the larger distances of an obstacle). Thus, for C responses frequencies never decrease with increasing distance. It is likely that the binning of the distances resulted in some respondents providing PN and PU type responses, for which at least one instance of frequency decreasing with distance occurs. For PN responses, respondents provided PDF style responses with the apparent intent that the frequencies sum to 100% (e.g., Table 15). PU responses are PDF style responses where the respondents were apparently not trying to normalize the sum of the frequencies to 100% (e.g., Table 15).

Table 15. Examples of different response types for frequency vs. distance questions.

Distance Range (ft)	Cumulative Frequency (C) Response Example	Probability Density Function-Normalized (PN) Response Example	Probability Density Function-Unnormalized (PU) Response Example
≤ 25	Sometimes	Never	Always
26-50	Sometimes	Never	Often
51-100	Sometimes	Never	Sometimes
101-200	Often	Always	Sometimes
201-500	Often	Never	Sometimes

Responses were automatically classified as C, PN, and PU responses. For C responses, frequencies never decrease with increasing distance. For PN and PU responses, at least one instance of frequency decreasing with distance occurs. PN responses are identified when the sum of the quantified frequencies is > 50% and ≤ 200%. While this seems to be a large range, manual evaluation of responses indicated that this captured apparent respondent intent well. One of the factors that likely contributes to this range being rather large is the subjectivity of the quantification of frequencies (e.g., a respondent might think that "Sometimes" is associated with a lower frequency than 50%).

PN and PU responses had to be converted into C type responses so that they were consistent with SFs. Otherwise, one could have a very low SF at a large distance because respondents indicated, in a PDF style, that they generally pass closer to an obstacle than that large range. For PN responses, values were normalized to sum to 100% (since that was the apparent intent of the respondent) and the corresponding Cumulative Distribution Function was computed. For PU responses, values were updated such that any decrease from one value to the next (with increasing distance) was removed by replacing the value at the larger distance with the value at the preceding distance.

Once values were placed into a cumulative form, they were averaged across respondents by horizontal and vertical distances from obstacles. In addition, standard deviations were computed to understand variability. These computations required careful processing to properly handle non-responses and ensure accurate results.

4.3.2.4.3.2 Estimation of Distances of Behavior Changes

Discussions with the FAA indicated that determining distances at which operators changed their behavior owing to the presence of obstacles is valuable. These distances were estimated using the following two approaches:

1. For SF curves that are nearly straight or possibly concave up, the distance at which behavior changes is the point at which the SF decreases from the largest value by a defined percentage of the range of SF values.
2. For SF curves that are concave down, the distance at which behavior changes is the point where the derivative decreases from the largest (least negative) value by a defined percentage of the range of (negative) derivative values.

Herein, 25% is the percentage change used for both rules. This value seemed to perform well. It is, however, subjective. It is also noted that analysis was performed only on composite results—those that used C, PN, and PU type responses.

To avoid identifying behavior changes only at sample locations, which would occur if treating the SF curves as linear between each sample, curve fitting was applied. To find candidate curves, numerous SFs were analyzed using the software CurveExpert Professional (Hyams Development 2023). From that, the Exponential Plus Linear Model was identified as a curve that both fit SF curves well and enabled straightforward estimation of derivatives. This model is given by

$$SF = a + br^{x} + cx, \quad (20)$$

where *a*, *b*, *c*, and *r* are coefficients and *x* represents distance. This model has the first derivative

$$SF' = \left(br^{x}\right)\ln r + c\,. \quad (21)$$

Curve fitting was conducted only if SF changes across the range of distances were ≥ 0.1.

Tests indicated that residuals (differences between curve fit estimations and SF values from the survey) are generally < 0.05. Residuals occasionally exceed 0.05, which generally occurs when abrupt changes in slope occur (e.g., Low Altitude Infrastructure Inspection near Powerline Poles/Towers). In addition, curve fitting failed for a couple SF curves:

1. For Air Ambulance or Medical Services the vertical SF curve for Commercial Buildings.
2. For Training the vertical SF curve for Commercial Buildings.

These issues likely arise owing to the relatively small number of samples associated with those curves. To perform curve fitting, each sample value in a curve had to have 5 or more responses that contributed to that value.

4.3.2.4.4 Analysis of Cooperative Aircraft Data

The best approach to estimating SFs is use of actual flight data. This approach is being utilized as discussed in Section 4.3.2.4.1. It is also an approach that could be executed by leveraging the NAAA-provided data set used by Ryker et al. (2022). The A45 team is working to access that data set. In the interim, it has acquired its own data to support estimations of SFs.

The A45 team acquired data from four ADS-B receivers distributed in the Grand Forks, ND, area. The intent was to capture data for agricultural aircraft while they were applying material.

Raw ADS-B data are passed through a pre-processor that decodes the data. The decoded data are then processed in steps. The first step is identification of relevant aircraft. This was accomplished by cross-referencing aircraft N numbers (FAA registration numbers) with aircraft make and identifying Air Tractor aircraft using the OpenSky Network aircraft data base (OpenSky 2023). The second step is conversion of MSL aircraft altitudes to AGL altitudes. This was accomplished by subtracting elevations obtained using an application programming interface for the digital elevation map provided by USGS (2023). In this conversion, no modifications were applied to account for barometric altitudes versus geometric (e.g., GPS) altitudes. Unpublished research by the lead author of this report has shown that differences between barometric and geometric altitudes are small at low altitudes. The third step was retaining data for which altitudes were below 500 ft AGL. The final steps involved manual inspection of flight paths and computation of distances relative to powerlines for aircraft that were identified as operating near powerlines.

4.3.3 Ground Risk

The A45 team focused on air risk. Thus, evaluation of ground and infrastructure risk is much less refined. Others (e.g., Breunig et al. 2018) have evaluated ground risk in much more detail. The team performed the following with regards to ground risk:

- Determined that a fatality is the worst-credible outcome (severity of 1)
- Reviewed environmental definitions that impact likelihood such as the definition of urban vs rural
- Evaluated the likelihood of a fatal impact using a tool similar to that described by Breunig et al. (2018)
- Identified hazard causes and ranked mitigations in order of greatest expected safety impact

The likelihood of a fatal impact at the ground utilized a modified form of (1) from Breunig et al. (2018)

$$\bar{P}_{fatality} = \bar{P}_{fail}\,\rho_{people} S A_{lethal} P_{collide} P_{fatality|collision}\,, \tag{22}$$

where $\bar{P}_{fatality}$ is the number of fatalities per flight hour, $\bar{P}_{fail}$ is the rate of aircraft failure per flight hour, ρ_{people} is the density of people at the ground (per square unit area), S is a shelter factor (unitless factor between 0 and 1), $P_{collide}$ is the probability a collision was not avoided, and $P_{fatality|collision}$ is the probability of a fatality given a collision. The modified form of (22) added an estimate for fatalities associated with colliding with persons on roads and with penetrating vehicles resulting in fatalities of passengers. This estimation was performed using a tool provided by MITRE (Jeff Breunig, personal communication).

4.3.4 Infrastructure Risk

The risk associated with colliding with infrastructure depends heavily upon the type of infrastructure that is being leveraged for shielded operations. An operation along a tree row, for instance, would likely be categorized as having a severity of 5 since a collision with a tree is likely to be viewed as having no impact. At the other end of the spectrum is infrastructure that could experience a catastrophic disruption of > 24 hrs owing to its being susceptible to a UA collision. Depending upon the complexity of the problem, evaluating infrastructure collision severity could require detailed modeling like that used for evaluation of ground collision severity (e.g., Arterburn et al. 2017) and air collision severity (e.g., Oliveras et al. 2022).

Evaluation of likelihood also depends strongly upon the type of instrastructure being leveraged for shielded operations. Generally, the likelihood of an outcome can be expressed as

$$\mathcal{P}_{SL} = \mathcal{P}_{fail} P_{coll\_susc} P_{SL|coll} \,, \tag{23}$$

where $\mathcal{P}_{SL}$ is the occurrence rate (e.g., per flight hour) for a severity level, $\mathcal{P}_{fail}$ is the rate (e.g., per flight hour) at which a failure associated with the UAS results in a collision with infrastructure, P_{coll_susc} is the likelihood of collision with a susceptible portion of the infrastructure, and $P_{SL|coll}$ is the likelihood of of realizing the severity level given a collision. The UAS failure rate $\mathcal{P}_{fail}$ depends upon UAS characteristics, the environment, and the type of shielding object. If a building is being used for shielding, for instance, flow around the building can produce turbulence that increases $\mathcal{P}_{fail}$. Flight near powerlines exposes the aircaft to electromagnetic interference that can disrupt UAS systems and increase $\mathcal{P}_{fail}$. Operations in an urban canyon can disrupt GPS, increasing $\mathcal{P}_{fail}$. The likelihood of collision with a susceptible portion of the infrastructure P_{coll_susc} and likelihood of of realizing the severity level given a collision $P_{SL|coll}$ depend upon the characteristics of the infrastructure.

The dependence of infrastructure risk upon numerous factors results in the need to perform an SRA for combinations of those factors (inftrastructure type, environment, UAS characteristics, etc.). This results in an effort that is beyond the scope of this project. However, the A45 team did delineate hazard causes and ranked mitigations in order of greatest expected safety impact.

4.4 Uncertainties

Evaluation of uncertainties would be tremendously helpful for risk assessments such as those performed herein. The primary area where benefits would be realized is likelihood, as uncertainty in occurrence rates would not commonly result in changes in severity [e.g., in the time between occurrences exceeding 10^{14} hrs if using FAA Air Traffic Organization (2019) to determine outcome credibility].

Given the inherent uncertainties asociated with CA aircraft densities (e.g., Theisen et al. 2010; FAA Sponsored “Sense and Avoid” Workshop 2013, Appendix G) and, thus, with likelihoods of collisions with CA aircraft, it can be argued that a cleaner approach is to define risk matrices based upon likelihoods of outcomes given an encounter. Such an approach expresses risk directly in terms of system characteristics. When CA aircraft density variability influences likelihoods, on the other hand, that variability can completely mask the impact/benefits of an SAA/DAA system. This challenge is a topic of investigation for an upcoming ASSURE research effort.

Incorporating uncertainties associated with CA aircraft densities can be beneficial when collision rates are used to estimate risk, such as done herein. Doing so can enable retention of DAA system impacts and provide useful guidance by proving a range of likelihood values and, thus, risks. When compared to initial risk, this would show the impacts of SAA/DAA systems while also communicating the inherent variability in risk. Even if collision rates are not used to estimate risk, stakeholders may still desire to know potential collision rates. With incorporation of uncertainties, one can provide better information regarding the range of rates that can be expected.

Incorporation of uncertainties could also benefit evaluation of ground and infrastructure likelihoods. These could be used either to better understand the range of risks or to understand the range of rates at which certain outcomes are expected (e.g., collisions with persons on the ground, how often infrastructure damage resulting in an outage longer than a day is expected, etc.).

The fundamental challenge is quantifying uncertainties. Well defined rules exist for evaluating uncertainties associated with combined quantities such as that derived in (19) (Taylor 1997). However, the lack of data regarding terms in relations such as (19) make estimation of uncertainties challenging. One approach to addressing such challenges is Bayesian inference, which enables use of initial estimates of statistical properties that are updated as additional information becomes available (e.g., Wikipedia 2023).

The A45 team continues to explore estimation of uncertainties and utilization for risk estimation. It will provide updates for this topic either in an addendum to this report or in the A45 final report.

5 RESULTS

5.1 Hazard Causes and Mitigations

Generalized hazard causes, hazards/hazard outcomes, and mitigations were identified (Table 16). Mitigations were ranked in order of expected safety benefit. These are referred to as generalized because they are considered to be high level, with specifics depending upon the CONOPS.

Table 16. Generalized hazard causes, hazards/hazard outcomes, and mitigations. Mitigations are ranked in order of expected safety impact. Outcome applicability is indicated with an 'X'.

Causes	Mitigations Listed in Order of Greatest Safety Impact	Hazards			
		Coll. with Inf.	Coll. with Ground	Coll. with CA	Coll. with UA
Collision with wildlife (birds) that are often present around infrastructure	• Bird detect and avoid system (radar, etc.) • Seasonal restrictions (outside of migration season, winter in a cold region, outside of harvest season) • Time of day (night) • Collision avoidance system (ranked low due to uncertainty of effectiveness) • Bird deterrent system (acoustic system) (ranked last due to uncertainty of effectiveness)	X	X	X	X
EMI effects from infrastructure causing system failures/ degradations	• Shielding of critical systems on UAS • Fly further away from EMI source • Real-time monitoring of EMI onboard UAS • Forecasting EMI potential along flight path	X	X	X	X
Infrastructure causing change in air flow (e.g., turbulence, wind funneling)	• Real-time weather monitoring (onboard measurements) • Automation of control surfaces to account for rapid change in environmental conditions • Fly further away • Weather forecasting system (planning)	X	X	X	X
Degradations/failures of UAS navigation systems	• Redundant/alternative navigation systems • Automation of navigation systems (automatically adapt to degraded navigational performance) • Real-time monitoring of navigation system (human intervention) • Navigation system performance forecasting (planning)	X	X	X	X
Hardware failures on UAS and supporting systems	• Redundant systems • Contingency planning ○ (Health monitoring solutions are inherent in the above mitigations)	X	X	X	X
Loss of Command and Control (C2) owing to structure (interference, blockage, etc.)	• Redundant systems with different coverages [e.g., Point to Point (P2P), satellite, Long Term Evolution (LTE)] • Mesh networked C2 infrastructure • Flight planning to ensure C2 coverage using obstacle map/database • Lost link profile	X	X	X	X
C2 degraded owing to structure (interference, blockage, etc.)	• Redundant systems with different coverages (e.g., P2P, satellite, LTE) • Mesh networked infrastructure • Real time monitoring of the C2 link • Flight planning to ensure C2 coverage using obstacle map/database • Lost link profile	X	X	X	X

Clutter affecting subsystems (e.g., DAA)	• Layered approach to sensors providing data (e.g., radar + Electro-Optical/IR + acoustic, etc.) • Clutter filters/processing for data from sensors • Tracker software that processes sensor data prior to pilot receiving the data • Human in the loop data validation	X	X	X	X
Human error in flight planning and operations	• Automation in the UAS and supporting systems • Human input validation (automated/simulation or secondary human validation) prior to execution of the human input • Monitoring and alerting • Certification requirements or robust training	X	X	X	X
Software errors (geofence failures, etc.)	• Build software to some certification standard • Fully testing software in a controlled environment prior to conducting real-world flights • Automation in the UAS and supporting systems • Human intervention	X	X	X	X
Failure to comply with 14 CFR 91.111 and 91.113 (inability to avoid other aircraft)	• Standards-compliant DAA system • DAA system that is not standards-compliant • UA technical identification capability (includes crewed aircraft capability to receive information) • UA visible identification enhancement • Changing of right-of-way priority			X	X
Failure to comply with 14 CFR 91.13 (e.g., inability to avoid obstacles)	• Obstacle avoidance system • Collision impact mitigation system (frangible, cage, parachute, etc.) • Pre-flight planning	X	X		

5.2 Air Risk

5.2.1 SRA

The A45 team performed a detailed SRA for air risk. In doing so, it focused on 10 hazard causes that it considered to be specific to shielded operations. This list is not comprehensive, as other hazard causes could apply to a specific CONOPS. The hazard causes (for collision with a CA) and mitigations that were considered are shown in Table 17. This list of hazard causes is different from that provided in Table 16 as:

- The team did not evaluate wildlife-driven (e.g., birds) hazards in order to limit the scope of this effort
- Hardware failures (beyond navigation systems) were not evaluated in detail since they are common to all UAS operations (not special to shielded operations)
- Impacts of clutter were not evaluated in detail since they are common to all UAS operations (not special to shielded operations) and are the focus of a separate ASSURE research effort
- Human errors were not evaluated in detail since they are common to all UAS operations (not special to shielded operations)
- Software failures (beyond navigation systems—including geofencing) were not evaluated in detail since they are common to all UAS operations (not special to shielded operations)
- DAA and obstacle avoidance are purposefully included as mitigations in Table 17

It is noted that a DAA system that uses absolute position is assumed to be dependent upon the GPS unit of a UAS whereas a DAA system that uses relative position is not. Thus, a GPS failure results in failure of a DAA system that uses absolute position.

Table 17. Hazard causes and mitigations for air risk.

Hazard Causes and Mitigations for Air Risk
Hazard Causes
GPS failure
GPS Degradation [flight path disrupted by <= 10 ft horizontal or vertical (SME estimated threshold)…this is in addition to 99.99% standard GPS error of 21.68 ft horizontal, 30.15 ft vertical; Wide Area Augmentation System (WAAS) 7.9 ft horizontal, 18.99 ft vertical]
GPS Degradation [flight path disrupted by > 10 ft horizontal or vertical…this is in addition to 99.99% standard GPS error of 21.68 ft horizontal, 30.15 ft vertical; Wide Area Augmentation System (WAAS) 7.9 ft horizontal, 18.99 ft vertical]
Loss of C2 Link longer than 5 s
Improper Lost Link Procedure (e.g., flyaway)
Geofence Failure (not GPS related; software bugs)
EMI (flight path disruption <= 10 ft horizontal or vertical)
EMI (flight path disruption > 10 ft horizontal or vertical)
Turbulence (flight path disruption <= 10 ft horizontal and vertical)
Turbulence (flight path disruption > 10 ft horizontal or vertical)
Potential Mitigations
Redundancy (2nd GPS)
Secondary Navigation Source of Same Quality that Enables Continuation of Mission
Video that can be Used to Maintain Shielding-Object-Relative Position
GPS Health Monitoring to Provide Larger Buffers Relative to Obstacles
Altitude Measurement System to Move to a Safe State (e.g., landing)
Moving to Safe State Using Secondary Navigation or Lost Link Profile (e.g., land)
DAA System that Uses Absolute Position
DAA System that Uses Relative Position (onboard systems only)
Obstacle Avoidance System Installed on UAS
Collision Avoidance System Installed on UAS

For each mitigation for each hazard cause, the expected SL was identified based upon SME consensus. That SL defined the CA collision likelihood based upon the background aircraft encounter rate and the SME-based SF as indicated in Table 13. If something that enables avoidance of CA is included, such as a DAA system, then the benefit of shielding is generally assumed to decrease owing to the need to maneuver outside of the current SL. It is noted that this is a conservative approach, as the period of time associated with a maneuver is relatively small and, without considering interactions with multiple aircraft, one could assume that the SL prior to the maneuver applied. In addition, the spreadsheet used for the air risk SRA was built to compute the number of hours between events and to provide the range of risk outcomes even though a method for estimating uncertainties was not finalized (Figure 8).

Obstacle Avoidance System Installed on UAS

Shielding Catagory	Loss of Well Clear Risk Ratio	NMAC Risk Ratio	MAC Risk Ratio	Rationale	Risk
				#N/A	#N/A
NS	1.0	1.0	0.9	2,272,313	1C
				#N/A	#N/A

Figure 8. Portion of air risk SRA spreadsheet showing SL and SME-estimated risk ratios for a GPS failure hazard cause and obstacle avoidance mitigation. The lower and upper cells for the Rationale and Risk columns are present to hold bounding values for Rationale (number of hours between events) and risk.

Given the estimated background CA encounter rate, the SME-based SFs, and the resulting number of hours between collisions with CA, the required net risk ratio for a MAC [$RR_{WCV|Enc}(ST,SAA) \times RR_{NMAC|WCV}(ST,SAA) \times RR_{MAC|NMAC}(ST,SAA)$] when operating in the different shielded environments to produce an E occurrence rate (1 occurrence every 1,000,000,000 hrs) is provided in Table 18. It is apparent from Table 18 that the net MAC risk ratio requirements are quite strict. These requirements could be reduced by:

- Identifying areas of lower traffic densities
- Determining that shielding provides more benefit (if, in fact, it does)
- Incorporating the likelihood of a fatality given a collision with a CA. If that were on the order of 0.1, for instance, and a severity of 1 was defined to include a fatality associated with the collision, then that would occur at an E rate for net MAC risk ratios 10 times higher than the values in Table 18.

- Using the target level of safety of 1×10^6 hrs between NMACs as utilized by FAA Sponsored "Sense and Avoid" Workshop (2013, Appendix G). Dividing the number of hours between occurrences in Table 18 by 10, the factor associated with going from NMAC to MAC (Weinert et al. 2018), and dividing by 1×10^6 increases the net risk ratios (net NMAC risk ratios in this case) by an order of magnitude. This is complicated by a lack of knowledge regarding flight characteristics near shielding objects, as it is not known whether shielding would decrease the likelihood of NMACs.

It is noted that if the target is a D rate of occurrence, that occurs for the values in Table 18 for net MAC risk ratios of 1.0, 0.67, 0.41, and 0.2 for SL1, SL2, SL3, and NS environments, respectively.

Table 18. Net MAC risk ratios required to reach an E occurrence for the four shielding levels.

Shielding Level	Shielding Distance (ft)	Shielding Factor (SME-Based)	Number of Hours Between Occurrences	Shielding only Risk	$RR_{WCV\|Enc}(ST,SAA) \times RR_{NMAC\|WCV}(ST,SAA) \times RR_{MAC\|NMAC}(ST,SAA)$
SL1	≤ 50	0.1366209	14,969,025	1D	0.014969025
SL2	≤ 100	0.3070232	6,660,999	1C	0.006660999
SL3	≤ 200	0.5003421	4,087,366	1C	0.004087366
NS	> 200	1.0	2,045,081	1C	0.002045081

5.2.2 Shielding Factor Survey Results

Response to the survey was excellent, though not every operation garnered a strong response. This was expected given that outreach to every type of operator was not possible. The minimum and maximum number of respondents to the frequency vs. distance questions (questions 6, 8, 10, 12, 14, 16, 18, 20, 22, and 25 in Appendix A) for the operations considered in the survey are provided in Table 19. As indicated in Table 19, Agricultural Application (Spraying and Dusting) were the dominant type of respondent. Recreational and Air Ambulance or Medical Services were the next most common type of operator, with the number of responses an order of magnitude smaller than from Agricultural Application operators. The total number of respondents for frequency vs. distance questions, taken as the total of the maximum number of respondents, is 359. As indicated in Table 19, not all respondents completed all components of the survey.

Table 19. Minimum and maximum number of respondents to frequency vs. distance questions for all obstacles except for those in the other category for each type of operation.

Operation	Minimum Number of Respondents	Maximum Number of Respondents
Agricultural Application	286	313
Air Ambulance or Medical Services	10	12
Low-Altitude Infrastructure Inspection	5	5
Air Tours	2	2
News Gathering	0	0
Public Safety	1	1
External Load	1	1
Training	6	6
Animal/Earth/Plant Sciences	0	0
Recreational	12	14
Ultralight	0	1
Other	4	4

Plots of all of the SFs for operations that had at least a minimum of 5 responses (Agricultural Application, Air Ambulance or Medical Services, Low-Altitude Infrastructure Inspection, Training, and Recreational) are provided in Appendix B. Results for operations having less than at least 5 responses are considered to be unreliable owing to the associated small sample size.

Shapes of SFs are classified according to values at the minimum distance (12.5 ft) and maximum distance (350 ft). Ranges of SFs are categorized as shown in Table 20. These categories are based roughly upon dividing the range of values into three equal bins, with the bin for the larger values wider given that a risk ratio larger than 0.5 is associated with relatively poor performance with an associated safety benefit realized less than half of the time. Given these, Table 21 provides the SF shape classes for obstacles considered in the survey for operations having at least a minimum of 5 responses. For SF curves where a categorical boundary is different for horizontal and vertical distances, the average of the SF factors for the two is used to determine the category.

As illustrated in Table 21, L-H type curves are the most common, and is the dominant shape class for Air Ambulance or Medical Services and Low-Altitude Infrastructure Inspection Operations. The H shape class is the next most common, being dominant for Agricultural Application and Recreational operations (L-H and H are tied for Training operations). The L-M shape class, followed by the M-H shape class, are the next most common, though neither is dominant for any operations. The L shape class arises only a couple of times, while the M shape class has no entries in Table 21.

Across operations, Powerlines and Powerline Poles/Towers arise frequently in the H shape class. Wind Turbines and Bridges tend to arise in the L and L-M shape classes. Residential and Commercial Buildings are commonly in the L-H shape class.

The operations that seem to present the most danger when operating close to obstacles are Agricultural Applications, Training, and Recreational, owing to the high number of H shape classes. Air Ambulance or Medical Services and Low-Altitude Infrastructure Inspection are dominated by the L-H shape class. From the survey data the safest shielding environments would be near Wind Turbines when the CA traffic is dominated by Air Ambulance or Medical Services operations and Bridges when the CA traffic is dominated by Training operations.

Table 20. SF value categories used to classify SF curves.

Range of SF Values	Descriptive Category
$SF \leq 0.3$	Low (L)
$0.3 < SF \leq 0.6$	Moderate (M)
$SF > 0.6$	High (H)

Table 21. Operations and obstacles having the SF shape classes delineated in the first row.

Operation	Low (L)	Moderate (M)	High (H)	Low-Moderate (L-M)	Low-High (L-H)	Moderate-High (M-H)
Agricultural Application			Powerlines Powerline Poles/Towers Trees/Shelter Belts Other Structures	Wind Turbines Bridges	Residential Buildings Commercial Buildings	Other Towers Guy Wires
Air Ambulance or Medical Services	Wind Turbines			Guy Wires Bridges	Powerlines Powerline Poles/Towers Other Towers Residential Buildings Commercial Buildings Trees/Shelter Belts	
Low-Altitude Infrastructure Inspection				Bridges	Wind Turbines Powerlines Other Towers Guy Wires Residential Buildings Commercial Buildings Trees/Shelter Belts	Powerline Poles/Towers

Training	Bridges		Powerlines Powerline Poles/Towers Trees/Shelter Belts	Wind Turbines Commercial Buildings	Other Towers Guy Wires Residential Buildings	
Recreational			Powerlines Powerline Poles/Towers Trees/Shelter Belts	Wind Turbines Bridges	Residential Buildings Commercial Buildings	Other Towers Guy Wires

Figure 9 provides examples of the different shape classes and curve types (concave down or linear or slightly concave up). Shapes for horizontal and vertical SFs are generally similar, though some differences are present (e.g., Training near Wind Turbines). All of the curves in Figure 9 are concave down except for Air Ambulance or Medical Services near Wind Turbines, which are linear (or nearly so) and possibly slightly concave up. SF curves derived from a large number of respondents tended to be relatively smooth (Agricultural Operations; cf. Figure 9 and Appendix B). Curves derived from a smaller number of respondents can exhibit more irregularity (e.g., bottom image in Figure 9).

In Figure 9, estimated distances at which behavior changes varies from < 50 ft to > 250 ft, depending upon the operation and obstacle. This range is consistent with the range obtained by analyzing the figures in Appendix B. Distances at which behavior changes are commonly nearly equivalent for horizontal and vertical SF curves. Some differences do occur (cf. Appendix B). For Agricultural Application horizontal SF curves, the distances at which behavior is estimated to change are ≤ ~50 ft.

An oddity is the Training near Commercial Buildings horizontal SF curve. For that curve, the estimated distance at which behavior changes is on the very far left side of the plot (near the minimum distance). This computation was checked and confirmed to be correct. Fitting this irregularly-shaped curve (concave up and flat in different portions of the curve) appears to have produced this odd result.

The methods used to identify behavior changes generally identified locations that are at least close to locations that one would visually identify. This does not always occur, however, with examples being the vertical SF curve for Training near Wind Turbines (middle left image of Figure 9) and the SF curves for Recreation near Other Towers (bottom image of Figure 9). For these, the identified behavior-change locations appear to be at distances that are too large. While availability of more responses would likely produce smoother curves and more accurate estimates using the current approach, it is expected that more complex shapes (e.g., curves that are relatively flat at larger distances that drop rapidly over a range of distances and then flatten again) may naturally occur. For such complex shapes, the current approach is expected to struggle. Thus, a future area of improvement could be enhancement of the algorithm used to identify behavior changes.

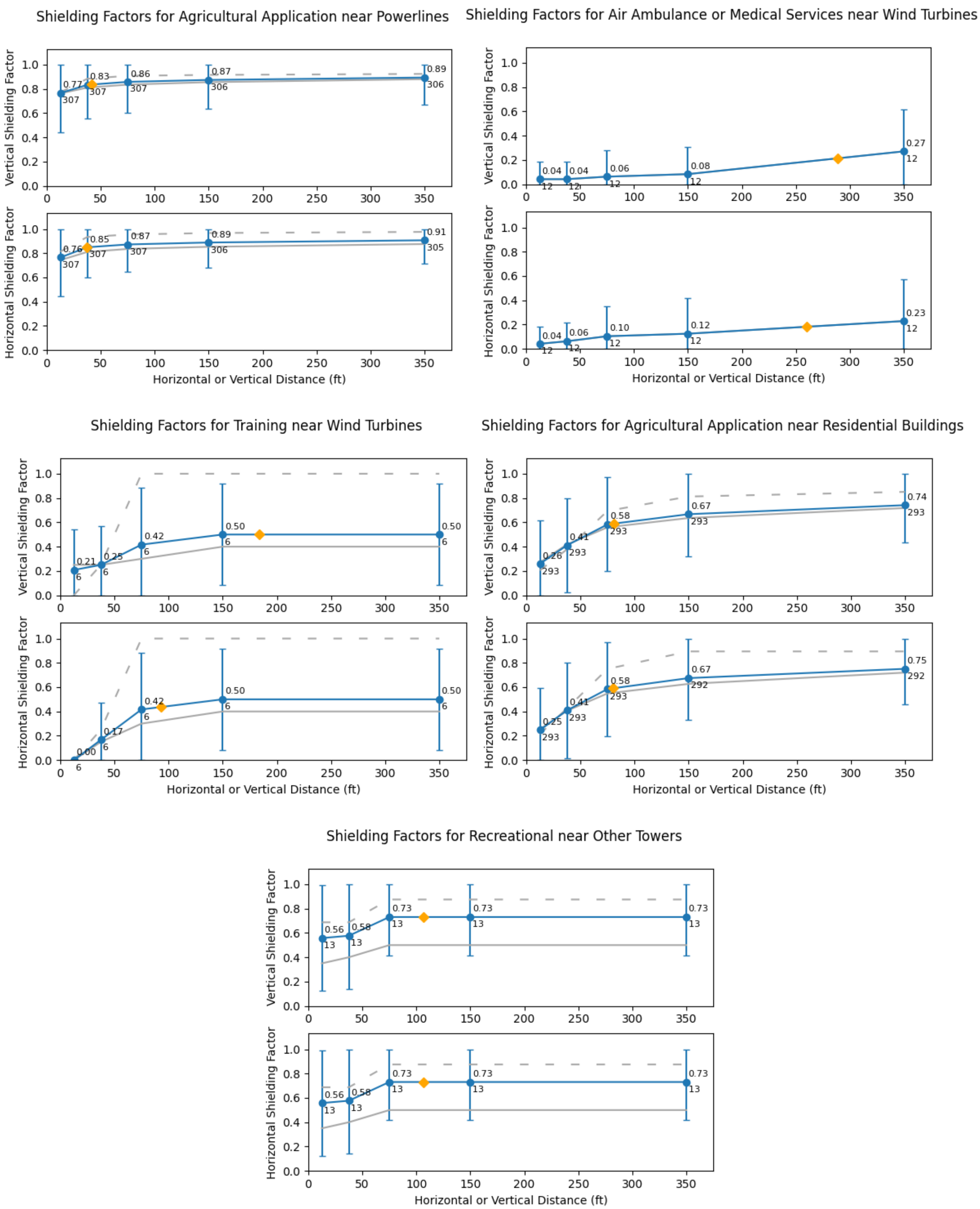

Figure 9. Examples of shape classes and curve types. The solid blue lines indicate the average estimated SF for all types of responses (C, PN, and PU), the solid grey lines indicate the average estimated SF for C responses, and the dashed grey lines indicate the average estimated SF for PN and PU responses (combined). The blue whiskers illustrate error bars associated with a single standard deviation of the SF

values for all types of responses (to the physical limits of 0.0 and 1.0). The number of responses and values for SFs derived from all types of response are provided below and above plotted points. Orange diamonds indicate estimated distances at which behavior changes. Shape classes are H (upper left), L (upper right), L-M (middle left), L-H (middle right), and M-H (bottom).

Tables 22-26 provide comparisons of SME-estimated SFs (Table 12) with those derived from the survey. As indicated in these tables, differences between SME-estimated and survey-derived SFs vary significantly depending upon operation and obstacle. SME-estimated SFs are too low for almost every obstacle and distance (all but three values) for both Agricultural Application operations (Table 22) and Recreational operations (all but two values; Table 26). This is not terribly surprising given that Agricultural Application operations are characterized by so many SFs in the H shape class and Recreational operations has a large number of H and M-H SF shapes. For the operations that had at least a minimum of 5 responses, SME-estimated SFs were generally too low. The exception is Air Ambulance or Medical Services operations, for which the magnitudes of average SF differences are ≤ 0.07 and SME-estimated values are generally within the uncertainty window of survey-derived values. Plots of SF differences (not shown) show that SF difference magnitudes generally decrease with increasing distance. Low-Altitude Infrastructure Inspection is the exception here, with SF difference magnitude increasing from the closest distance (25 ft) to the next distance (75 ft) and then decreasing from that distance to the greatest distance (150 ft). Averages have been computed from the summary differences provided in Tables 22-26. For both horizontal and vertical SFs, SME-based values are too low by ~0.25 for distances of 25 ft and 75 ft, and too low by ~0.14 for 150 ft. Of course, SME-based estimates are effectively an average for all of the types of operations (e.g., Table 19), whereas these values are derived from the 5 types of operations for which at least a minimum of 5 responses was provided. Thus, it is difficult to definitively conclude that the SME-based SF estimates are too low. Acquisition of data regarding low-altitude traffic and subsequent computation of SFs is the definitive approach for estimating SFs and for determining the accuracy of SME-estimated and survey-derived SFs.

Table 22. Comparison of SME-estimated and survey-derived SFs for both horizontal (Horiz.) and vertical (Vert.) survey-derived SFs for Agricultural Application operations. Results are provided only for obstacles for which at least a minimum of 5 responses was provided. Values are shown for the mid-range distances associated with the SME-estimated SFs. Differences (Diff.) between SFs are provided as is whether SME-estimated SFs are within (w/i) the uncertainty (Unc.) window of survey-derived results (within one standard deviation of the mean value as shown by the blue whiskers in, for example, Figure 9), which is indicated by 'Y' (yes) and 'N' (no) for the mid-range distances associated with SME-estimated SFs. The symbol ' is used to indicate ft to save space. The last row provides summary information (Info.).

Obstacle	25 ft Horiz. Diff.	75 ft Horiz. Diff.	150 ft Horiz. Diff.	25 ft Vert. Diff.	75 ft Vert. Diff.	150 ft Vert. Diff.	25' Horiz. w/i Unc. Window	75' Horiz. w/i Unc. Window	150' Horiz. w/i Unc. Window	25' Vert. w/i Unc. Window	75' Vert. w/i Unc. Window	150' Vert. w/i Unc. Window
Wind Turbines	-0.200	-0.197	-0.061	-0.116	-0.127	0.001	Y	Y	Y	Y	Y	Y
Powerlines	-0.670	-0.565	-0.388	-0.663	-0.551	-0.374	N	N	N	N	N	N
Powerline Poles/Towers	-0.645	-0.556	-0.381	-0.654	-0.548	-0.368	N	N	N	N	N	N
Other Towers	-0.354	-0.400	-0.252	-0.314	-0.360	-0.218	Y	N	Y	Y	N	Y
Guy Wires	-0.439	-0.449	-0.294	-0.413	-0.420	-0.264	N	N	N	N	N	Y
Residential Buildings	-0.192	-0.277	-0.174	-0.198	-0.276	-0.167	Y	Y	Y	Y	Y	Y
Commercial Buildings	-0.119	-0.166	-0.084	-0.121	-0.156	-0.071	Y	Y	Y	Y	Y	Y
Trees/Shelter Belts	-0.609	-0.527	-0.346	-0.615	-0.521	-0.340	N	N	N	N	N	N
Bridges	-0.149	-0.118	0.006	-0.142	-0.120	0.007	Y	Y	Y	Y	Y	Y
Other Structures	-0.648	-0.536	-0.379	-0.610	-0.524	-0.344	N	N	N	N	N	N
Summary Info.	-0.403	-0.379	-0.235	-0.384	-0.360	-0.214	5 Y's; 5 N's	4 Y's; 6 N's	5 Y's; 5 N's	5 Y's; 5 N's	4 Y's; 6 N's	6 Y's; 4 N's

Table 23. As in Table 22, but for Air Ambulance or Medical Services operations.

Obstacle	25 ft Horiz. Diff.	75 ft Horiz. Diff.	150 ft Horiz. Diff.	25 ft Vert. Diff.	75 ft Vert. Diff.	150 ft Vert. Diff.	25' Horiz. w/i Unc. Window	75' Horiz. w/i Unc. Window	150' Horiz. w/i Unc. Window	25' Vert. w/i Unc. Window	75' Vert. w/i Unc. Window	150' Vert. w/i Unc. Window
Wind Turbines	0.085	0.203	0.375	0.095	0.245	0.417	Y	Y	N	Y	N	N
Powerlines	-0.147	-0.148	-0.022	-0.125	-0.125	0.000	Y	Y	Y	Y	Y	Y
Powerline Poles/Towers	-0.126	-0.193	-0.075	-0.126	-0.168	-0.050	Y	Y	Y	Y	Y	Y
Other Towers	-0.038	-0.068	0.050	-0.026	-0.068	0.025	Y	Y	Y	Y	Y	Y
Guy Wires	0.043	0.132	0.225	0.043	0.132	0.225	Y	Y	Y	Y	Y	Y
Residential Buildings	-0.063	-0.118	-0.025	-0.063	-0.118	-0.025	Y	Y	Y	Y	Y	Y
Commercial Buildings	-0.151	-0.143	-0.100	-0.151	-0.143	-0.175	Y	Y	Y	Y	Y	Y
Trees/Shelter Belts	-0.176	-0.343	-0.200	-0.151	-0.318	-0.200	Y	N	N	Y	N	N
Bridges	-0.001	0.082	0.175	-0.001	0.082	0.150	Y	Y	Y	Y	Y	Y
Summary Info.	-0.064	-0.066	0.045	-0.056	-0.053	0.041	9 Y's; 0 N's	8 Y's; 1 N's	7 Y's; 2 N's	9 Y's; 0 N's	7 Y's; 2 N's	7 Y's; 2 N's

Table 24. As in Table 22, but for Low-Altitude Infrastructure Inspection operations.

Obstacle	25 ft Horiz. Diff.	75 ft Horiz. Diff.	150 ft Horiz. Diff.	25 ft Vert. Diff.	75 ft Vert. Diff.	150 ft Vert. Diff.	25' Horiz. w/i Unc. Window	75' Horiz. w/i Unc. Window	150' Horiz. w/i Unc. Window	25' Vert. w/i Unc. Window	75' Vert. w/i Unc. Window	150' Vert. w/i Unc. Window
Wind Turbines	-0.072	-0.093	-0.150	0.012	-0.143	-0.200	Y	Y	Y	Y	Y	Y
Powerlines	-0.338	-0.543	-0.350	-0.313	-0.543	-0.350	Y	N	N	Y	N	N
Powerline Poles/Towers	-0.313	-0.543	-0.350	-0.313	-0.543	-0.350	Y	N	N	Y	N	N
Other Towers	-0.013	-0.210	-0.150	-0.013	-0.210	-0.150	Y	N	Y	Y	N	Y
Guy Wires	-0.013	-0.143	-0.100	-0.013	-0.143	-0.100	Y	Y	Y	Y	Y	Y
Residential Buildings	-0.113	-0.293	-0.200	-0.063	-0.243	-0.150	Y	N	Y	Y	Y	Y
Commercial Buildings	-0.013	-0.143	-0.100	-0.013	-0.143	-0.100	Y	Y	Y	Y	Y	Y
Trees/Shelter Belts	-0.113	-0.443	-0.350	-0.113	-0.493	-0.400	Y	N	N	Y	N	N
Bridges	0.037	0.207	0.100	0.037	0.207	0.100	Y	Y	Y	Y	Y	Y
Summary Info.	-0.106	-0.245	-0.183	-0.088	-0.250	-0.189	9 Y's; 0 N's	4 Y's; 5 N's	6 Y's; 3 N's	9 Y's; 0 N's	5 Y's; 4 N's	6 Y's; 3 N's

Table 25. As in Table 22, but for Training operations.

Obstacle	25 ft Horiz. Diff.	75 ft Horiz. Diff.	150 ft Horiz. Diff.	25 ft Vert. Diff.	75 ft Vert. Diff.	150 ft Vert. Diff.	25' Horiz. w/i Unc. Window	75' Horiz. w/i Unc. Window	150' Horiz. w/i Unc. Window	25' Vert. w/i Unc. Window	75' Vert. w/i Unc. Window	150' Vert. w/i Unc. Window
Wind Turbines	0.053	-0.110	0.000	-0.093	-0.110	0.000	Y	Y	Y	Y	Y	Y
Powerlines	-0.634	-0.651	-0.458	-0.655	-0.651	-0.458	N	N	N	N	N	N
Powerline Poles/Towers	-0.634	-0.485	-0.291	-0.634	-0.485	-0.291	N	N	Y	N	N	Y
Other Towers	-0.232	-0.276	-0.083	-0.232	-0.276	-0.083	Y	Y	Y	Y	Y	Y
Guy Wires	-0.191	-0.235	-0.083	-0.191	-0.235	-0.083	Y	Y	Y	Y	Y	Y
Residential Buildings	-0.113	-0.401	-0.208	-0.113	-0.401	-0.208	Y	N	Y	Y	N	Y
Commercial Buildings	-0.072	0.057	0.084	-0.072	0.015	0.084	Y	Y	Y	Y	Y	Y
Trees/Shelter Belts	-0.530	-0.360	-0.166	-0.530	-0.360	-0.166	N	Y	Y	N	Y	Y
Bridges	0.095	0.182	0.375	0.095	0.182	0.375	Y	Y	N	Y	Y	N
Summary Info.	-0.251	-0.253	-0.092	-0.269	-0.258	-0.092	6 Y's; 3 N's	6 Y's; 3 N's	7 Y's; 2 N's	6 Y's; 3 N's	6 Y's; 3 N's	7 Y's; 2 N's

Table 26. As in Table 22, but for Recreational operations.

Obstacle	25 ft Horiz. Diff.	75 ft Horiz. Diff.	150 ft Horiz. Diff.	25 ft Vert. Diff.	75 ft Vert. Diff.	150 ft Vert. Diff.	25' Horiz. w/i Unc. Window	75' Horiz. w/i Unc. Window	150' Horiz. w/i Unc. Window	25' Vert. w/i Unc. Window	75' Vert. w/i Unc. Window	150' Vert. w/i Unc. Window
Wind Turbines	-0.096	-0.086	0.072	-0.096	0.003	0.125	Y	Y	Y	Y	Y	Y
Powerlines	-0.613	-0.558	-0.384	-0.613	-0.558	-0.384	N	N	N	N	N	N
Powerline Poles/Towers	-0.604	-0.539	-0.365	-0.604	-0.539	-0.365	N	N	N	N	N	N
Other Towers	-0.431	-0.424	-0.230	-0.431	-0.424	-0.230	Y	N	Y	Y	N	Y
Guy Wires	-0.415	-0.360	-0.187	-0.415	-0.401	-0.229	N	N	Y	N	N	Y
Residential Buildings	-0.124	-0.117	-0.090	-0.082	-0.117	-0.090	Y	Y	Y	Y	Y	Y
Commercial Buildings	-0.165	-0.214	-0.104	-0.165	-0.214	-0.104	Y	Y	Y	Y	Y	Y
Trees/Shelter Belts	-0.686	-0.630	-0.437	-0.634	-0.568	-0.375	N	N	N	N	N	N
Bridges	-0.103	-0.193	-0.104	-0.103	-0.130	-0.041	Y	Y	Y	Y	Y	Y
Summary Info.	-0.360	-0.347	-0.203	-0.349	-0.328	-0.188	5 Y's; 4 N's	4 Y's; 5 N's	6 Y's; 3 N's	5 Y's; 4 N's	4 Y's; 5 N's	6 Y's; 3 N's

5.2.3 Analysis of Cooperative Aircraft Data

Two weeks of ADS-B data were collected for analysis, as the capability for data collection was established close to the end of the growing season. These data are from the growing season and were collected in North Dakota. The A45 team expects to perform further analyses using data collected during the 2023 growing season.

Multiple agricultural applicator aircraft were identified as operating at low altitudes, with a few operating close to powerlines. One example is shown in Figure 10. In this example, the agricultural aircraft crosses the powerline. Aircraft distances from the powerline at times when samples were available are provided in Table 27. As indicated in that table, the minimum horizontal distance from the data that were gathered is ~36 ft. The minimum horizontal distance is actually 0 ft, of course, since the aircraft crossed the powerline. The minimum vertical distance, from the collected data, is ~84 ft. When considering horizontal and vertical distance pairs, the maximum of the two defines the relevant distance from a shielding object (last column in Table 27).[12] From the set of maximum distances of the pairs of horizontal and vertical distances at the sample times, the minimum then defines the distance at the time of maximum risk d_{mr}. This follows Askelson and Stephens (2022), with the difference that unit distances in the horizontal and vertical directions are assumed here to engender the same amount of risk. For this powerline-crossing example, then, d_{mr} = ~84 ft. It is noted that in this context risk could be considered to be collision between a UA operating in the shielding environment and a CA or collision of the CA with the shielding object. Furthermore, analysis of such data would be enhanced by separating the cases when d_{mr} results from horizontal and vertical separation (distances h_{mr} and v_{mr} for horizontal and vertical distances, respectively), as characteristics of CA separations from shielding objects likely vary in the horizontal and vertical directions.

[12] An aircraft could be miles from a shielding object horizontally and at the same altitude as that object. The horizontal distance, in that case, is what is relevant.

Figure 10. Example of an aircraft interaction with a powerline. The yellow pins show aircraft locations and the red line indicates the powerline.

Table 27. Locations and distances from powerline for an agricultural aircraft that crossed a nearby powerline. Powerline height is assumed to be 25 ft.

Latitude	Longitude	Altitude AGL (ft)	Horizontal Distance from Powerline (ft)	Vertical Distance from Powerline (ft)	Maximum of Horizontal and Vertical Distances (ft)
48.790734	-101.583742	108.87	140.7	83.87	140.7
48.790884	-101.583924	108.76	97.4	83.76	97.4
48.791013	-101.584032	108.74	71.3	83.74	83.74
48.791163	-101.584182	108.73	36.2	83.73	83.73
48.791442	-101.584504	108.72	41.89	83.72	83.72
48.791592	-101.584611	108.79	67.36	83.79	83.79
48.791764	-101.584793	109.31	111.74	84.31	111.74

Another example is provided in Figure 11. Data for this example were sparse. However, one data point indicating a horizontal distance of ~32 ft was available. This indicates that agricultural aircraft do pass quite close to powerlines.

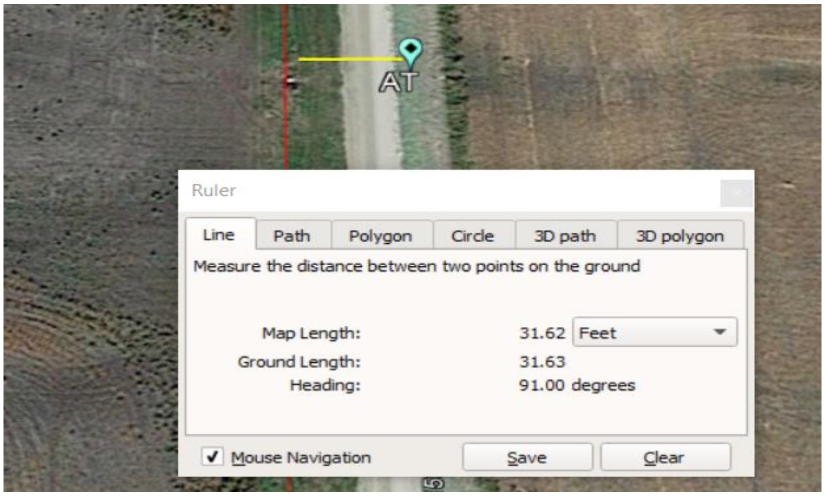

Figure 11. Example of an aircraft operating near a powerline. The pin indicates aircraft location and red line indicates the powerline.

The preliminary analysis conducted to this point indicates that approximately one out of 4 agricultural aircraft operate within 100 ft of powerlines. This is very preliminary, however, and should not be utilized until a more comprehensive analysis is completed.

Significant limitations impact this type of analysis. The first is the challenge of collecting data for aircraft that are operating at very low altitudes. In addition, the data used herein were limited to a two-week period and four locations. Finally, powerline databases are flawed. Examples of issues identified in this analysis are provided in Figure 12. As shown, powerlines can be present when the database indicates no powerlines. Moreover, an incorrect number of powerlines can be indicated, with a horizontal spatial error in the location of the edge of a set of powerlines of about 31 ft for the example shown. This underscores the importance of verifying powerline locations if using them as shielding objects, as shielding object databases are imperfect.

Figure 12. Examples of powerline database limitations. Example where a powerline is not indicated in the database (left) and where an incorrect number of wires is indicated (right). In the image on the left,

powerline towers (dark, nearly vertical features near the bottom of the image) are apparent. In the image on the right, the white lines indicate the powerlines while the red lines are powerline locations indicated by the database.

5.3 Ground Risk

The list of hazard causes, hazards/hazard outcomes, and mitigations are provided in Table 16. Well known mitigations such as reducing the size/weight of the UA and use of parachutes to reduce impact severity, fall under generalized mitigations such as contingency planning ("Hardware failures on UAS and supporting systems") hazard cause.

The following values were used in the ground risk evaluation tool:

- $P_{fail} = 1\times10^{-4}$ hr^{-1}, which is the failure rate for aircraft having weights between 4.5-20.9 lbs from Bruenig et al. (2018).
- $\rho_{people} = 101$ mi^{-2}, which is slightly higher than the average population density of the U.S. of ~90 mi^{-2} (U.S. Census Bureau 2015).
- S=0.5.
- Aircraft airspeed = 87 kts
- Windspeed = 25 kts
- Aircraft altitude = 400 ft
- Navigational performance = 50 ft
- A road density consistent with a rural environment

The last five of these parameters contribute to the terms in (22) given that the exact formulation used in the tool is based upon (22) but not necessarily equivalent to it. With these settings, $P_{fatality} = 2.93\times10^{-10}$ hr^{-1} for unsheltered persons and $P_{fatality} = 6.47\times10^{-9}$ hr^{-1} for roadways. These combine to produce $P_{fatality} = 6.76\times10^{-9}$ hr^{-1}, which corresponds to a fatality every 147,928,994 hrs. Thus, an estimate for fatality rate results in a risk of 1D. Incorporation of mitigations, including those listed in Table 16, could significantly reduce this risk. Conservatively, a reduction by an order of magnitude results in a 1E residual risk.

5.4 Infrastructure Risk

As previously discussed, infrastructure risk, including severity and likelihood, is highly variable and depends upon UAS characteristics (affect severity and likelihood), the type of shielding object (affects severity and likelihood), and the environment (generally affects likelihood). Some shielding objects are expected to have low severity. A tree row, for instance, is expected to have a severity of 5 owing to a collision with a tree being viewed as having no impact. Collision with infrastructure, including critical infrastructure, on the other hand, could easily have a severity of 1. It is noted that a severity of 2 was realized when a UA collided with a powerline in California causing a power outage for ~3 hrs (Bay City News 2017).

Evaluation of likelihood is complicated owing to dependence upon UAS characteristics, the environment, and the type of shielding object. While an evaluation of likelihoods for this broad set of characteristics is beyond the scope of this task, Task 3 is expected to provide insights that can be used to estimate likelihoods for some scenarios.

6 CONCLUSIONS

6.1 Future Work

Throughout this report, areas of future work have been identified. These include:

- Collection of data regarding low-altitude CA operations. This is challenging and critical. While analysis methods can be very enabling, there is no replacement for data. Some data needs include:
    - Data regarding low-altitude CA densities, including variations in location and time.
    - CA flight patterns relative to different types of shielding objects.
- Development of a more complex algorithm to improve identification of features in SF curves (e.g., locations where operator behavior seems to change).
- Establishment of severities (e.g., severity of a collision between a UA and a CA) that can be used to update severity scales such as those used herein.
- Establishment of methods for estimating uncertainties. These are very important to understand the range of expected outcomes and to enable expression/retention of the benefits of mitigations when conducting analyses like those performed herein.
- Incorporation of additional factors identified herein, such as agricultural locations vs. non-agricultural locations in establishment of air risk classes.
- Revision of ground risk classes using more population density categories, according to number of persons taking part in an outside gathering, according to shielding factor differences, etc.
- Revision of the low-altitude airspace density estimate developed in Section 4.3.2.2 using the potential improvements identified in that section.

6.2 Summary

The demand for BVLOS operations using UASs is high owing to the numerous associated benefits, including humanitarian and economic (improved health outcomes, increased efficiency, etc.). One approach that can enable sUAS BVLOS operations is shielded operations, wherein a sUAS is operated near objects such as buildings, powerlines, etc. Operation near such objects is assumed to produce a safety benefit relative to encounters with CA since CA will generally maintain separation from such objects. Shielded operations have significant potential for increasing sUAS BVLOS operations. While the amount of low-altitude airspace that could be accessed using shielding is relatively small, such operations could be used, in addition to serving directly-related use cases such as powerline inspection, to serve as a network (e.g., powerline networks) that enables operations to reach stakeholders customers.

This ASSURE project (A45) has numerous associated tasks. Herein, the focus is on SRA for shielded operations. Processes follow those defined by the FAA, including U.S. Department of Transportation (2017a, 2019) and FAA Air Traffic Organization (2019). This effort is divided into two primary tasks:

- Development of a set of shielding classes, which can be used to support an SRA
- Hazard analysis (SRA)

The set of shielding classes was developed by considering three primary hazard categories: air risk, ground risk, and infrastructure risk. Potential outcomes in these categories are collision with a CA, collision with a person on the ground, and collision with infrastructure. For these hazard categories, the environments, which indicate likelihoods of outcomes, were characterized and comprised the entry/value for that hazard category.

For the air risk category, the team characterized low-altitude CA operations, which was greatly supported by previous work performed by Weinert and Barrera (2020). The team added operations, including infrastructure inspection, infrastructure work, and recreational flying. It also provided additional information regarding characteristics of these low-altitude CA operations. To further understand low-altitude CA operations, the team also reviewed relevant regulations. This review enabled identification of regulatory drivers of low-altitude traffic, which are:

- Airspace class
- IMC vs. VMC
- Congested vs. other-than congested area.
- Daytime vs. nighttime

The team also identified other potential drivers. Numerous location factors were identified, with an important one that impacts Spraying and Dusting operations being agricultural/horticultural/forest areas versus non. This factor was not used in the analysis performed herein, but could be easily incorporated. An important temporal factor that was identified is season (growing vs. non-growing), which impacts Spraying and Dusting operations. This factor was utilized in the analysis performed herein.

Given the identified factors, SME input was used to evaluate expected qualitative traffic levels, using a Likert scale, for all values associated with these drivers (e.g., B, C, D, E, and G for airspace class). Resulting relative activity levels were discretized into three air-risk-driven classes:

A1. IMC conditions
A2. VMC conditions at night
A3. VMC conditions during the daytime

The method utilized herein can easily be adapted for different/new low-altitude CA operations and location/temporal variations in activity levels.

For ground risk, previous work (e.g., Joint Authorities for Rulemaking of Unmanned Systems 2019) was leveraged to identify classes. This resulted in:

G1.Controlled area with no third-party persons present
G2. Rural area (< 500 persons mi^{-2})
G3. Urban area (≥ 500 persons mi^{-2})
G4. Gathering of people outside (un-sheltered)

Of the categories, infrastructure risk had the least amount of preexistent effort related to identifying classes. The team identified the following as a set of potential classes:

I1. Non-infrastructure and non-property (e.g., tree rows)
I2. Property
I3. Infrastructure
I4. Critical infrastructure

The final category that was identified for delineation of shielding classes is the type of shielded operation/shielding object. The suggested set of classes is:

SO-LL: Long Linear shielding objects, such as powerlines

SO-R: Rectangular shielding objects, such as buildings (rectangular in both horizontal and vertical planes)

SO-NV: Narrow Vertical shielding objects, such as towers, wind turbines, etc.

Specification of shielding class requires aggregation of the specific classes for the categories. It is recommended that this be done using a format like SO-X | AN-GN-IN, where X represents of the SO classes and N indicates a number. A specific example is SO-LL | A3-G2-I3, which indicates a Long Linear shielding object with flights in VMC conditions during the daytime in a rural area near infrastructure.

The first step in hazard analysis is identification of assumptions. Key assumptions used in the SRA performed herein are:

- Group 1 or 2 UAS
- Operations below 400 ft
- Base equipage does not include alternative navigation systems (e.g., INS), a DAA system, collision avoidance system, or obstacle avoidance system (enables evaluation of safety impact of such systems).

In addition, the following shielding levels are used:

- SL1: Within 50 ft (horizontally or vertically) of shielding object
- SL2: Within 100 ft (horizontally or vertically) of shielding object
- SL3: Within 200 ft (horizontally or vertically) of shielding object
- No Shielding (NS): Beyond 200 ft (horizontally or vertically) of shielding object

These are based primarily upon SME input, but are also consistent with the UAS BVLOS ARC (2022) recommendation that shielding be defined to occur within 100 ft of an obstacle. Efforts, including a survey of low-altitude CA operators and analysis of cooperative data for low-altitude CA operations, are underway to refine these definitions. It is noted that use cases generally provide critical insight into operational conditions. Some relevant use cases are described herein, but are not critical to this analysis as it is intended to be general enough to apply to any CONOPS.

Processes following U.S. Department of Transportation (2017a, 2019) and FAA Air Traffic Organization (2019) are followed for the SRA. Severity scales are defined for each hazard category. Challenges include definition of the highest risk category for air risk given uncertainties around air collision severity and establishment of a severity scale for infrastructure that has measurable impacts. The team applied a conservative approach for air risk, defining a collision with a CA as having a severity of 1 (a severity of 1 generally involves a fatality, which is not guaranteed with a sUAS-CA collision). The team developed an infrastructure severity scale that leverage length of (infrastructure) system outage, which is directly measurable as opposed to fatalities relative to damage to infrastructure, which can be very challenging to identify.

To enable quantification, likelihoods are expressed per UAS flight hour, following FAA Air Traffic Organization (2019). The risk matrix that is applied is that used for General Aviation Operations/Small Aircraft and Rotorcraft.

A framework for evaluating the likelihood of events associated with interactions with CA (well clear violation, NMAC, MAC) is developed. This framework illustrates how risk ratios, which are ratios of probabilities of events with and without a system (e.g., a DAA system), combine when sequential events occur (e.g., well clear violation, NMAC, and MAC). This framework is also used to illustrate how shielding reduced air risk, with SFs filling the same role as risk ratios. A mathematical framework for the combined effects of shielding and utilization of SAA systems is presented and utilized. It is noted that SF could easily be redefined such that the corresponding risk ratio is 1-SF. With that redefinition, a higher SF would correspond to more protection from CA. Moreover, while SF, as defined herein, acts mathematically like a risk ratio, it could be renamed as something like Strategic Mitigation Ratio (SMR). Doing so explicitly recognizes that SF is a strategic mitigation, as opposed to a risk ratio, which is generally used to evaluate performance with and without utilization of a system (e.g., SAA).

Traditional methods for evaluating air risk depend upon CA encounter rates. While it is suggested herein that an alternative approach may be better, details regarding that approach have not yet been developed. Estimation of encounter rates at low altitudes is very challenging given the lack of data regarding low-altitude CA operations. An approach for such an estimation is presented herein. Future work should focus on estimating uncertainties associated with this approach and with other aspects of the SRA performed herein.

Shielding factors are estimated using both SME input and a survey. The survey was well received, with input provided by 359 respondents. The respondents were predominantly from the Agricultural Application operator category, with the number of respondents for other types of operations at least an order of magnitude smaller. Shielding factors for both horizontal and vertical distances were derived for five types of operations, for which at least five respondents provided input. Shielding factor curves vary, with some operations avoiding certain obstacles at relatively large distances (>200 ft) and others regularly flying close (<25 ft) to obstacles (e.g., Agricultural Application operating near Powerlines). Given that survey results are uncertain, further work to obtain data regarding operations near low-altitude obstacles would greatly help with SF estimation.

Methods for estimating ground and infrastructure risk are briefly described. Of the risk categories, approaches for infrastructure risk are the least developed. Moreover, severity and likelihood for infrastructure are both dependent on numerous factors (sUAS characteristics, type of shielding object, environment). Thus, an SRA for infrastructure risk requires knowledge of specifics regarding the sUAS, shielding object, and environment.

Challenges associated with uncertainties are discussed. Uncertainties can mask the impact of mitigations, such as utilization of a DAA system, as underlying variability can exceed beneficial impacts of mitigations. To prevent this, a range of risks associated with uncertainties could be presented. While the team has not yet determined how to estimate uncertainties for the analysis performed herein, it has identified an approach—Bayesian inference—that could be leveraged to provide uncertainties and update them as additional data become available.

For all hazard categories, a list of generalized hazard causes, hazards/hazard outcomes, and mitigations is provided. Mitigations are ranked in order of expected safety benefit.

The air risk for SL1 is estimated to be 1D (yellow) and for SL2-3 and NS to be 1C (red). Required risk ratios to reduce risk to 1E (yellow) are provided for all shielding levels. This results in a significant requirement for DAA systems (MAC risk ratios of ≤ 0.015). Required ratios can be increased, and required DAA performance decreased, by:

- Identifying areas of lower traffic densities
- Determining that shielding provides more benefit (if, in fact, it does)

- Incorporating the likelihood of a fatality given a collision with a CA. If that were on the order of 0.1, for instance, and a severity of 1 was defined to include a fatality associated with the collision, then that would occur at an E rate for net MAC risk ratios that are an order of magnitude larger.
- Using the target level of safety of 1×10^6 hrs between NMACs as utilized by FAA Sponsored "Sense and Avoid" Workshop (2013, Appendix G), which increases the net MAC risk ratios by an order of magnitude.

Analysis of cooperative aircraft data was limited by the small amount of data that could be collected. This analysis will be improved based upon data collected during the 2023 growing season. While results are limited, they do indicate that agricultural applicators can fly very close to powerlines (within 31 ft). They also show that powerline databases contain errors, including not indicated the presence of a powerline when one is present and indicating an incorrect number of powerlines resulting in an incorrect powerline coverage area. Thus, the safety of shielded operations using obstacle location data would be significantly enhanced if the locations of obstacles were verified. Alternatively, an obstacle avoidance capability would also significantly enhance safety and would enable avoidance of dynamic obstacles (e.g., a tree blown down by high winds).

A risk estimate for ground collisions in a rural environment is 1D (yellow). This can be reduced using mitigations identified herein, with an order of magnitude decrease in rate produced a 1E risk (yellow). No estimate for infrastructure risk is provided, though it is noted that a collision of an sUAS with a powerline did result in a power outage of ~3 hrs (severity of 2).

6.3 Potential Regulations/Policies that Enable Shielded Operations

Given the work performed herein, potential enablers of shielded operations include:

- Outfitting aircraft that present the greatest challenge to shielded UAS operations (Spraying and Dusting, Infrastructure Inspection, Infrastructure Work, Helicopter Air Ambulance, Helicopter External Load Operations) with ADS-B out capability. While low-altitude operators may not be able to commonly communicate their information to ground stations owing to their altitudes, they would generally communicate their information to other aircraft. Thus, a sUAS with ADS-B in would be able to utilize this information to SAA such aircraft.
- Utilization of an approach like the Reserved Airspace Concept (RAC; Appendix A), which has been developed by ASSURE project A54. With this, if a CA that is not equipped with ADS-B out reserves airspace, only UA that can detect all aircraft are allowed in that airspace (UA that only detect cooperative aircraft are not allowed). If airspace is reserved by a UA that cannot detect all aircraft, only CA equipped with ADS-B out are allowed in that airspace.
- Requiring aircraft that operate near shielding objects to provide information regarding their operations via some sort of mechanism. This could have capabilities similar to Unmanned Aircraft System Traffic Management.
- Requiring that sUAS improve their conspicuity, thus enabling CA to avoid them (e.g., UAS BVLOS ARC 2022). It is noted that this could have limited effectiveness for agricultural application operators given their need for intense focus on avoiding obstacles such as powerlines—especially while applying material.

- Utilization of alternate definitions of well clear and NMAC (that would change separation criteria). While this would likely require additional research, the modification of CA trajectories owing to the presence of obstacles could enable redefinition of NMAC. Moreover, sUAS could “hide” behind infrastructure to prevent collisions with CA, which would mean that well clear status could be maintained with much smaller separations than are used with the typically-used definition of well clear. Even without “hiding”, the modification of CA trajectories could support reduction of well clear distances.
- Definition of a base set of requirements for shielded operations. While this could be challenging to identify, some examples are apparent. For instance, planned sUAS flight paths should be far enough from shielding objects such that GPS (or whatever navigation system is used) uncertainties would not result in collisions with infrastructure. This was an assumption that was commonly applied in the SRA performed herein. It is noted that GPS uncertainties can be dynamic—especially in environments where signals could be blocked. Thus, an additional requirement could be use of proper spacing for conditions that are forecasted to occur during the operation. An additional example is requirement of proper electromagnetic shielding to prevent failures owing to EMI that would be present in the operating area.

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Appendix A: Low-Altitude Manned Aircraft Operations Near Structures Survey

The following is the survey that was developed by the A45 team to acquire information regarding likelihoods that, as part of low-altitude CA operations, aircraft are flown within specified distances of shielding objects. Respondents generally would not answer every question, as some questions are presented only if certain responses are provided. For questions formatted like 6, the options for horizontal and vertical distances are Never, Rarely, Sometimes, Often, and Always. It is noted that six additional questions (31-36) were added to assist the ASSURE project A54-Propose UAS Right-of-Way Rules for Unmanned Aircraft Systems (UAS) Operations and Safety Recommendations.

Low Altitude Operator Survey

Start of Block: Default Question Block

Purpose Survey of Low-Altitude Manned Aircraft Operations Near Structures

Basis: The FAA desires information to understand how much safety benefit results from flying Unmanned Aircraft (UA; Drones) near structures. Doing so is expected to reduce risk owing to Manned Aircraft (MA) maintaining stand-off distances to enhance safety. However, some operations do occur very near to structures, and data are needed to understand characteristics of those operations.

Background: The FAA UAS Center of Excellence for UAS Research (ASSURE; Alliance for System Safety of UAS through Research Excellence) is gathering data regarding low-altitude MA operations to:

1) Determine the degree to which shielded operations can be made safe,
2) Determine Detect And Avoid (DAA) requirements for UA operating near structures
3) Determine other mitigations needed to ensure safe operations (e.g., collision avoidance systems, system redundancy, etc.)

In order to understand DAA requirements, the team seeks information regarding low-altitude MA operations near structures.

Data Collection: All data and information collected will be held confidential and responses gathered will be made anonymous and not traceable to an individual or group. These data are collected solely for the purpose of understanding low-altitude MA operations near structures, with the goal of ensuring safe integration of UA into the National Airspace System (NAS).

Page Break

Q1 What type of low altitude operations do you primarily perform?

- ○ Agricultural Application
- ○ Air Ambulance or Medical Services
- ○ Low-Altitude Infrastructure Inspection
- ○ Air Tours
- ○ News Gathering
- ○ Public Safety
- ○ External Load (e.g. fire fighting, mulching, etc.)
- ○ Training
- ○ Animal/Earth/Plant Sciences
- ○ Recreational
- ○ Ultralight
- ○ Other (please specify in the box below)

____

Page Break

Q2 What Make and Model Aircraft do you primarily fly for these low altitude operations?

○ Make ____

○ Model ____

Page Break

Q3 On average, how many flight hours do you fly each year?

____

Page Break

Q4 Do you fly within 500 ft horizontally and/or vertically of **any** low-altitude structures?

- ◯ Yes
- ◯ No

Page Break

Q5 In a year, how often do you fly within 500 ft of **wind turbines**?

- ○ Never
- ○ Rarely
- ○ Sometimes
- ○ Often
- ○ Always

Page Break

Q6 When flying near **wind turbines**, please indicate how often you fly within the specified distances.

	Horizontal	Vertical
≤25 ft	▼ Never ... Always	▼ Never ... Always
26-50 ft	▼ Never ... Always	▼ Never ... Always
51-100 ft	▼ Never ... Always	▼ Never ... Always
101-200 ft	▼ Never ... Always	▼ Never ... Always
201-500 ft	▼ Never ... Always	▼ Never ... Always

Page Break

Q7 In a year, how often do you fly within 500 ft of **powerlines** (not including poles or towers)?

- ○ Never
- ○ Rarely
- ○ Sometimes
- ○ Often
- ○ Always

Page Break

Q8 When flying near **powerlines**, please indicate how often you fly within the specified distances.

	Horizontal	Vertical
≤25 ft	▼ Never ... Always	▼ Never ... Always
26-50 ft	▼ Never ... Always	▼ Never ... Always
51-100 ft	▼ Never ... Always	▼ Never ... Always
101-200 ft	▼ Never ... Always	▼ Never ... Always
201-500 ft	▼ Never ... Always	▼ Never ... Always

Page Break

Q9 In a year, how often do you fly within 500 ft of **powerline poles or powerline towers**?

- ○ Never
- ○ Rarely
- ○ Sometimes
- ○ Often
- ○ Always

Page Break

Q10 When flying near **powerline poles or powerline towers**, please indicate how often you fly within the specified distances.

	Horizontal	Vertical
≤25 ft	▼ Never ... Always	▼ Never ... Always
26-50 ft	▼ Never ... Always	▼ Never ... Always
51-100 ft	▼ Never ... Always	▼ Never ... Always
101-200 ft	▼ Never ... Always	▼ Never ... Always
201-500 ft	▼ Never ... Always	▼ Never ... Always

Page Break

Q11 In a year, how often do you fly within 500 ft of **other towers (other than powerline towers)**?

- Never
- Rarely
- Sometimes
- Often
- Always

Page Break

Q12 When flying near **other towers (other than powerline towers)**, please indicate how often you fly within the specified distances.

	Horizontal	Vertical
≤25 ft	▼ Never ... Always	▼ Never ... Always
26-50 ft	▼ Never ... Always	▼ Never ... Always
51-100 ft	▼ Never ... Always	▼ Never ... Always
101-200 ft	▼ Never ... Always	▼ Never ... Always
201-500 ft	▼ Never ... Always	▼ Never ... Always

Page Break

Q13 In a year, how often do you fly within 500 ft of **guy wires**?

- ◯ Never
- ◯ Rarely
- ◯ Sometimes
- ◯ Often
- ◯ Always

Page Break

Q14 When flying near **guy wires,** please indicate how often you fly within the specified distances.

	Horizontal	Vertical
≤25 ft	▼ Never ... Always	▼ Never ... Always
26-50 ft	▼ Never ... Always	▼ Never ... Always
51-100 ft	▼ Never ... Always	▼ Never ... Always
101-200 ft	▼ Never ... Always	▼ Never ... Always
201-500 ft	▼ Never ... Always	▼ Never ... Always

Page Break

Q15 In a year, how often do you fly within 500 ft of **residential buildings**?

○ Never

○ Rarely

○ Sometimes

○ Often

○ Always

Page Break

Q16 When flying near **residential buildings**, please indicate how often you fly within the specified distances.

	Horizontal	Vertical
≤25 ft	▼ Never ... Always	▼ Never ... Always
26-50 ft	▼ Never ... Always	▼ Never ... Always
51-100 ft	▼ Never ... Always	▼ Never ... Always
101-200 ft	▼ Never ... Always	▼ Never ... Always
201-500 ft	▼ Never ... Always	▼ Never ... Always

Page Break

Q17 In a year, how often do you fly within 500 ft of **commercial buildings**?

○ Never

○ Rarely

○ Sometimes

○ Often

○ Always

Page Break

Q18 When flying near **commercial buildings**, please indicate how often you fly within the specified distances.

	Horizontal	Vertical
≤25 ft	▼ Never ... Always	▼ Never ... Always
26-50 ft	▼ Never ... Always	▼ Never ... Always
51-100 ft	▼ Never ... Always	▼ Never ... Always
101-200 ft	▼ Never ... Always	▼ Never ... Always
201-500 ft	▼ Never ... Always	▼ Never ... Always

Page Break

Q19 In a year, how often do you fly within 500 ft of **trees/shelter belts?**

- ◯ Never
- ◯ Rarely
- ◯ Sometimes
- ◯ Often
- ◯ Always

Page Break

Q20 When flying near **trees/shelter belts**, please indicate how often you fly within the specified distances.

	Horizontal	Vertical
≤25 ft	▼ Never ... Always	▼ Never ... Always
26-50 ft	▼ Never ... Always	▼ Never ... Always
51-100 ft	▼ Never ... Always	▼ Never ... Always
101-200 ft	▼ Never ... Always	▼ Never ... Always
201-500 ft	▼ Never ... Always	▼ Never ... Always

Page Break

Q21 In a year, how often do you fly within 500 ft of **bridges?**

- ○ Never
- ○ Rarely
- ○ Sometimes
- ○ Often
- ○ Always

Page Break

Q22 When flying near **bridges**, please indicate how often you fly within the specified distances.

	Horizontal	Vertical
≤25 ft	▼ Never ... Always	▼ Never ... Always
26-50 ft	▼ Never ... Always	▼ Never ... Always
51-100 ft	▼ Never ... Always	▼ Never ... Always
101-200 ft	▼ Never ... Always	▼ Never ... Always
201-500 ft	▼ Never ... Always	▼ Never ... Always

Page Break

Q23 Is there any other structure **not listed previously** that you fly within 500 ft of? (Please specify type of structure below)

Leave blank if No

____

Page Break

Q24 When flying near these other structures **not listed previously**, please indicate how often you fly within the specified distances.

- ◯ Never
- ◯ Rarely
- ◯ Sometimes
- ◯ Often
- ◯ Always

Page Break

Q25 When flying near these **other structures**, please indicate how often you fly within the specified distances.

	Horizontal	Vertical
≤25 ft	▼ Never ... Always	▼ Never ... Always
26-50 ft	▼ Never ... Always	▼ Never ... Always
51-100 ft	▼ Never ... Always	▼ Never ... Always
101-200 ft	▼ Never ... Always	▼ Never ... Always
201-500 ft	▼ Never ... Always	▼ Never ... Always

Page Break

Q26 For your operation, do you have desired stand-off distances from structures? These are minimum separation distances from structures while performing your operation (such as inspection). If so, please provide desired stand-off distances (in ft):

	Distance in ft
Desired Horizontal Standoff Distance (ft)	
Desired Vertical Standoff Distance (ft)	

Page Break

Q27 What percentage of time have you observed drones flying **near your operations** in the past year?

- ○ Never
- ○ Rarely
- ○ Sometimes
- ○ Often
- ○ Always

Page Break

Q28 How many times has an unplanned drone encounter **altered your flight profile** in the past year?

- ◯ 0
- ◯ 1-5
- ◯ 6-10
- ◯ 11 or more

Page Break

Q29 How many times have you flown through **known drone operational areas** (e.g. NOTAMs) in the past year?

- ◯ 0
- ◯ 1-5
- ◯ 6-10
- ◯ 11 or more

Page Break

Q30 When flying through these known drone operational areas, how many times have you **observed** a drone in the past year?

○ 0

○ 1-5

○ 6-10

○ 11 or more

Page Break

Q31
ASSURE is working on something called Reserved Airspace Concept (RAC), which enables safety for Manned Aircraft and drones that operate at low-altitude.

For the purpose of providing equitable access and separating aircraft that cannot reasonably detect each other, a new concept called RAC is being considered. RAC is a volume of airspace with defined boundaries and times, reservable by either manned aircraft or drones. RAC would work as follows:

If RAC is reserved by a manned aircraft that is not equipped with ADS-B out, only drones that can detect all aircraft are allowed in that airspace (drones that only detect cooperative aircraft are not allowed).
If RAC is reserved by a drone that cannot detect all aircraft, only manned aircraft equipped with ADS-B out are allowed in that airspace.

We have a few additional questions for which your input would be greatly appreciated. Would you willing to help us with your feedback?

- ○ Yes
- ○ No

Page Break

Q32 Would you support a Reserved Airspace Concept as previously described?

- ○ Yes
- ○ No
- ○ Uncertain, but would be open to the concept

Page Break

Q33 Would you be willing to check for electronic airspace reservations prior to each flight?

○ Yes

○ No

Page Break

Q34 How much notice would you like to be given when airspace is reserved? (Reserved Airspace Concept)?

○ Seconds

○ Minutes

○ Hours

○ Days

Page Break

Q35 If the Reserved Airspace Concept was made available, how often would you want to reserve airspace for your operations?

- ◯ 0 times per month
- ◯ 1-2 times per month
- ◯ 3 – 6 times per month
- ◯ >6 times per month

Page Break

Q36 Does your aircraft have ADS-B out capability?

- ◯ Yes
- ◯ No

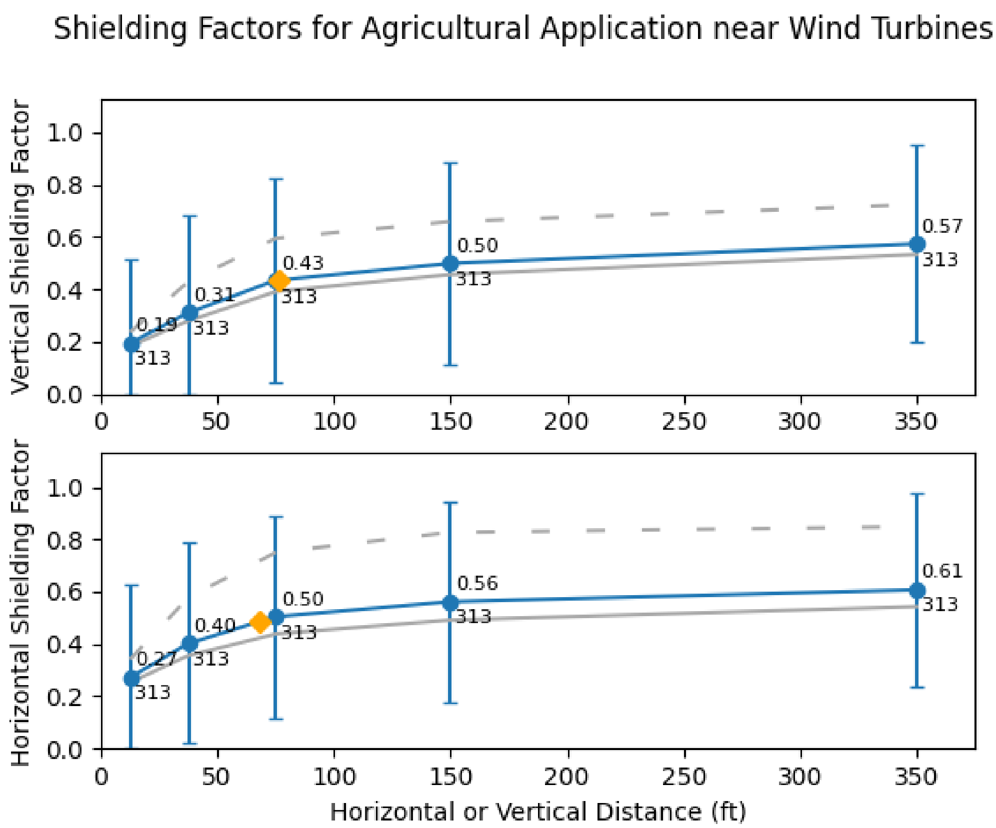
End of Block: Default Question Block

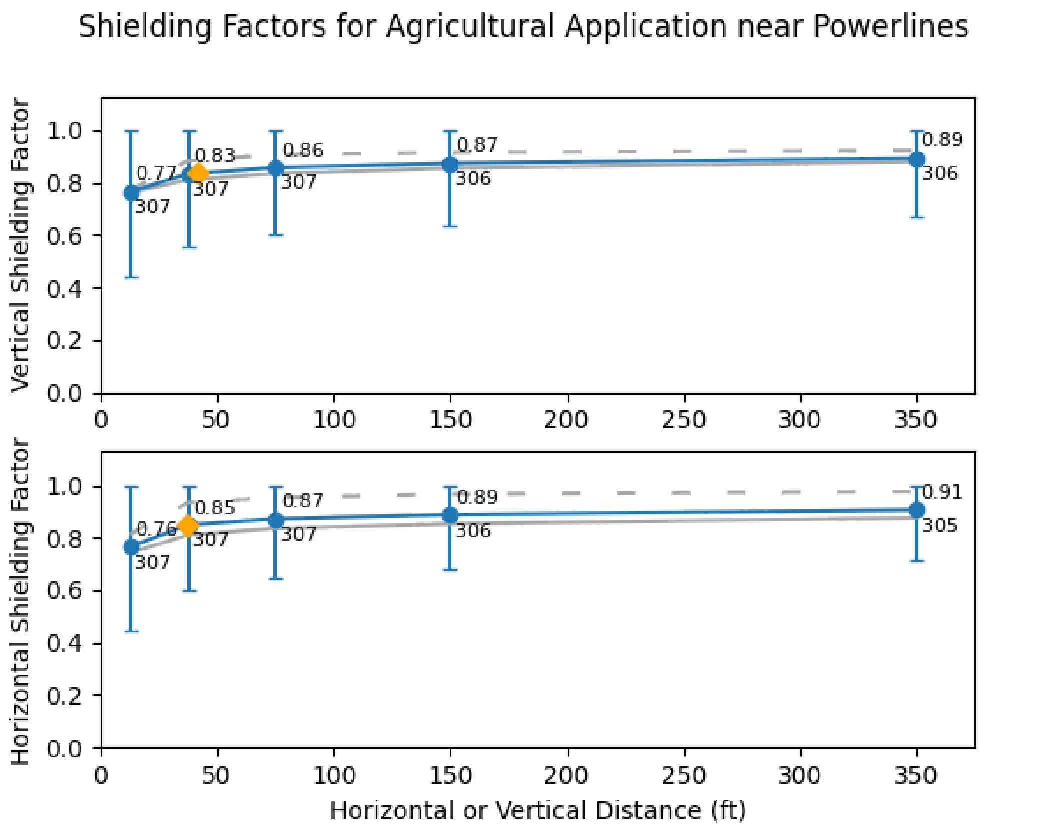
Appendix B: Survey-Derived Shielding Factor Plots for Operations with a Minimum of Five Respondents

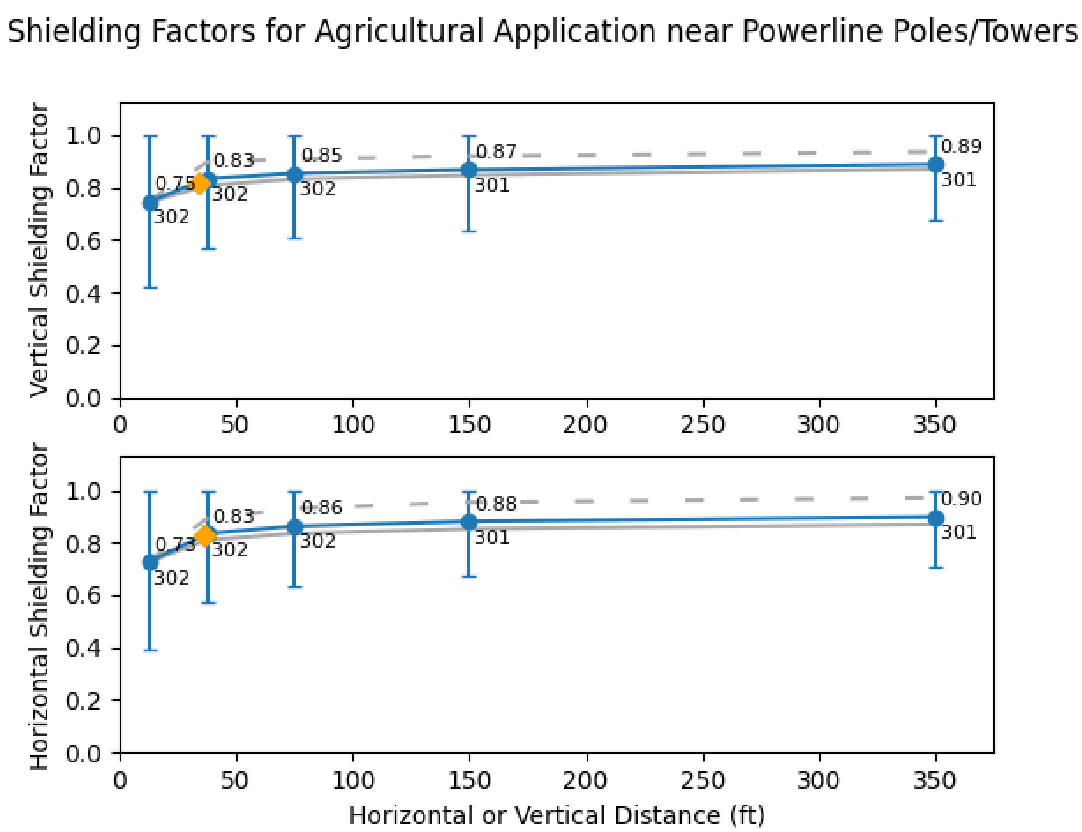
The following illustrate SFs for operations that had at least a minimum of 5 responses. Because of the number of figures, figure captions and labels such as a), b), etc., are not provided. Description of figures is provided for each type of operation and the type of operation and obstacle is labeled in each figure title.

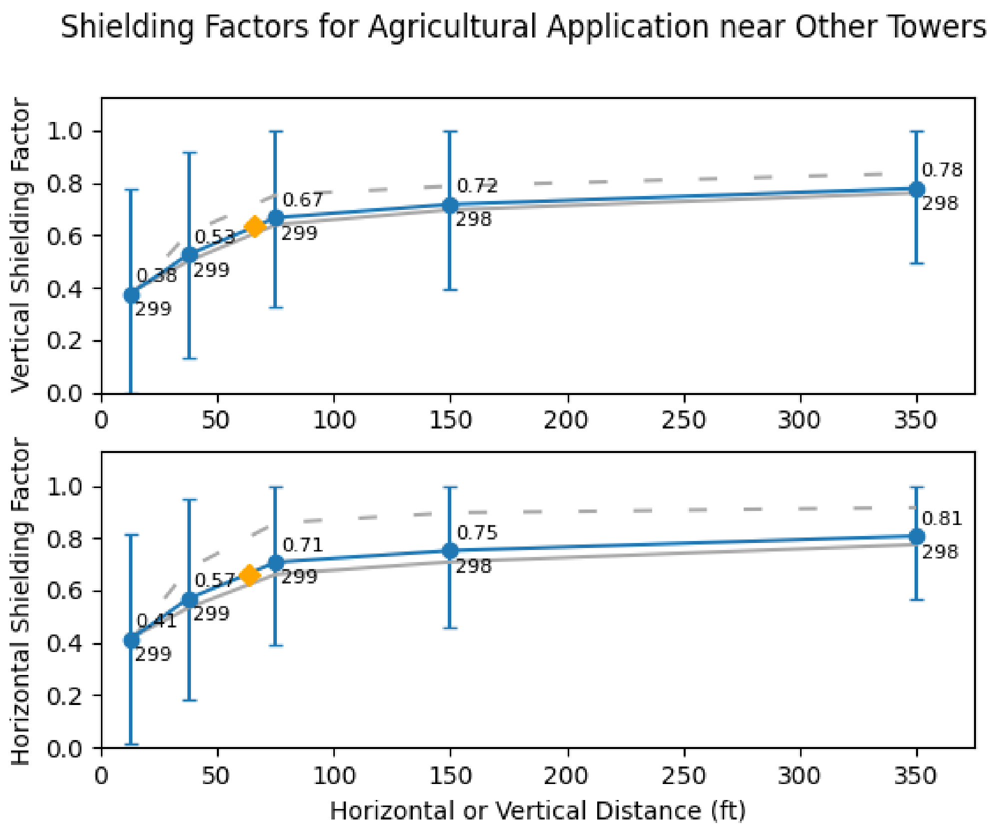
B.1 *Agricultural Application*

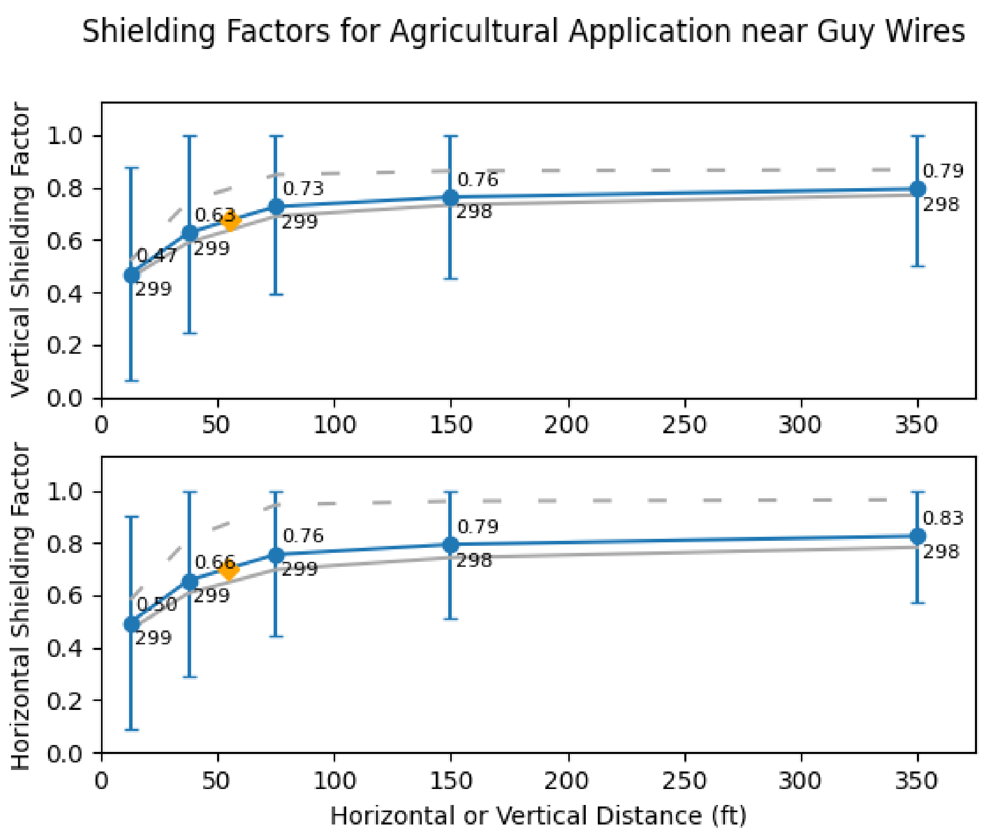
The following plots provide SFs for Agricultural Application operating near the obstacles identified in the titles. Each plot provides SFs as a function of distance for vertical distances (top) and horizontal distances (bottom) as derived from survey data. The solid blue lines indicate the average estimated SF for all types of responses (C, PN, and PU), the solid grey lines indicate the average estimated SF for C responses, and the dashed grey lines indicate the average estimated SF for PN and PU responses (combined). The blue whiskers illustrate the error bars associated with a single standard deviation of the SF values for all types of responses. Error bars are cropped to the physical limits of 0.0 and 1.0. The number of responses and values for SFs derived from all types of response are provided below and above plotted points. For curves for which curve fits using the model described in Section 4.3.2.4.3.2 could be produced, orange diamonds indicate estimated distances at which behavior changes (an obstacle significantly impacted an operation).

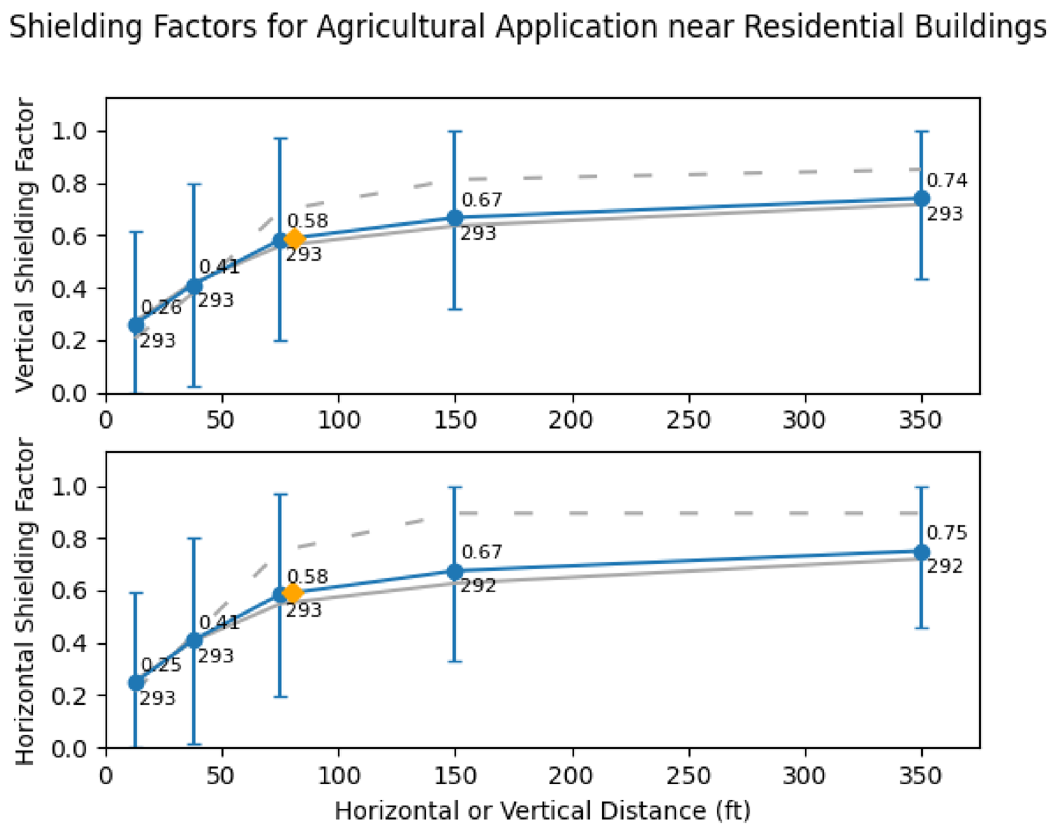


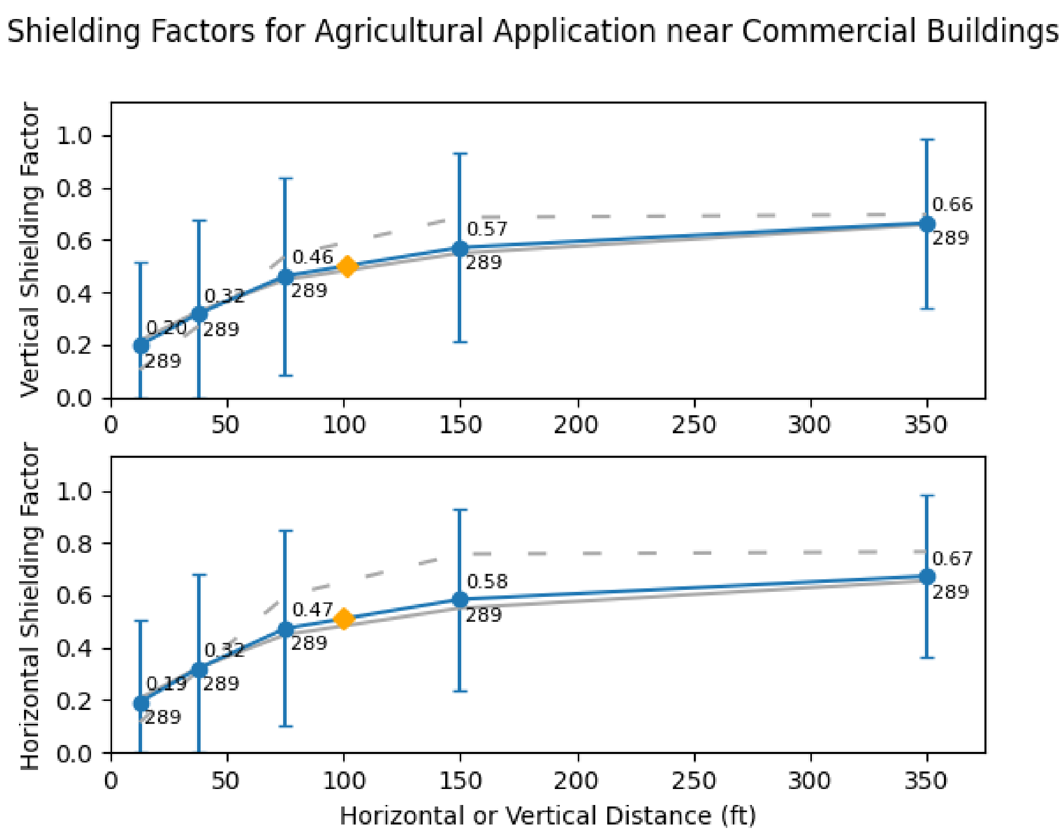

Shielding Factors for Agricultural Application near Powerlines
Vertical Shielding Factor
Horizontal Shielding Factor
Horizontal or Vertical Distance (ft)
0.77
307
0.83
307
0.86
307
0.87
306
0.89
306
0.76
307
0.85
307
0.87
307
0.89
306
0.91
305

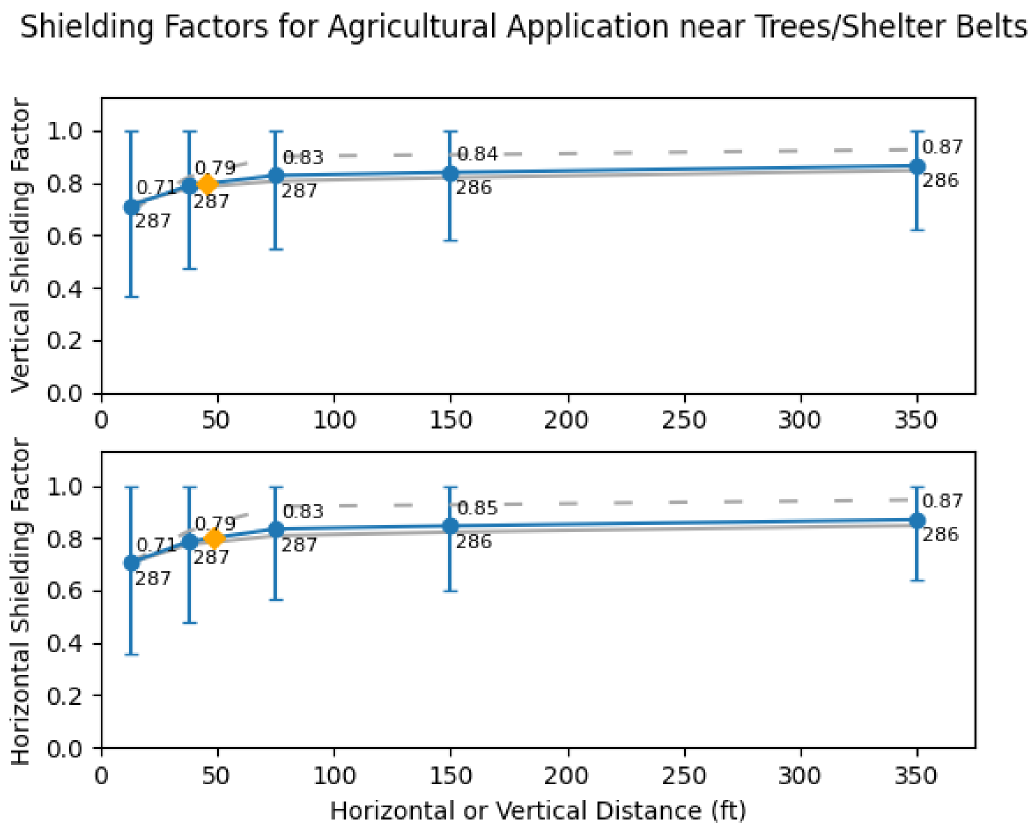

Shielding Factors for Agricultural Application near Powerline Poles/Towers
Vertical Shielding Factor
Horizontal Shielding Factor
Horizontal or Vertical Distance (ft)
0.75
302
0.83
302
0.85
302
0.87
301
0.89
301
0.73
302
0.83
302
0.86
302
0.88
301
0.90
301

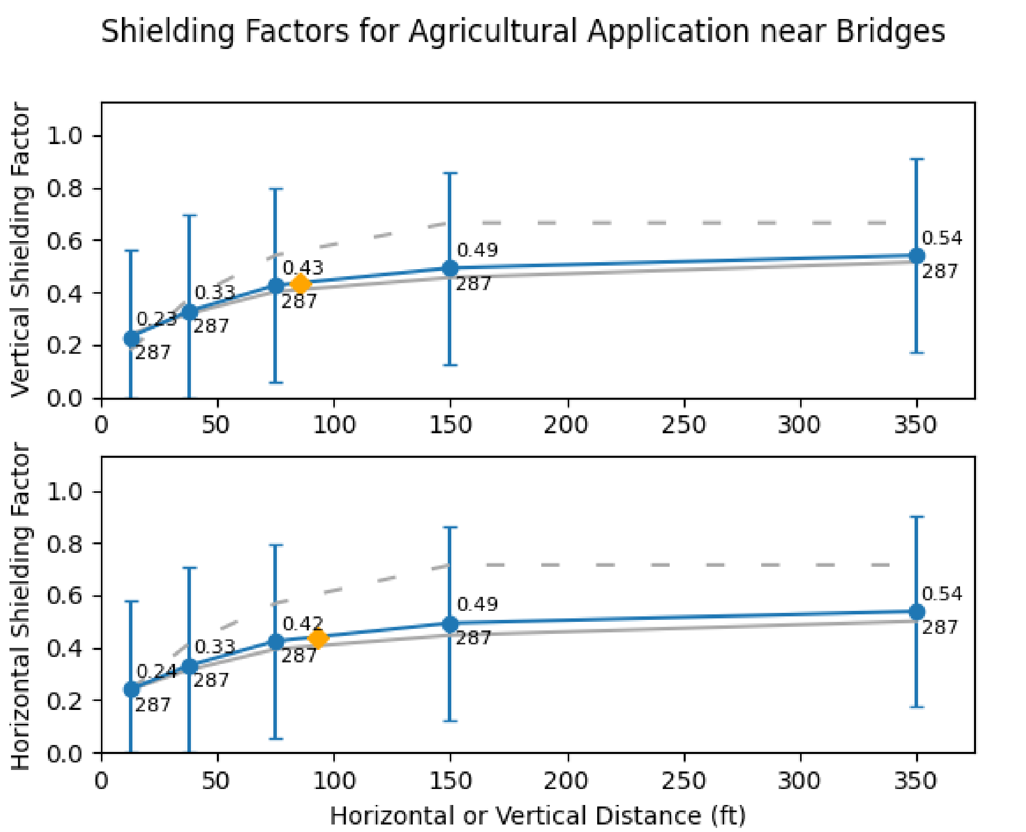

Shielding Factors for Agricultural Application near Other Towers
Vertical Shielding Factor
Horizontal Shielding Factor
Horizontal or Vertical Distance (ft)
0.38
0.53
0.67
0.72
0.78
0.41
0.57
0.71
0.75
0.81
299
298

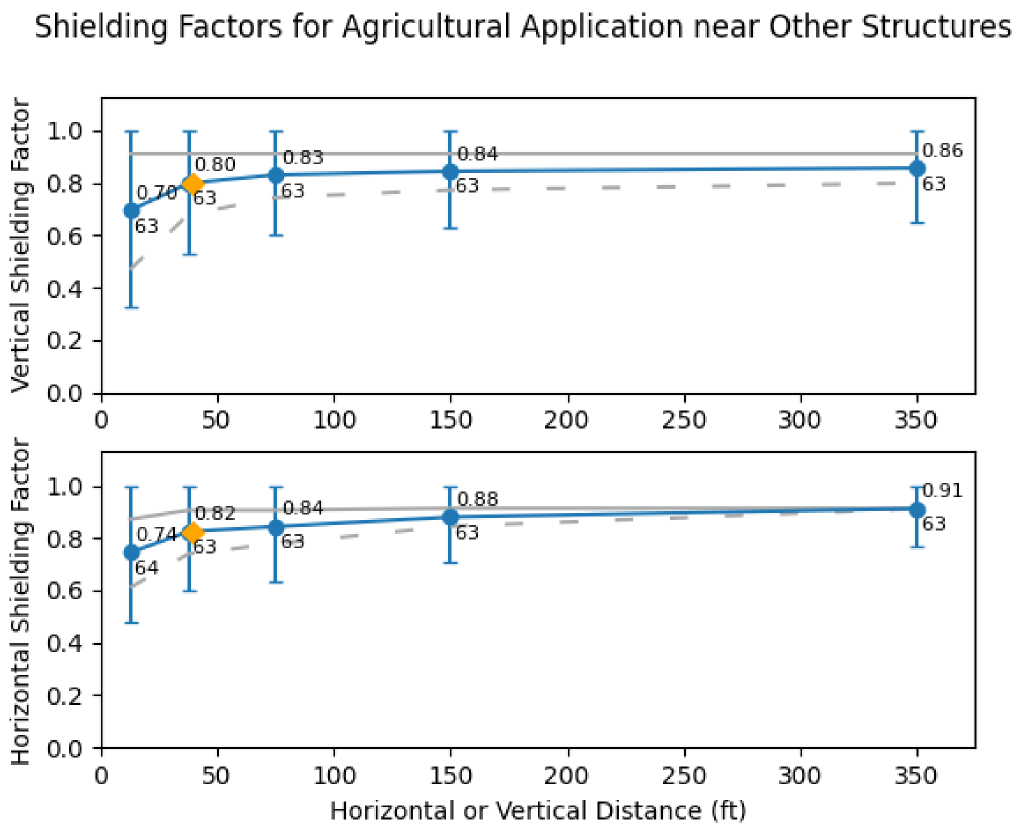

Shielding Factors for Agricultural Application near Guy Wires
Vertical Shielding Factor
Horizontal Shielding Factor
Horizontal or Vertical Distance (ft)
0.47
0.63
0.73
0.76
0.79
0.50
0.66
0.76
0.79
0.83
299
298


Shielding Factors for Agricultural Application near Residential Buildings
Vertical Shielding Factor
Horizontal Shielding Factor
Horizontal or Vertical Distance (ft)
0.0
0.2
0.4
0.6
0.8
1.0
0
50
100
150
200
250
300
350
0.26
0.41
0.58
0.67
0.74
0.25
0.41
0.58
0.67
0.75
293
292


Shielding Factors for Agricultural Application near Commercial Buildings
Vertical Shielding Factor
Horizontal Shielding Factor
Horizontal or Vertical Distance (ft)
0.0
0.2
0.4
0.6
0.8
1.0
0
50
100
150
200
250
300
350
0.20
0.32
0.46
0.57
0.66
0.19
0.32
0.47
0.58
0.67
289

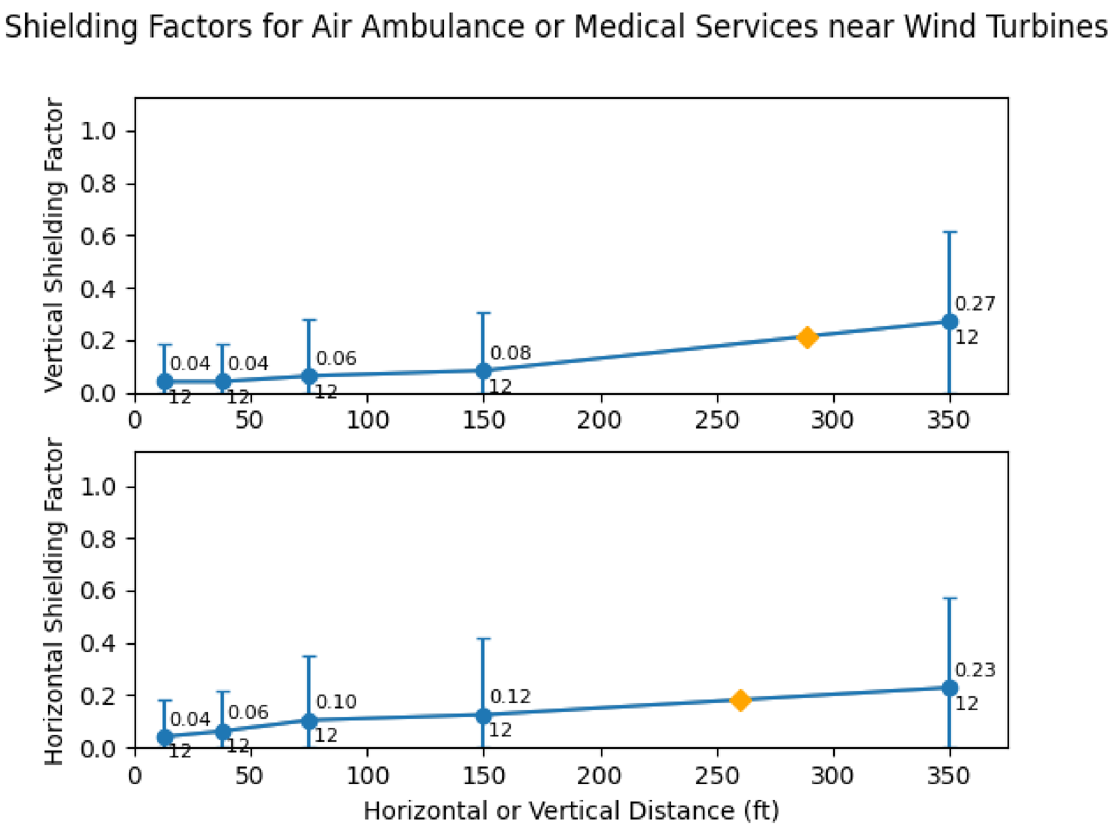

Shielding Factors for Agricultural Application near Trees/Shelter Belts
Vertical Shielding Factor
Horizontal Shielding Factor
0.71
0.79
0.83
0.84
0.85
0.87
287
286
Horizontal or Vertical Distance (ft)

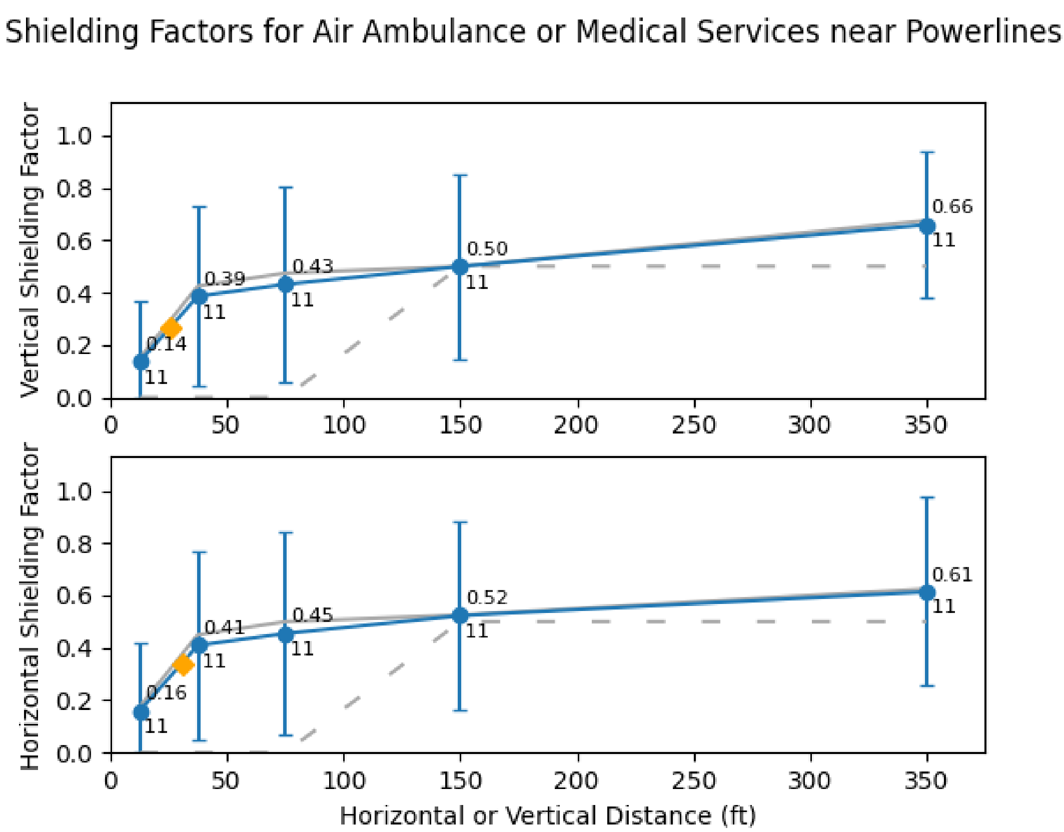

Shielding Factors for Agricultural Application near Bridges
Vertical Shielding Factor
Horizontal Shielding Factor
0.23
0.24
0.33
0.43
0.42
0.49
0.54
287
Horizontal or Vertical Distance (ft)

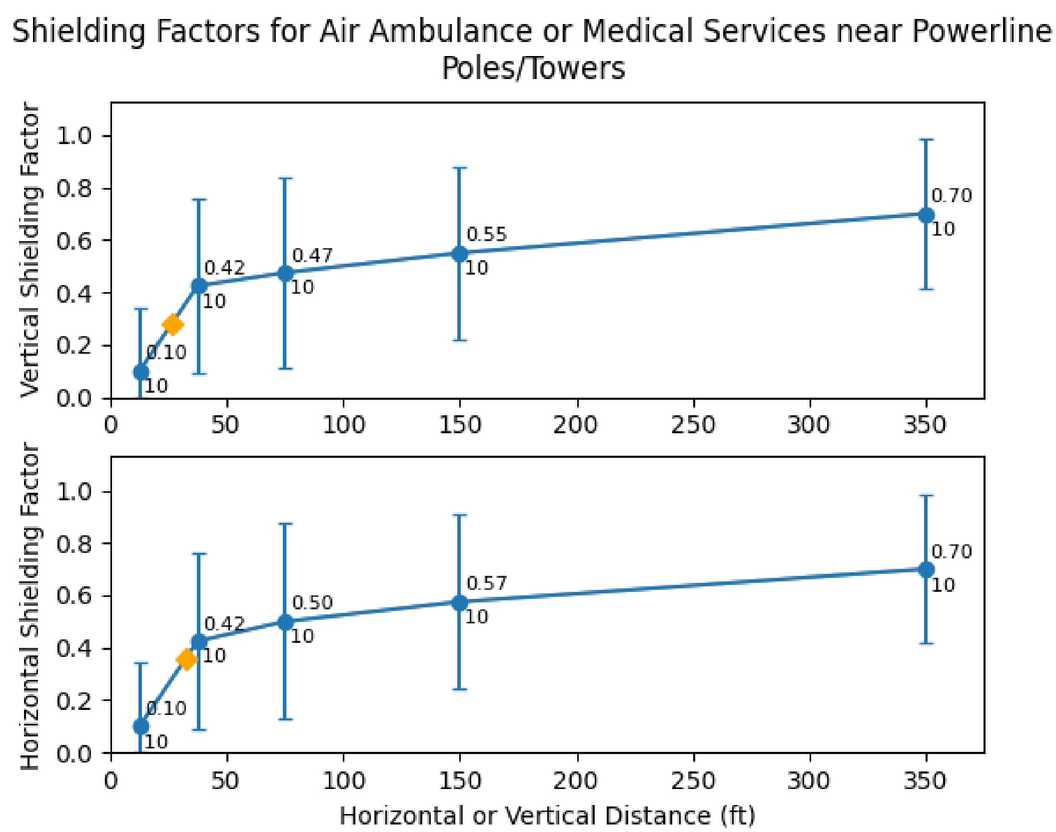

Shielding Factors for Agricultural Application near Other Structures
Vertical Shielding Factor
Horizontal Shielding Factor
Horizontal or Vertical Distance (ft)
0.70
0.80
0.83
0.84
0.86
63
0.74
0.82
0.84
0.88
0.91
64

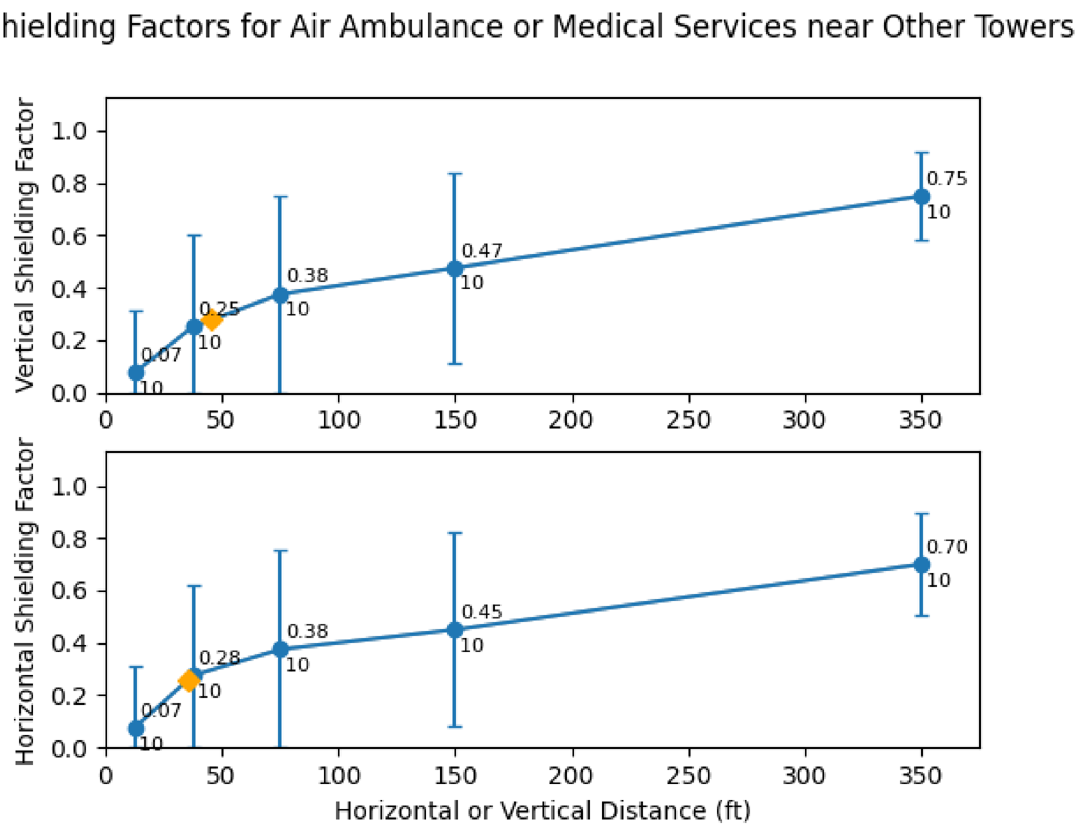
B.2 ***Air Ambulance or Medical Services***

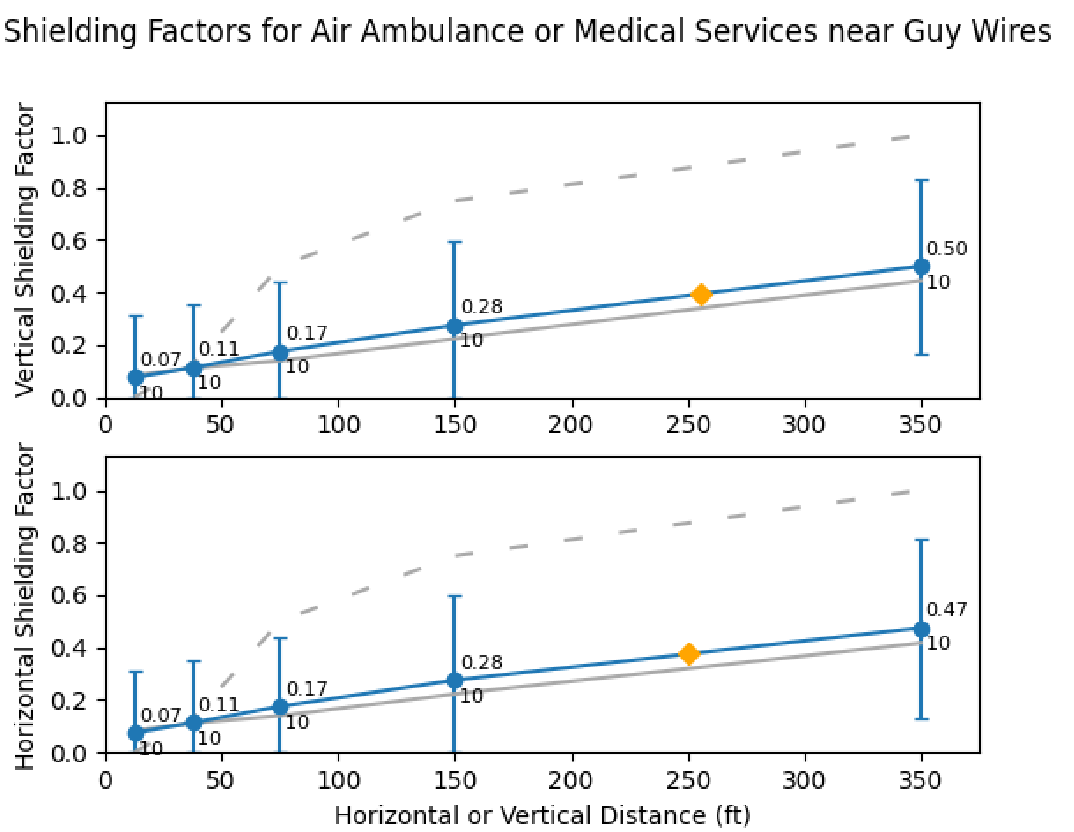
As with Agricultural Application (B.1), but for Air Ambulance or Medical Services.

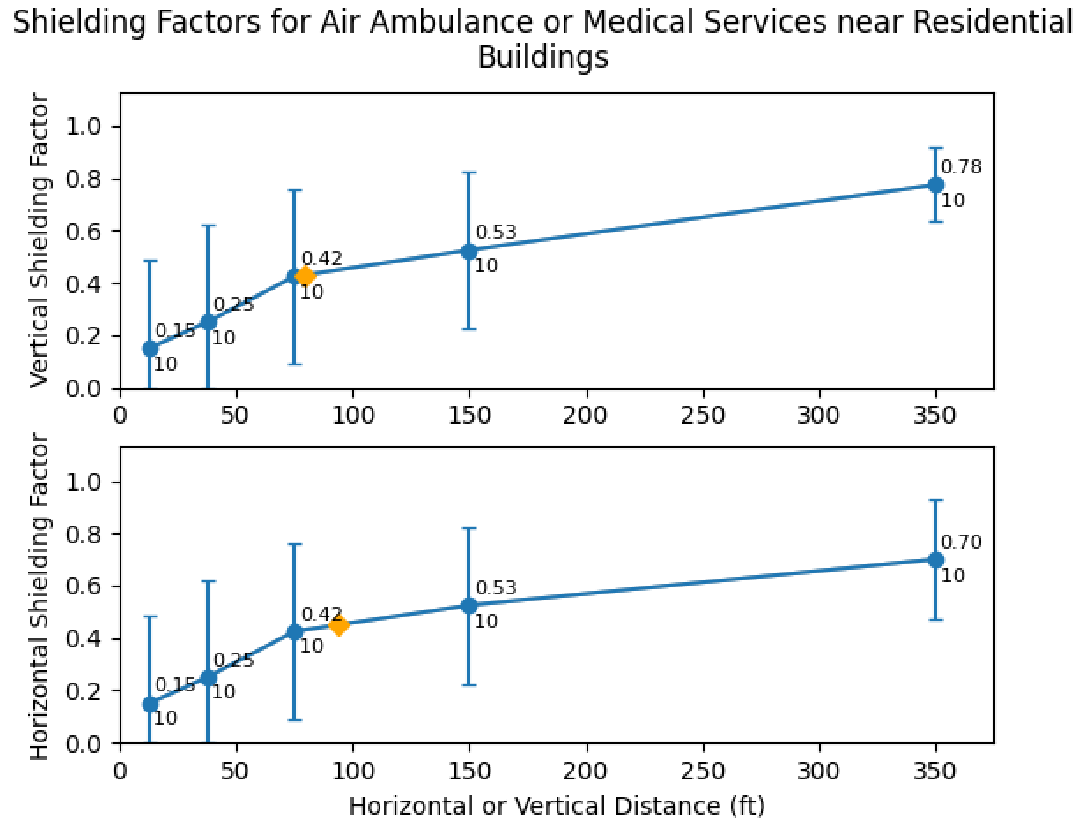


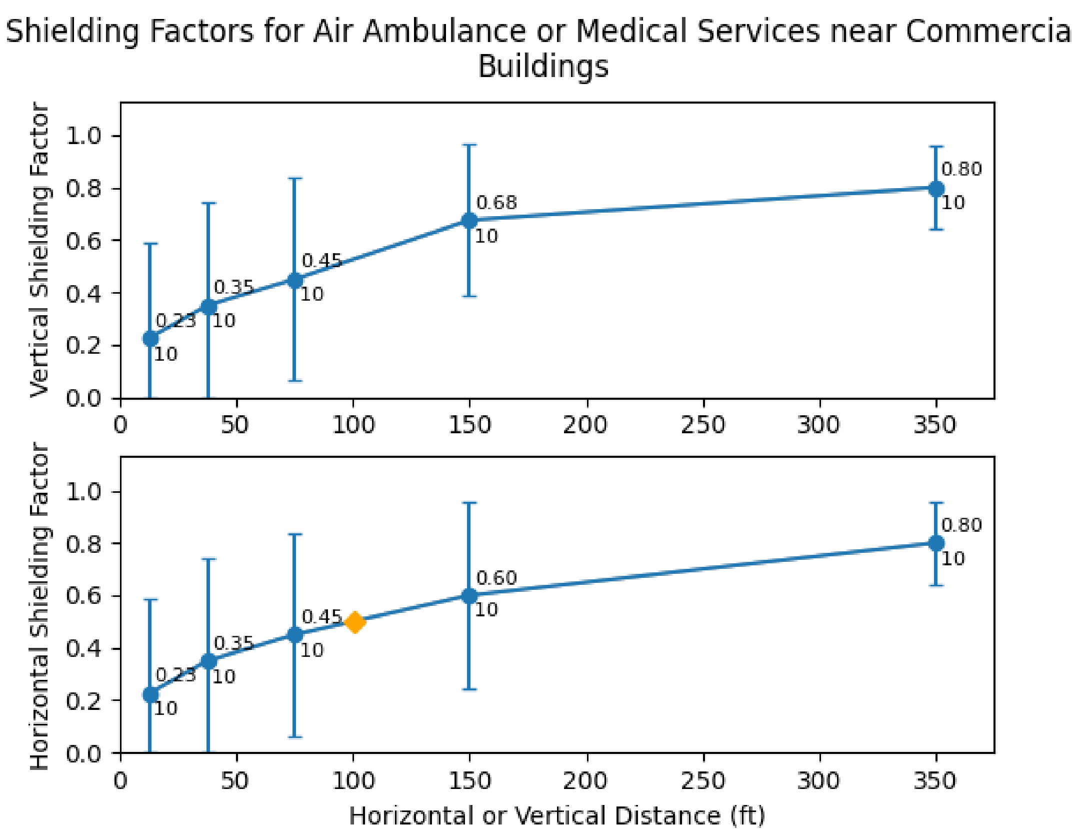

Shielding Factors for Air Ambulance or Medical Services near Powerlines
Vertical Shielding Factor
Horizontal Shielding Factor
Horizontal or Vertical Distance (ft)
0.14
0.39
0.43
0.50
0.66
0.16
0.41
0.45
0.52
0.61
11

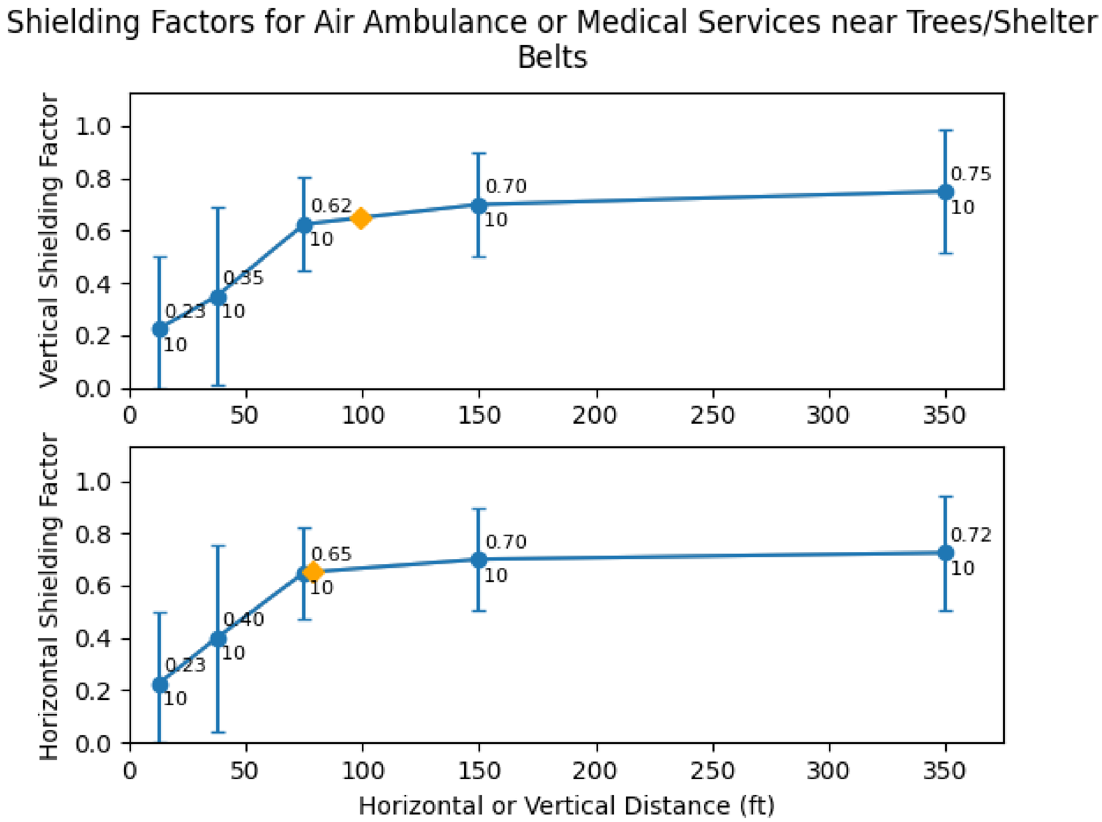

Shielding Factors for Air Ambulance or Medical Services near Powerline Poles/Towers
Vertical Shielding Factor
Horizontal Shielding Factor
Horizontal or Vertical Distance (ft)
0.10
0.42
0.47
0.55
0.70
0.50
0.57
10

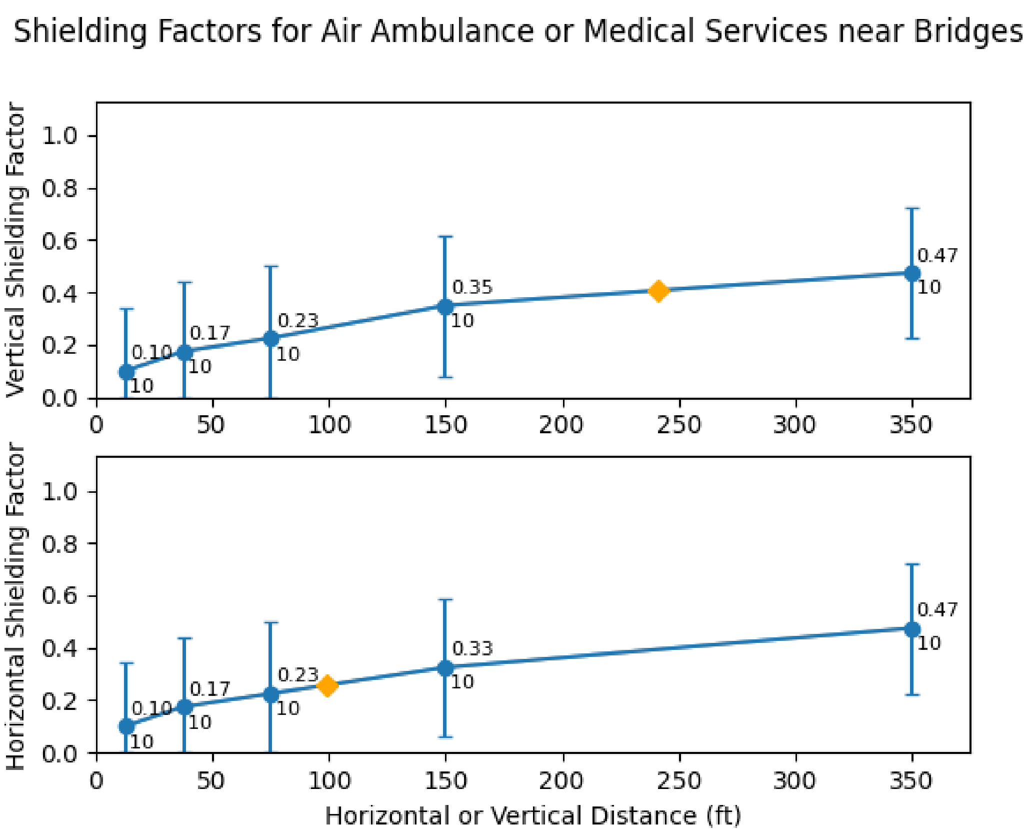

Shielding Factors for Air Ambulance or Medical Services near Other Towers
Vertical Shielding Factor
Horizontal Shielding Factor
Horizontal or Vertical Distance (ft)
0.07
0.25
0.38
0.47
0.75
0.07
0.28
0.38
0.45
0.70
10


Shielding Factors for Air Ambulance or Medical Services near Guy Wires
Vertical Shielding Factor
Horizontal Shielding Factor
Horizontal or Vertical Distance (ft)
0.07
0.11
0.17
0.28
0.50
0.07
0.11
0.17
0.28
0.47
10


Shielding Factors for Air Ambulance or Medical Services near Residential Buildings
Vertical Shielding Factor
Horizontal Shielding Factor
Horizontal or Vertical Distance (ft)
0.15
0.25
0.42
0.53
0.78
0.70
10

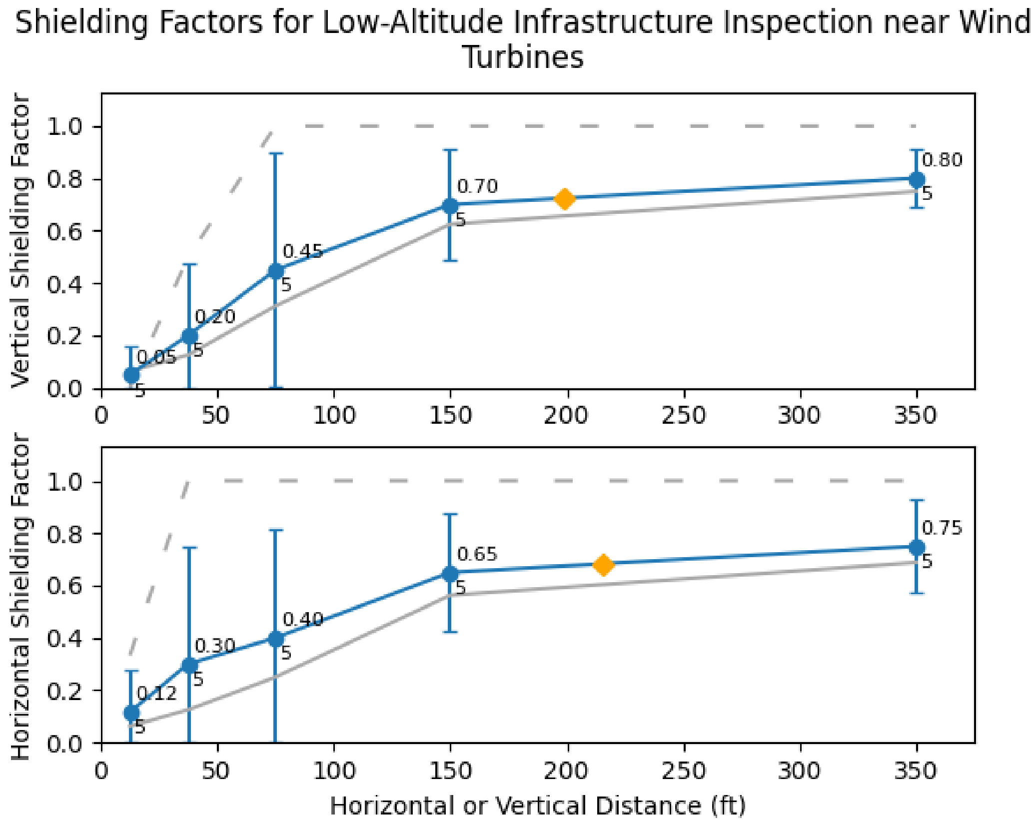

Shielding Factors for Air Ambulance or Medical Services near Commercial Buildings
Vertical Shielding Factor
Horizontal Shielding Factor
Horizontal or Vertical Distance (ft)
0.23
0.35
0.45
0.68
0.60
0.80
10

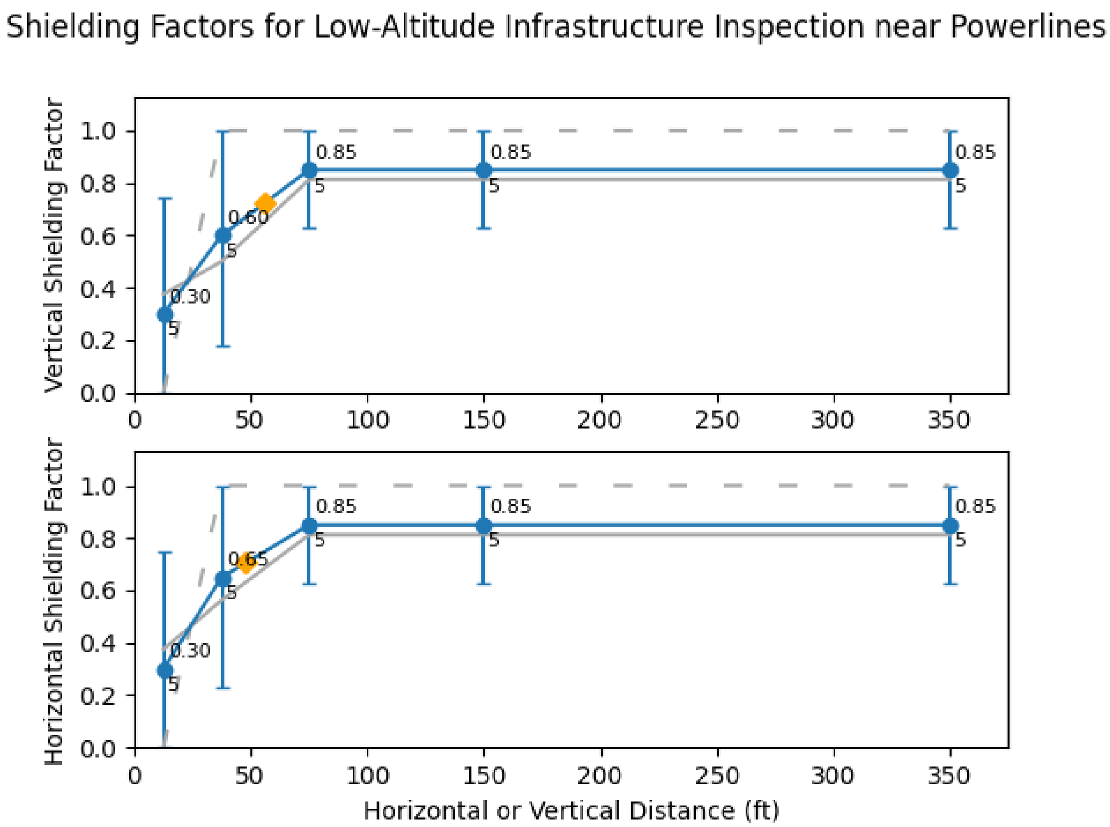

Shielding Factors for Air Ambulance or Medical Services near Trees/Shelter Belts
Vertical Shielding Factor
0.23
0.35
0.62
0.70
0.75
10
Horizontal Shielding Factor
0.23
0.40
0.65
0.70
0.72
10
Horizontal or Vertical Distance (ft)

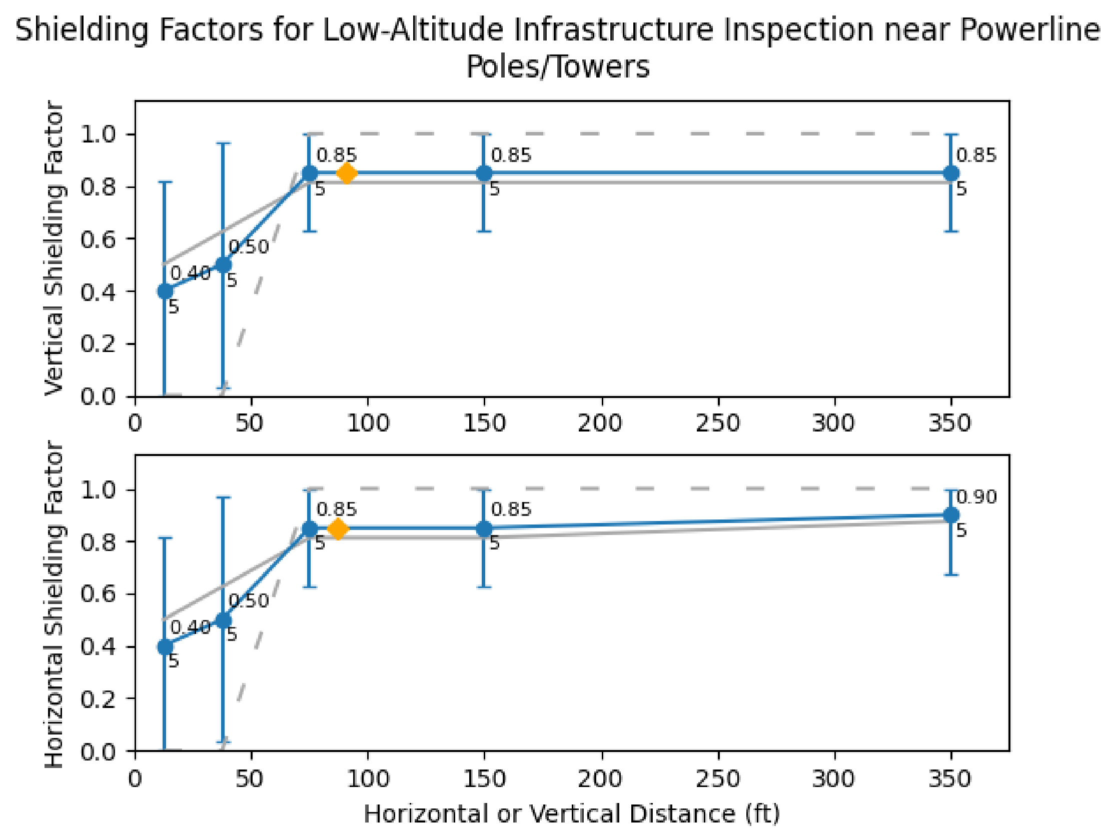

Shielding Factors for Air Ambulance or Medical Services near Bridges
Vertical Shielding Factor
0.10
0.17
0.23
0.35
0.47
10
Horizontal Shielding Factor
0.10
0.17
0.23
0.33
0.47
10
Horizontal or Vertical Distance (ft)

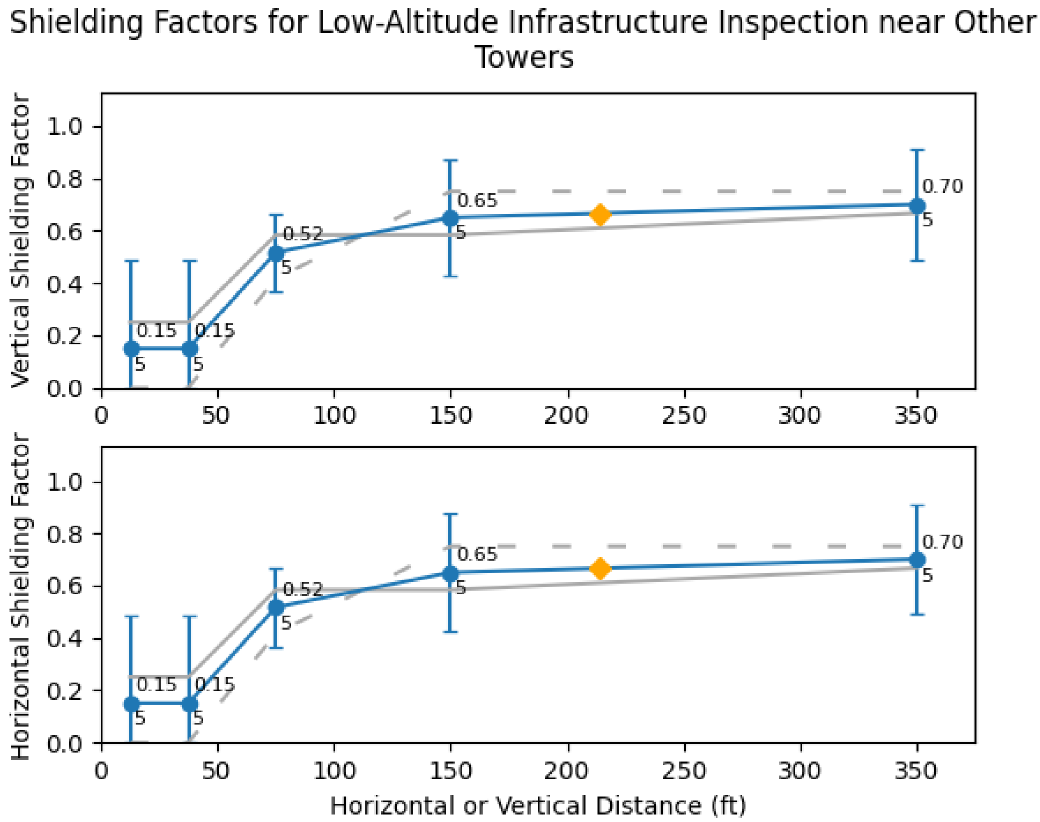
B.3 ***Low-Altitude Infrastructure Inspection***

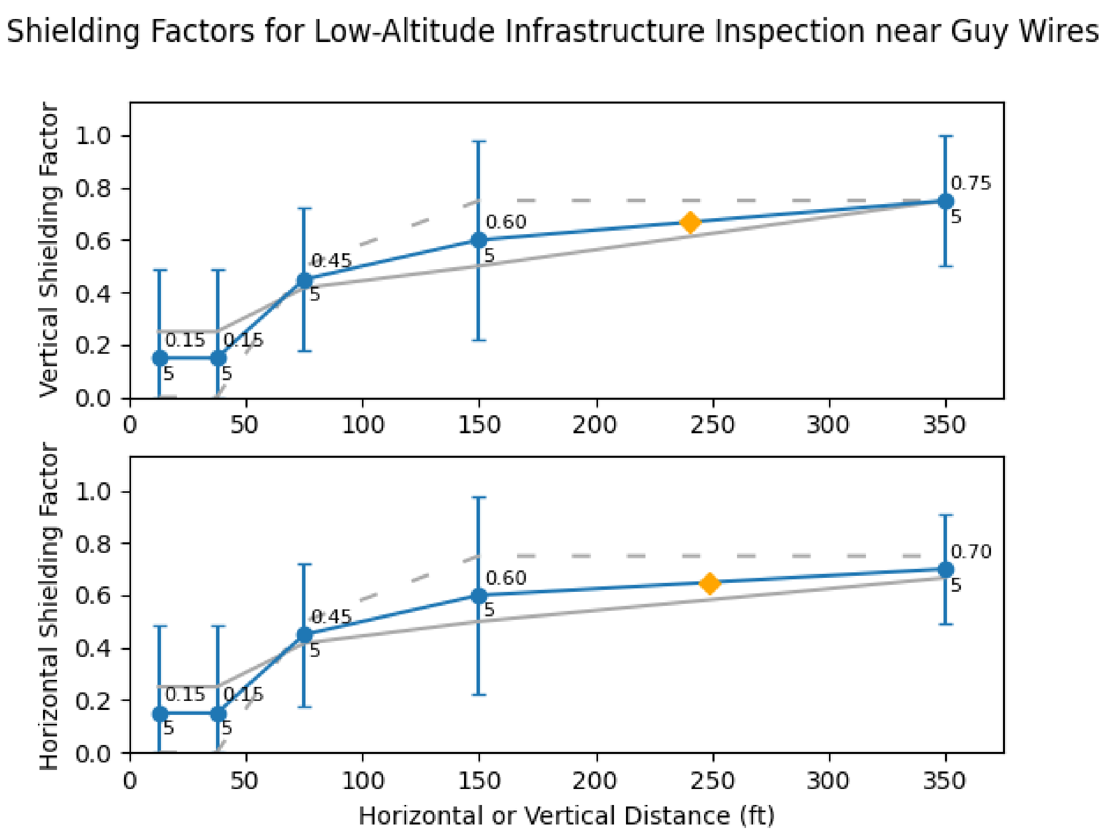
As with Agricultural Application (B.1), but for Low-Altitude Infrastructure Inspection.

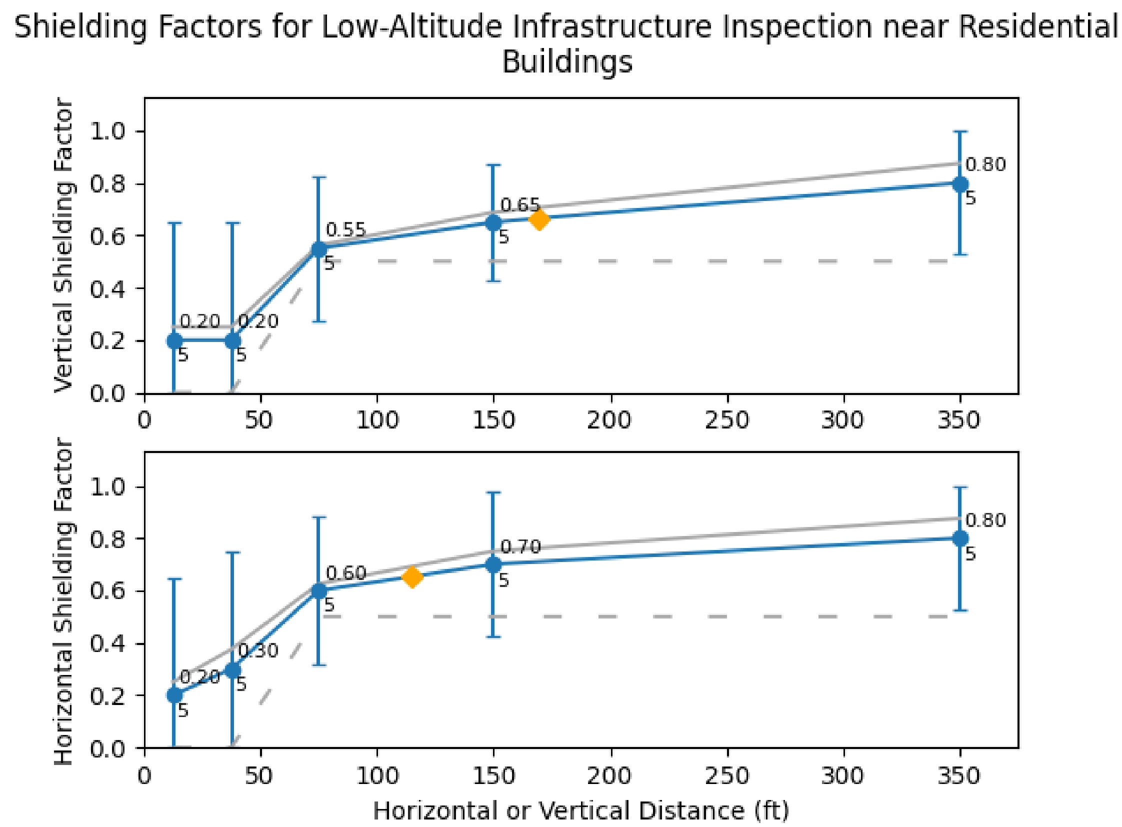


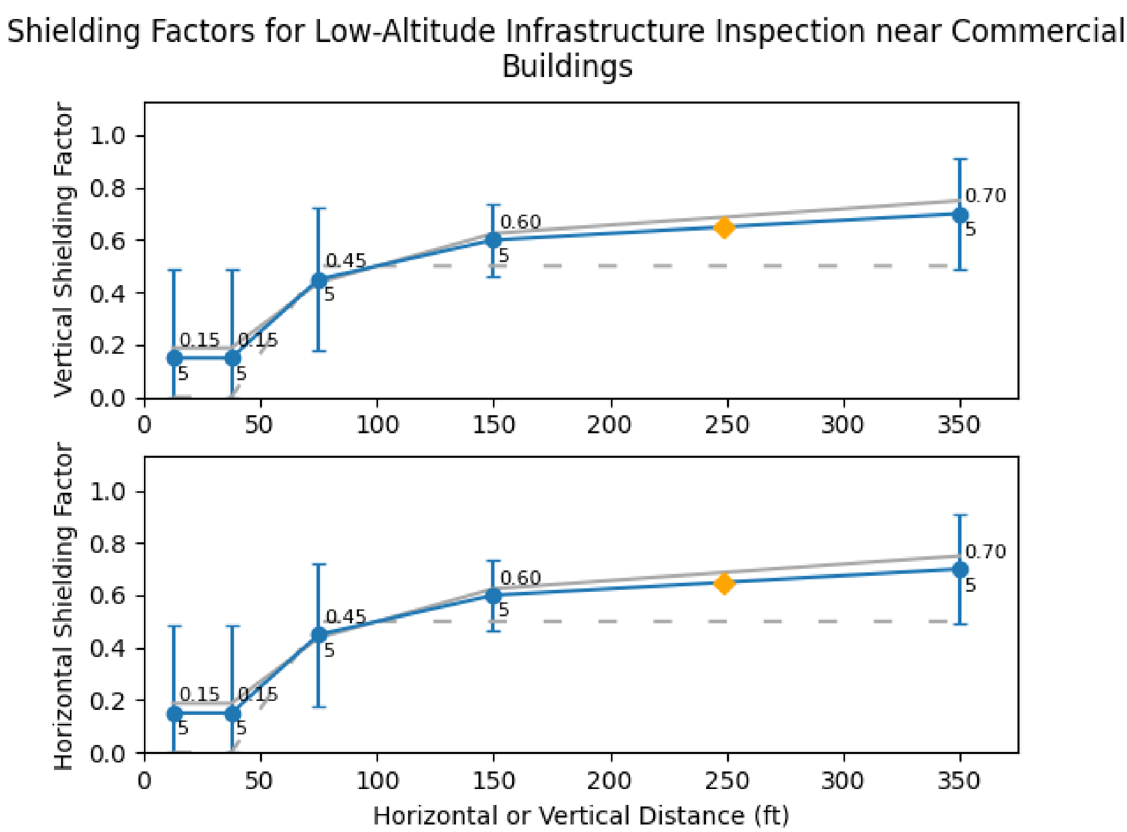

Shielding Factors for Low-Altitude Infrastructure Inspection near Powerlines
Vertical Shielding Factor
Horizontal Shielding Factor
0.30
0.60
0.65
0.85
5
Horizontal or Vertical Distance (ft)

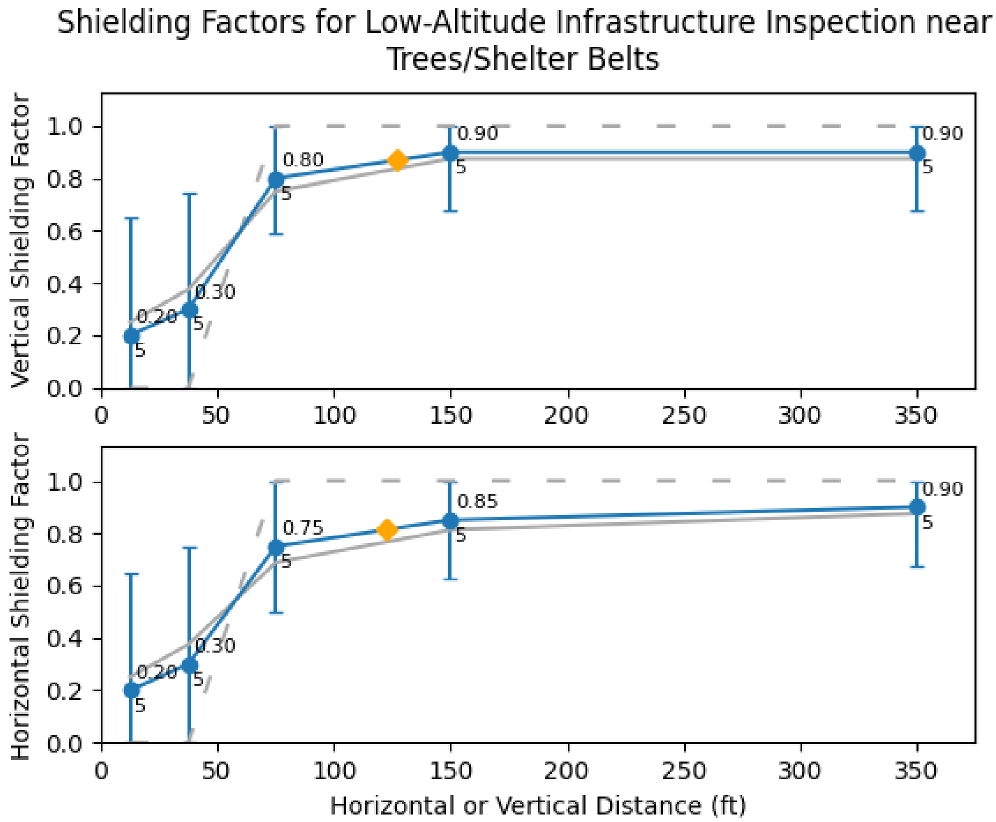

Shielding Factors for Low-Altitude Infrastructure Inspection near Powerline Poles/Towers
Vertical Shielding Factor
Horizontal Shielding Factor
0.40
0.50
0.85
0.90
5
Horizontal or Vertical Distance (ft)

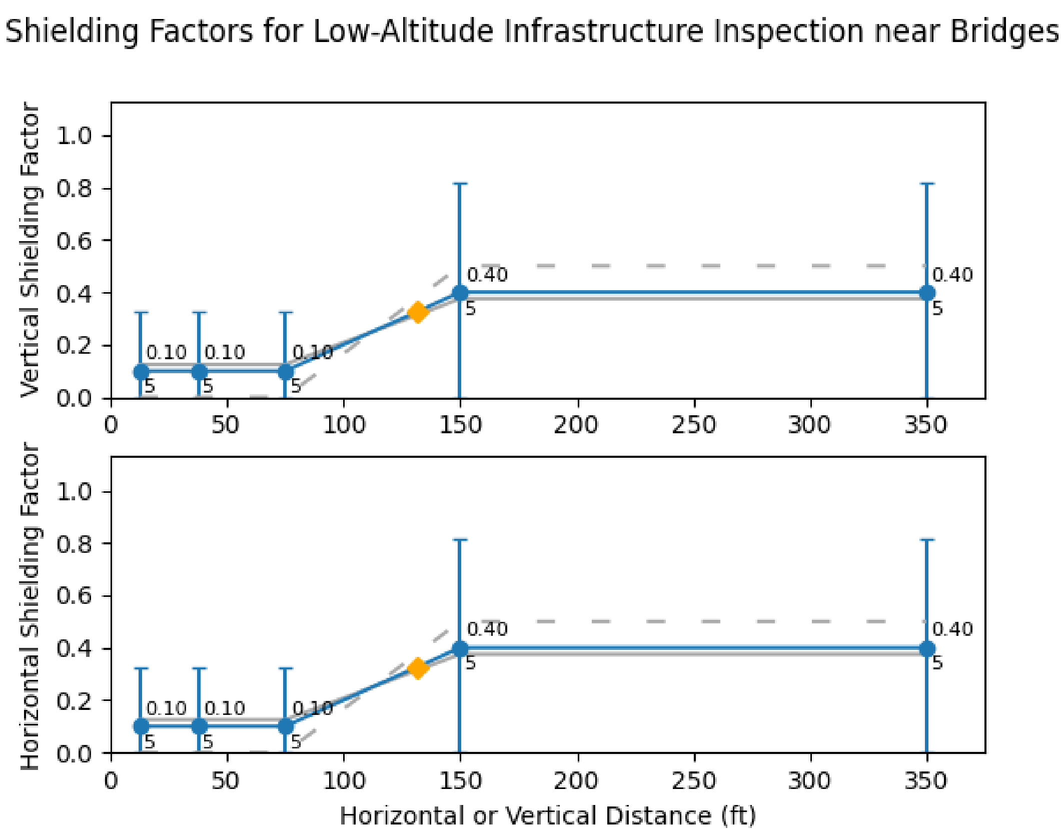

Shielding Factors for Low-Altitude Infrastructure Inspection near Other Towers
Vertical Shielding Factor
Horizontal Shielding Factor
Horizontal or Vertical Distance (ft)
0.15
0.15
0.52
0.65
0.70
5


Shielding Factors for Low-Altitude Infrastructure Inspection near Guy Wires
Vertical Shielding Factor
Horizontal Shielding Factor
Horizontal or Vertical Distance (ft)
0.15
0.15
0.45
0.60
0.75
0.70
5


Shielding Factors for Low-Altitude Infrastructure Inspection near Residential Buildings
Vertical Shielding Factor
Horizontal Shielding Factor
Horizontal or Vertical Distance (ft)
0.20
0.20
0.55
0.65
0.80
0.30
0.60
0.70

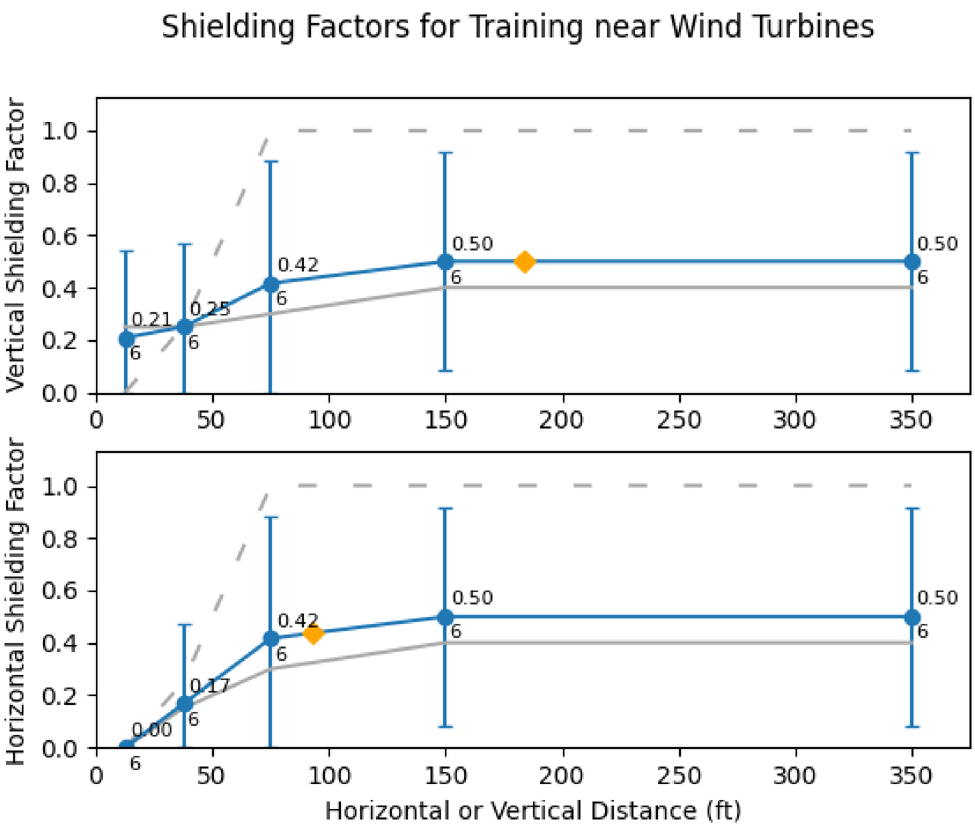

Shielding Factors for Low-Altitude Infrastructure Inspection near Commercial Buildings
Vertical Shielding Factor
Horizontal Shielding Factor
Horizontal or Vertical Distance (ft)
0.15
0.15
0.45
0.60
0.70

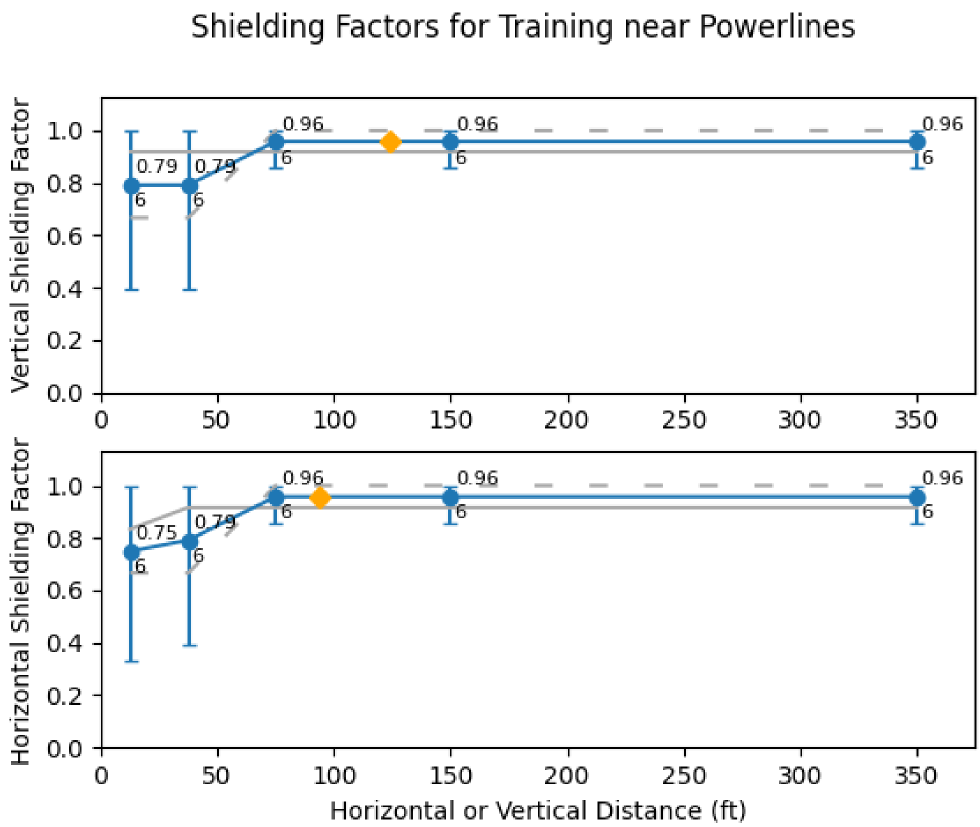

Shielding Factors for Low-Altitude Infrastructure Inspection near Trees/Shelter Belts
Vertical Shielding Factor
Horizontal Shielding Factor
Horizontal or Vertical Distance (ft)
0.20
0.30
0.80
0.90
0.90
0.20
0.30
0.75
0.85
0.90
5

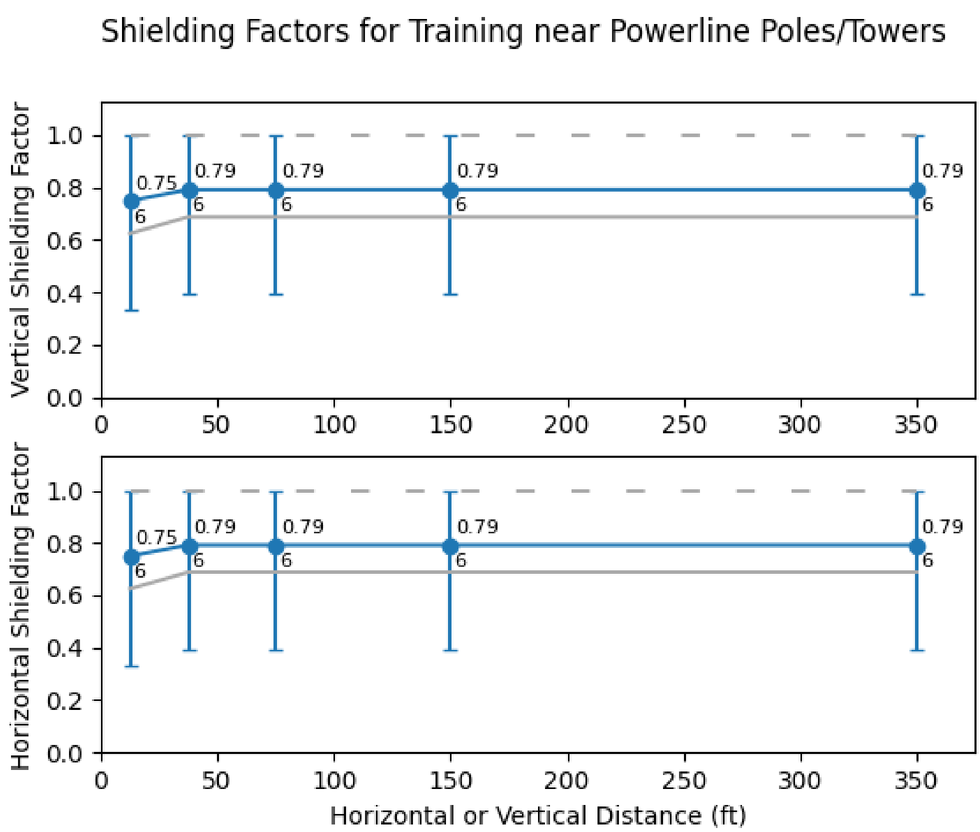

Shielding Factors for Low-Altitude Infrastructure Inspection near Bridges
Vertical Shielding Factor
Horizontal Shielding Factor
Horizontal or Vertical Distance (ft)
0.10
0.10
0.10
0.40
0.40
5

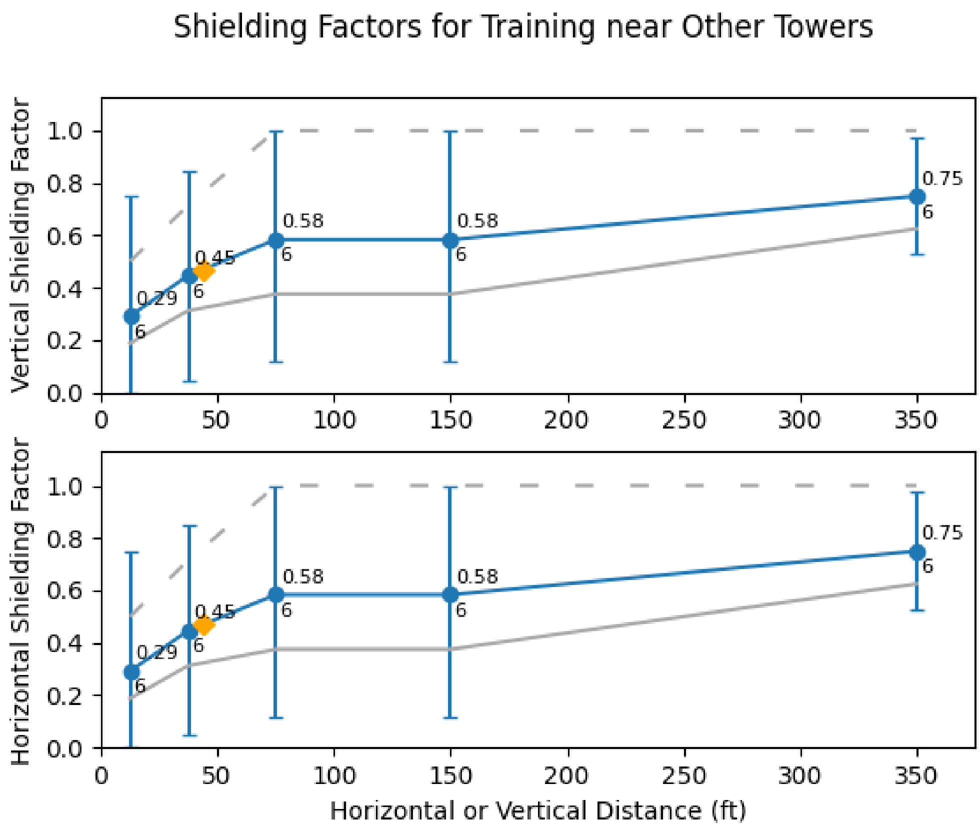
B.4 ***Training***

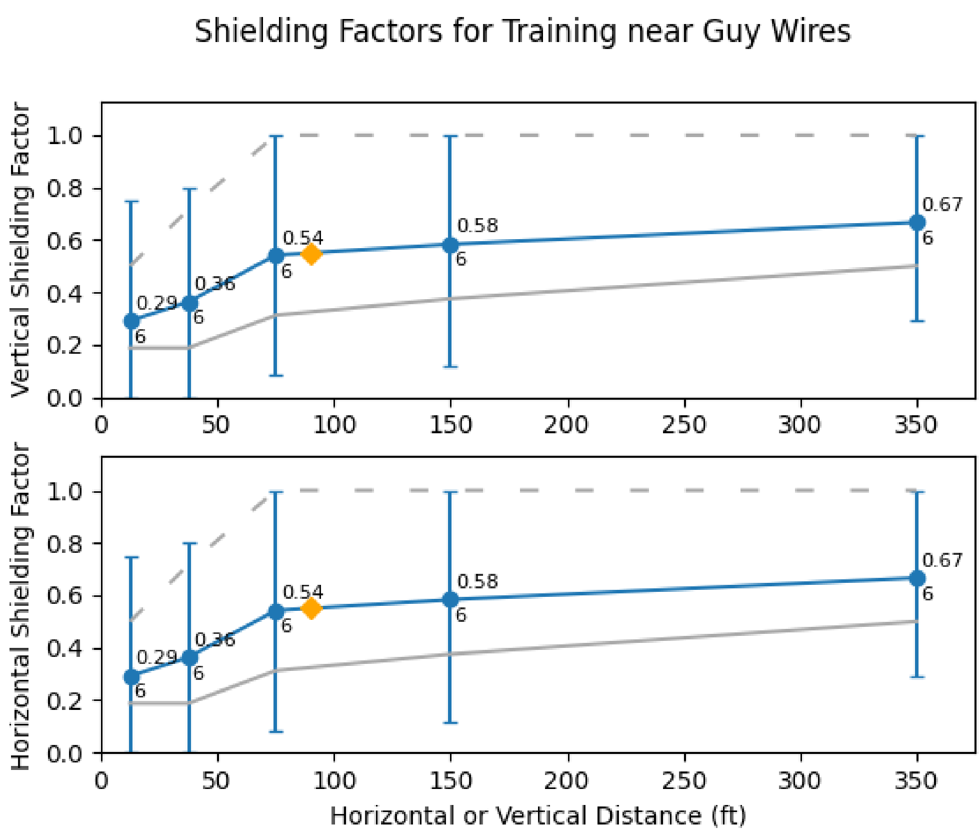
As with Agricultural Application (B.1), but for Training.

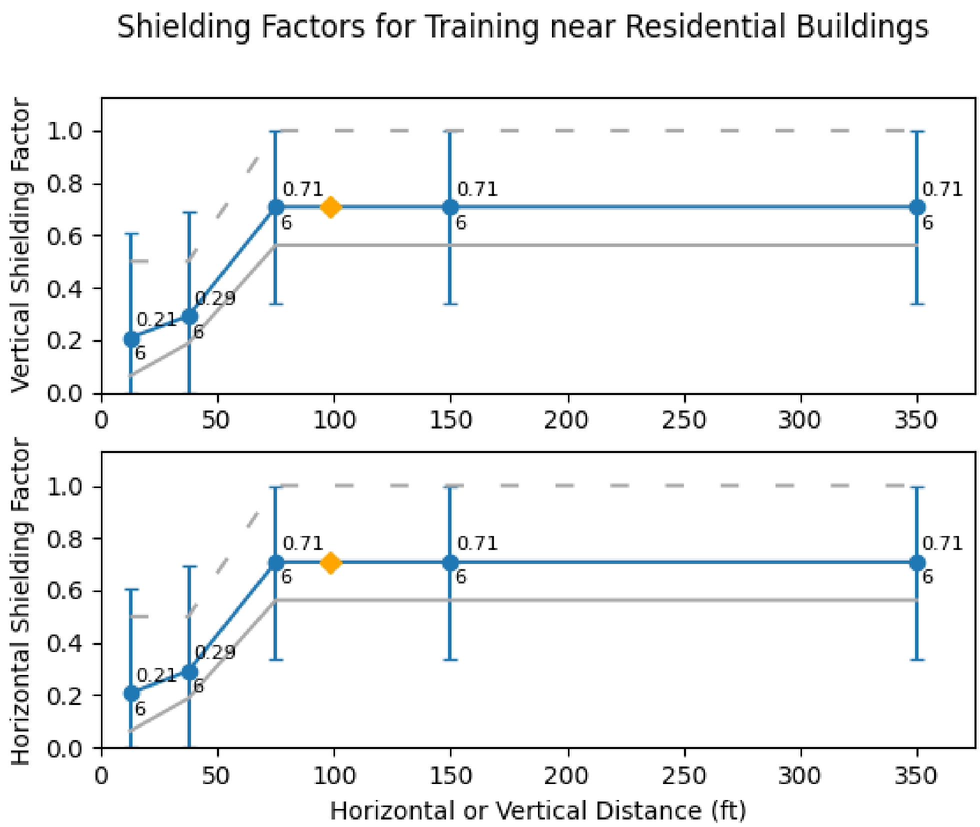


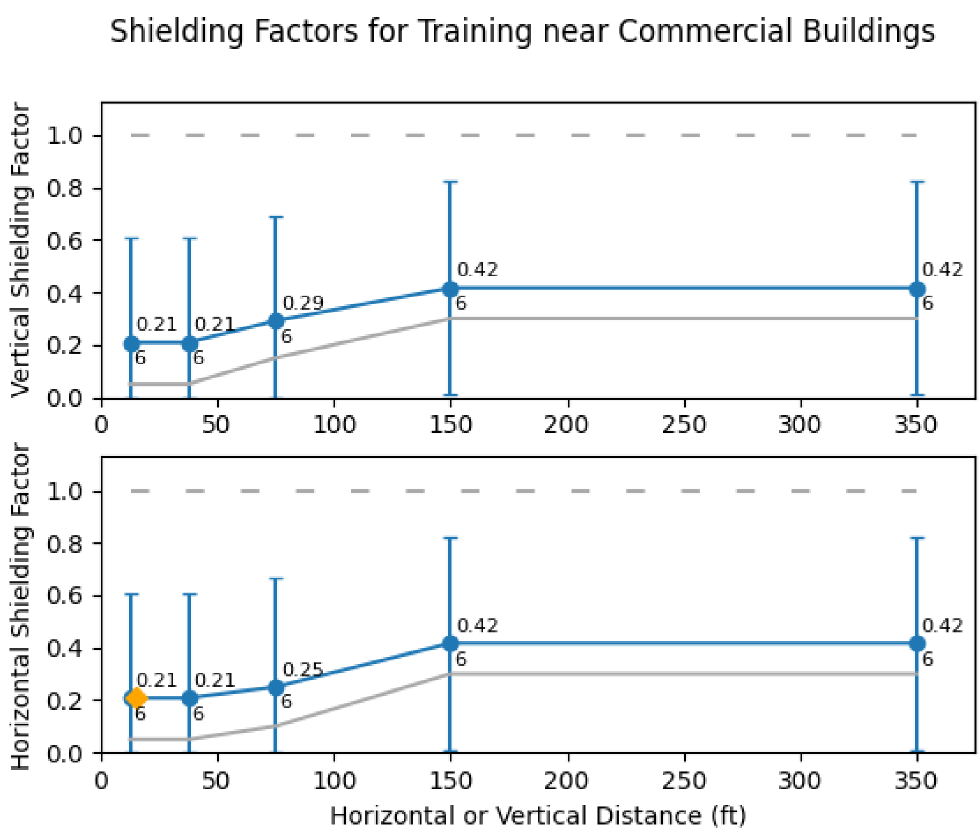

Shielding Factors for Training near Powerlines
Vertical Shielding Factor
Horizontal Shielding Factor
Horizontal or Vertical Distance (ft)
0.0
0.2
0.4
0.6
0.8
1.0
0
50
100
150
200
250
300
350
0.79
0.79
0.96
0.96
0.96
0.75
0.79
0.96
0.96
0.96
6

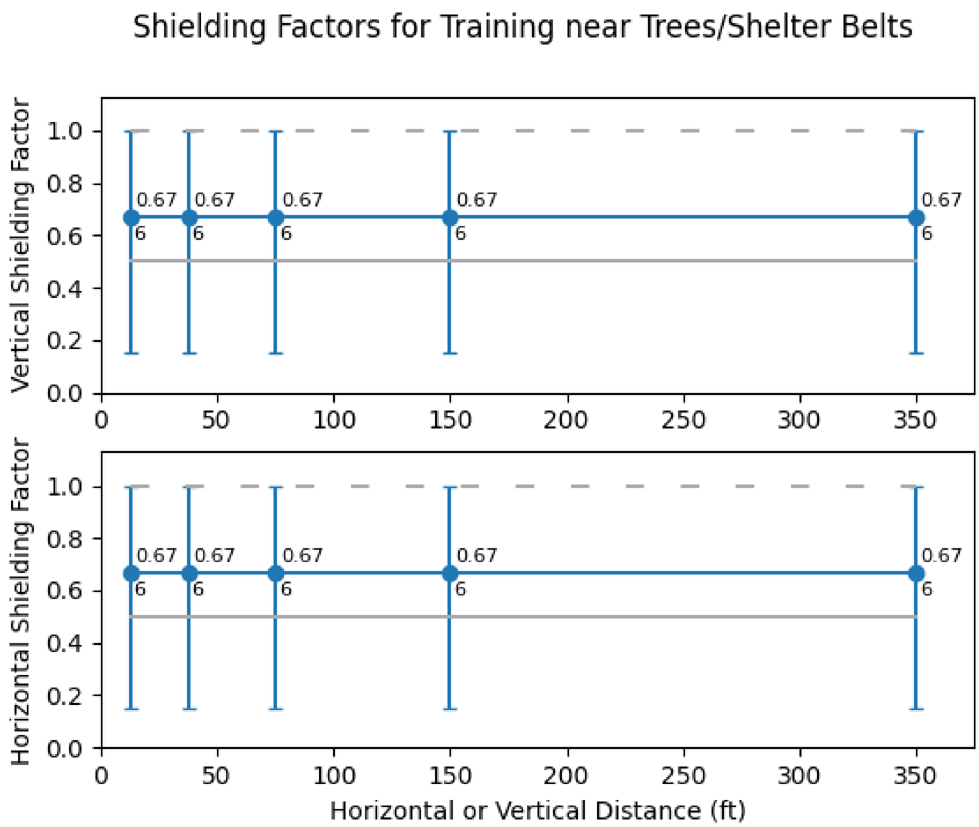

Shielding Factors for Training near Powerline Poles/Towers
Vertical Shielding Factor
Horizontal Shielding Factor
Horizontal or Vertical Distance (ft)
0.0
0.2
0.4
0.6
0.8
1.0
0
50
100
150
200
250
300
350
0.75
0.79
0.79
0.79
0.79
0.75
0.79
0.79
0.79
0.79
6

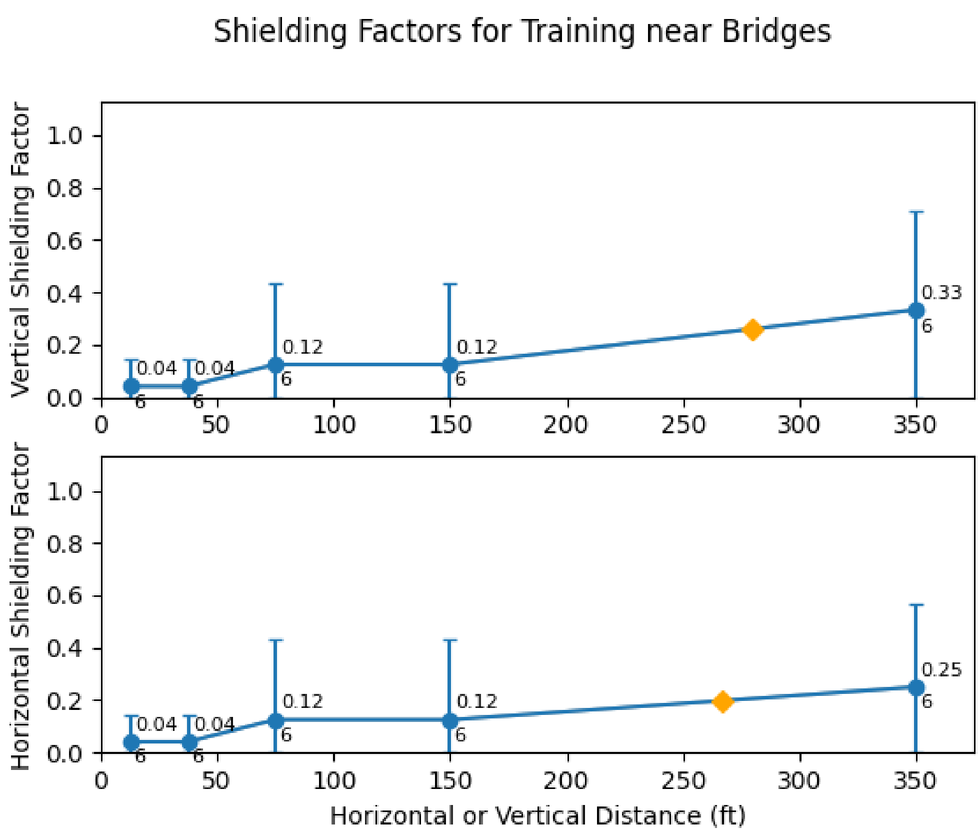

Shielding Factors for Training near Other Towers
Vertical Shielding Factor
Horizontal Shielding Factor
0.29
0.45
0.58
0.58
0.75
Horizontal or Vertical Distance (ft)


Shielding Factors for Training near Guy Wires
Vertical Shielding Factor
Horizontal Shielding Factor
0.29
0.36
0.54
0.58
0.67
Horizontal or Vertical Distance (ft)


Shielding Factors for Training near Residential Buildings
Vertical Shielding Factor
Horizontal Shielding Factor
0.21
0.29
0.71
0.71
0.71
6
Horizontal or Vertical Distance (ft)

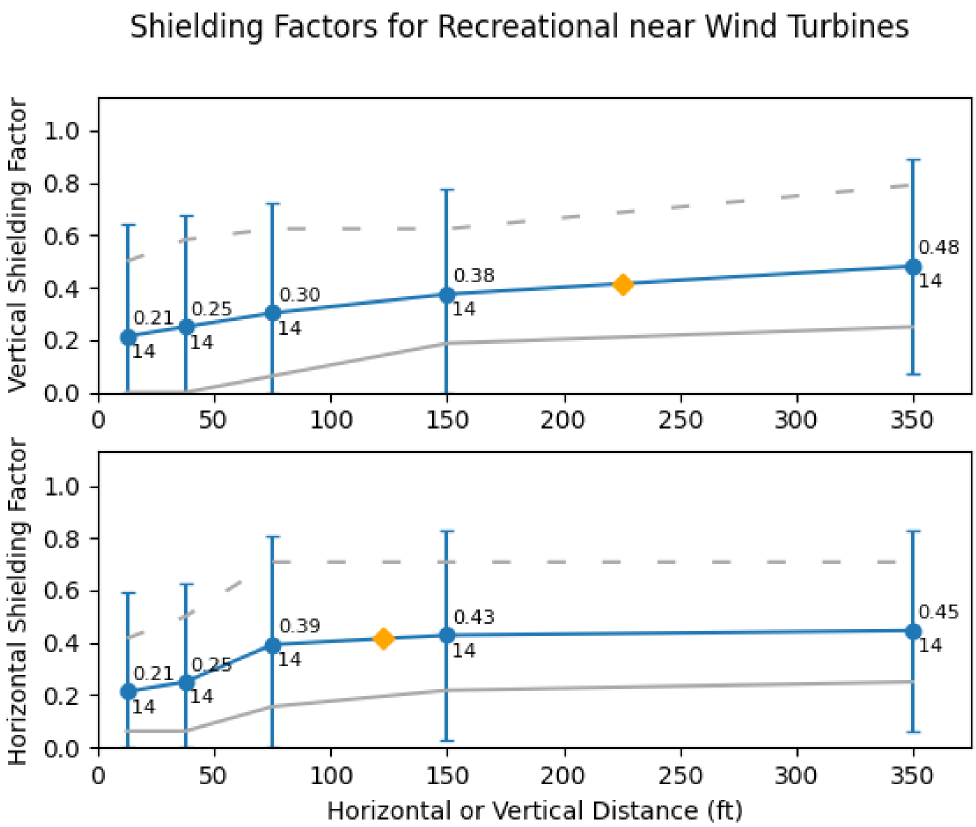

Shielding Factors for Training near Commercial Buildings
Vertical Shielding Factor
Horizontal Shielding Factor
0.21
0.21
0.29
0.25
0.42
0.42
6
Horizontal or Vertical Distance (ft)

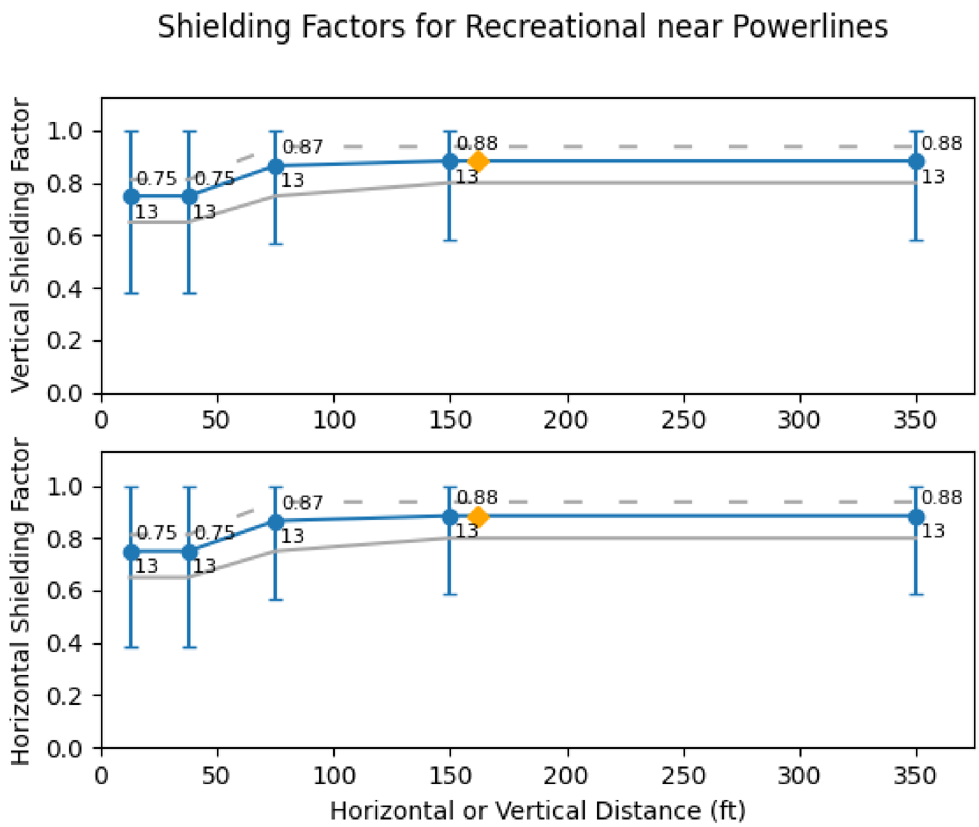

Shielding Factors for Training near Trees/Shelter Belts
Vertical Shielding Factor
Horizontal Shielding Factor
Horizontal or Vertical Distance (ft)
0.67
6
0.0
0.2
0.4
0.6
0.8
1.0
0
50
100
150
200
250
300
350

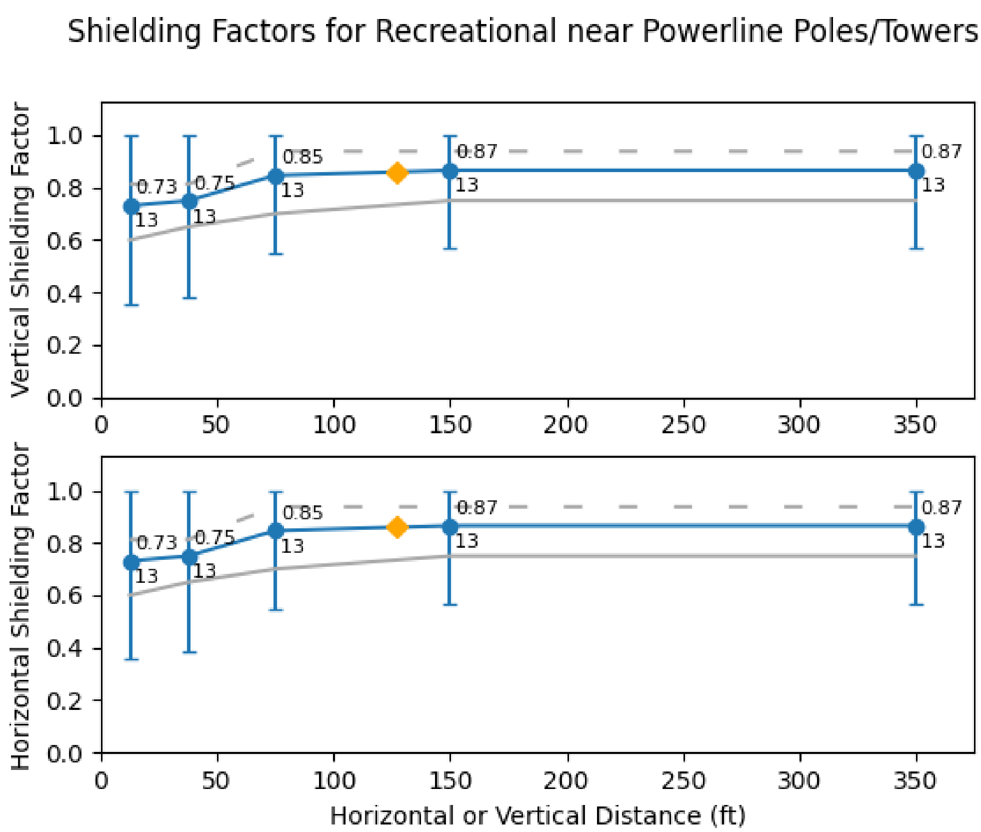

Shielding Factors for Training near Bridges
Vertical Shielding Factor
Horizontal Shielding Factor
Horizontal or Vertical Distance (ft)
0.04
0.12
0.33
0.25
6
0.0
0.2
0.4
0.6
0.8
1.0
0
50
100
150
200
250
300
350

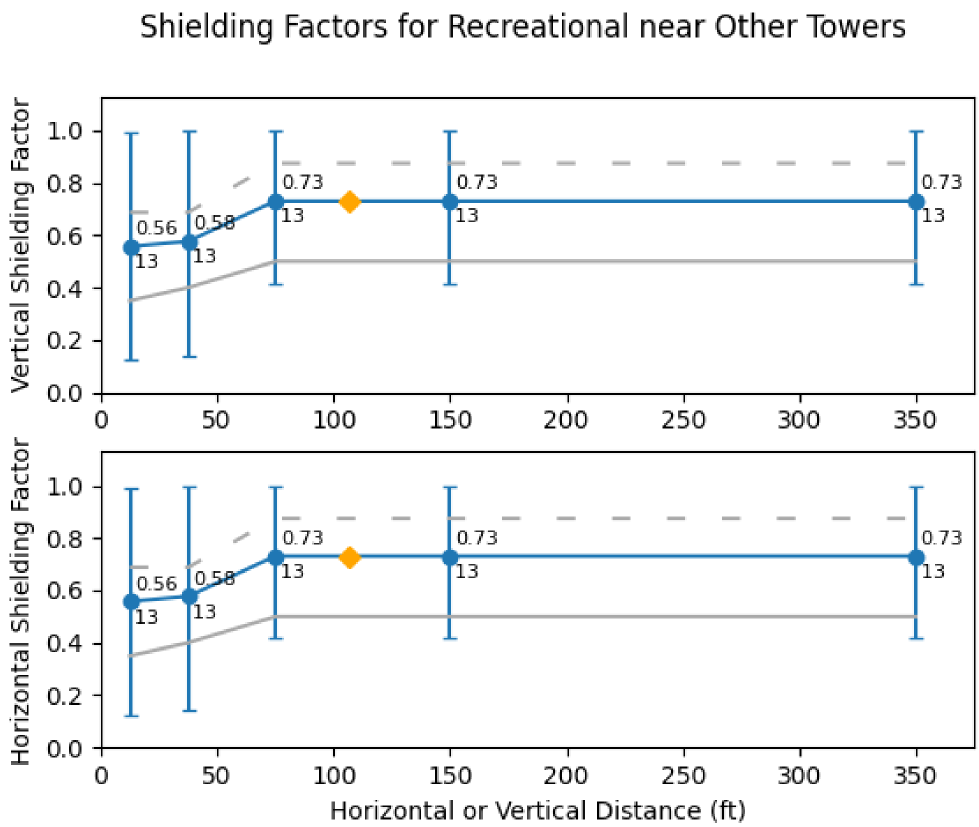
B.5 ***Recreational***

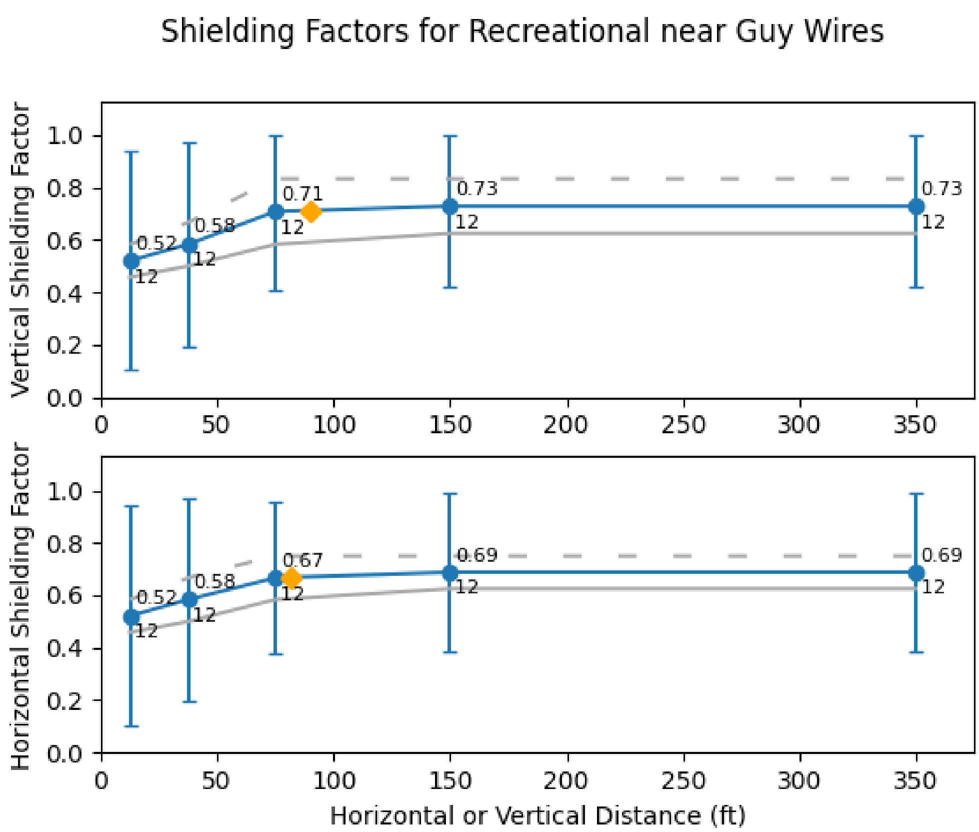
As with Agricultural Application (B.1), but for Recreational.

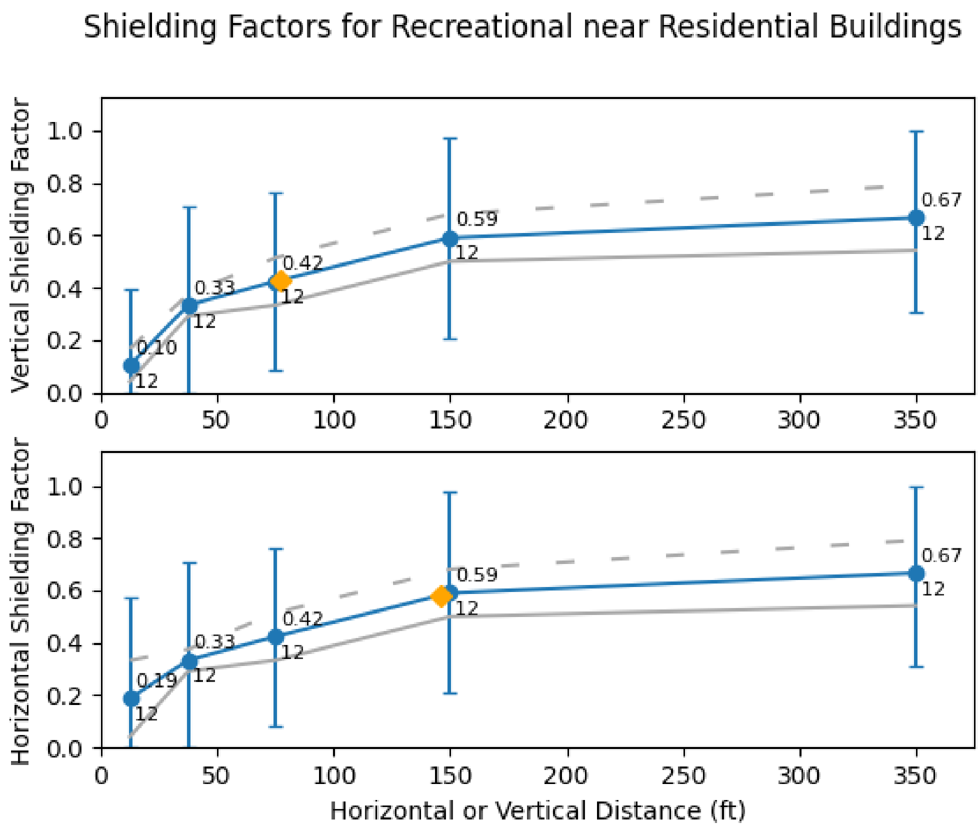


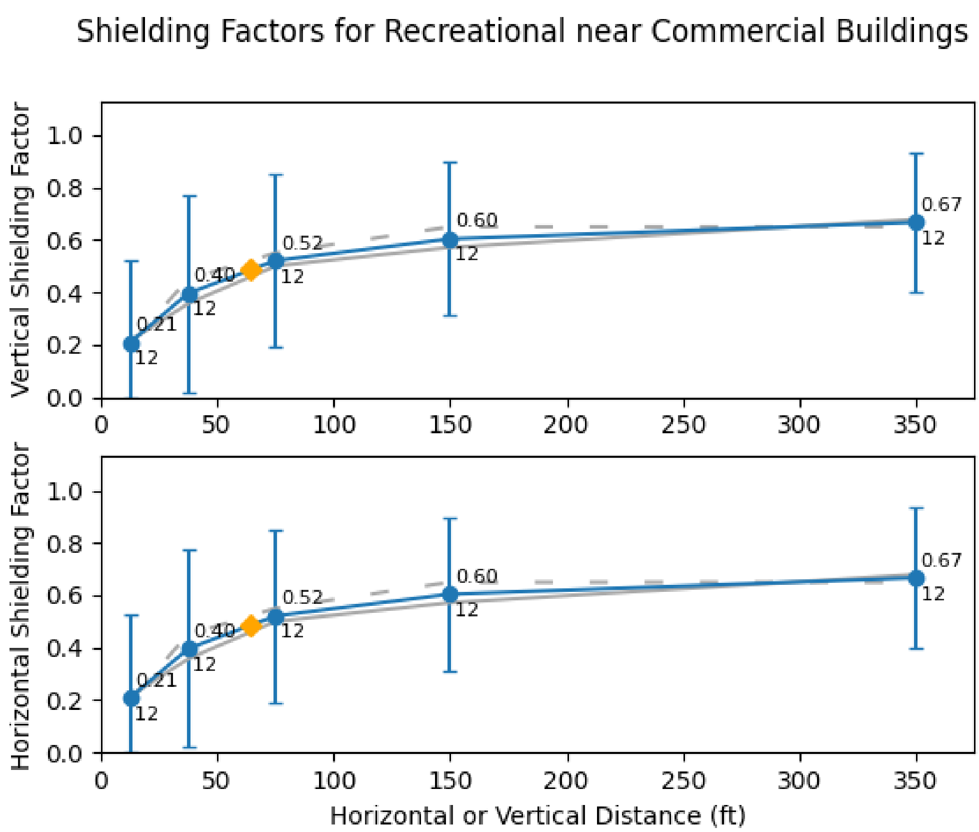

Shielding Factors for Recreational near Powerlines
Vertical Shielding Factor
Horizontal Shielding Factor
0.75
0.75
0.87
0.88
0.88
13
Horizontal or Vertical Distance (ft)

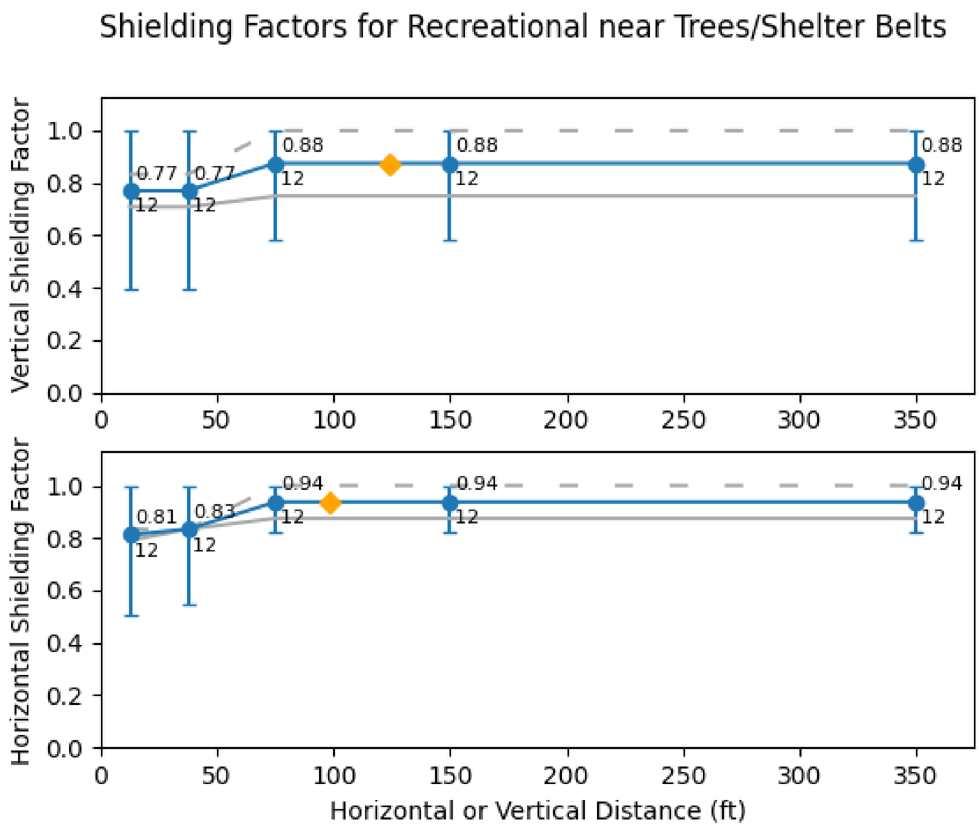

Shielding Factors for Recreational near Powerline Poles/Towers
Vertical Shielding Factor
Horizontal Shielding Factor
0.73
0.75
0.85
0.87
0.87
13
Horizontal or Vertical Distance (ft)

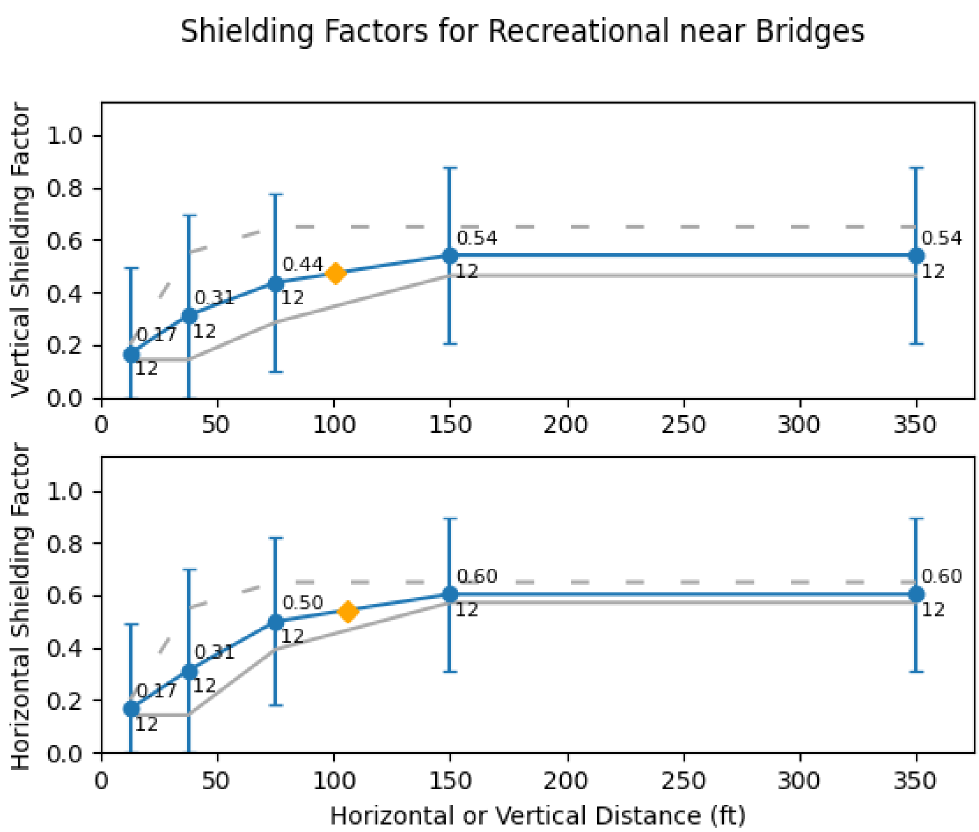

Shielding Factors for Recreational near Other Towers
Vertical Shielding Factor
Horizontal Shielding Factor
0.0
0.2
0.4
0.6
0.8
1.0
0.56
0.58
0.73
0.73
0.73
13
13
13
13
13
0
50
100
150
200
250
300
350
Horizontal or Vertical Distance (ft)


Shielding Factors for Recreational near Guy Wires
Vertical Shielding Factor
Horizontal Shielding Factor
0.0
0.2
0.4
0.6
0.8
1.0
0.52
0.58
0.71
0.73
0.73
0.67
0.69
0.69
12
12
12
12
12
0
50
100
150
200
250
300
350
Horizontal or Vertical Distance (ft)


Shielding Factors for Recreational near Residential Buildings
Vertical Shielding Factor
Horizontal Shielding Factor
Horizontal or Vertical Distance (ft)
0.10
0.33
0.42
0.59
0.67
0.19
0.33
0.42
0.59
0.67
12


Shielding Factors for Recreational near Commercial Buildings
Vertical Shielding Factor
Horizontal Shielding Factor
Horizontal or Vertical Distance (ft)
0.21
0.40
0.52
0.60
0.67
12


Shielding Factors for Recreational near Trees/Shelter Belts
Vertical Shielding Factor
Horizontal Shielding Factor
0.77 0.77 0.88 0.88 0.88
0.81 0.83 0.94 0.94 0.94
12
Horizontal or Vertical Distance (ft)


Shielding Factors for Recreational near Bridges
Vertical Shielding Factor
Horizontal Shielding Factor
0.17 0.31 0.44 0.54 0.54
0.17 0.31 0.50 0.60 0.60
12
Horizontal or Vertical Distance (ft)