A Risk-Based Approach for Small Unmanned Aircraft System (sUAS) Airworthiness and Safety Certification

Risk Model Review
National Academies of Science

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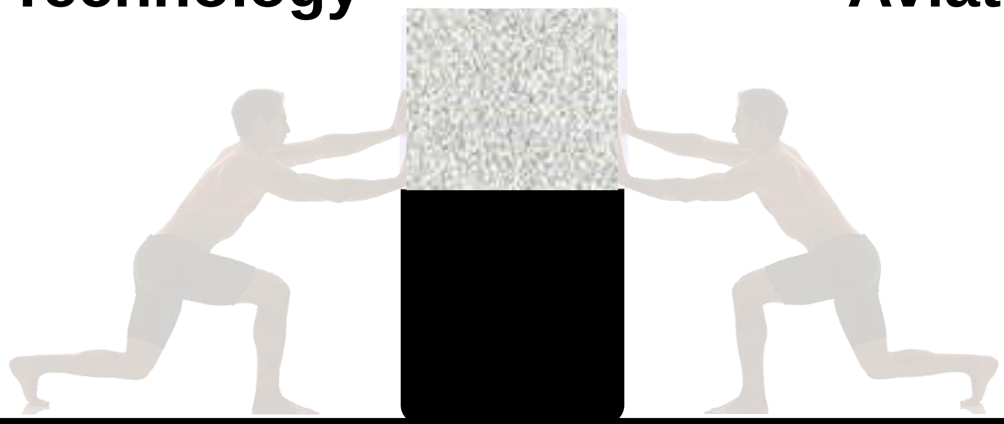
MITRE Corporation

Clash of Cultures in the sUAS Industry

Information Technology

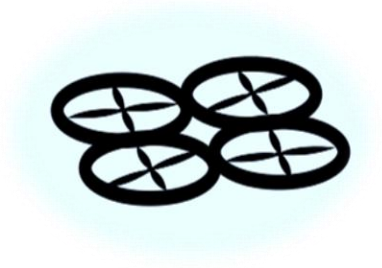
Innovation
Revolutionary
Speed to market
Entrepreneurial
Open
Minimally regulated
Risk rewarded



Aviation System

Safety
Evolutionary
Proven
Conservative
Proprietary
Tightly regulated
Risk avoided

Technology Innovations → ← **Safest Mode of Transportation**

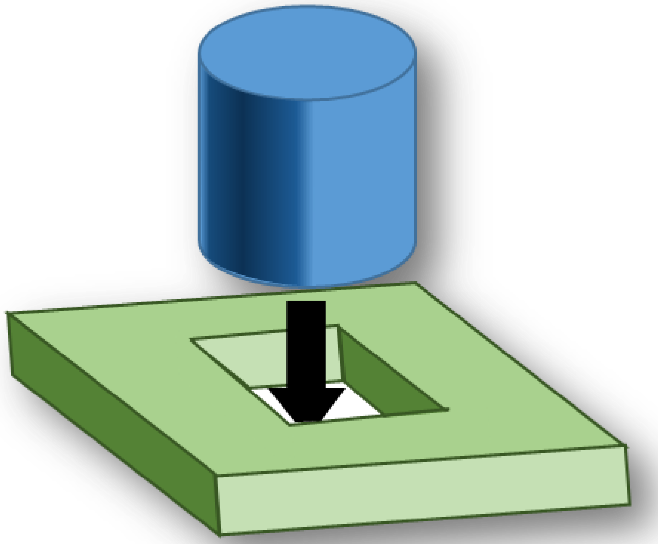


Small Unmanned Aircraft

- Rapidly evolving technology
- Very dissimilar vehicles
- Designed for multiple purposes
- Wide variety of missions (ocean to urban)

The Problem To Be Solved

The Problem



Manned aircraft airworthiness design standards do not scale down to the sUAS environment

- **Very limited design standards for the sUAS industry**
- **Wide variety of vehicles, missions, and users**

The current airworthiness approval process is not sustainable for sUAS operations

- **Rapid pace of development from a wide variety of companies**
- **Current rules are very restrictive for sUAS**
- **Waiver process is labor intensive, time consuming, and costly**

sUAS: a New Class of Aircraft

Manned Aircraft	*Unmanned Aircraft*
High Risk (crew & passengers onboard)	Low Risk (no occupants on aircraft)
Large Vehicles (1000s of lbs.)	Small Vehicles (10s of lbs.)
High Speed	Low Speed
Long Lifecycle	Short Lifecycle
Primary Risk - Vehicle Occupants (1^{st} Party Risk)	Primary Risk – Overflight Population/ Fly Away (3^{rd} Party Risk)

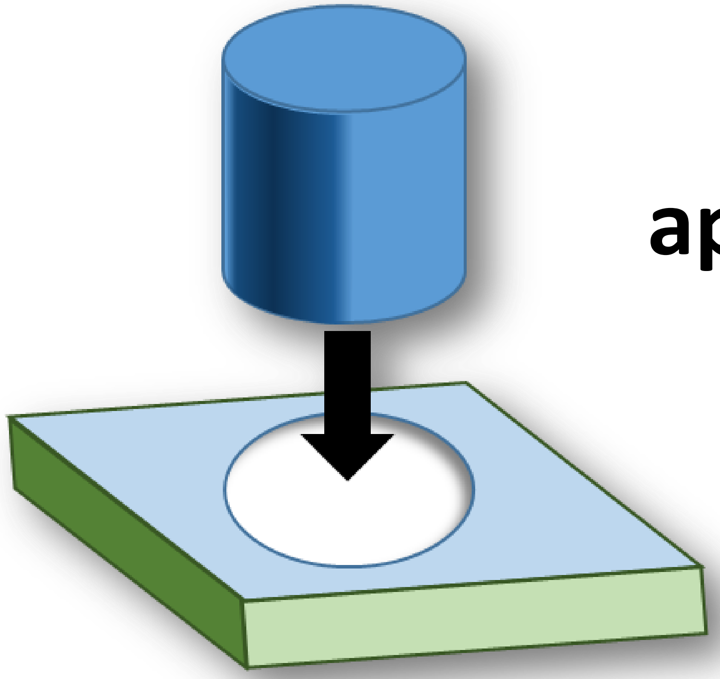
Different Types of Aircraft Need Different Approaches

Design Based vs Risk-Based Approach

Current *Design Based* Approach	*Risk-Based* Approach
Design Standards	Safety Performance Thresholds
Process Oriented	Operational Risk, Use Case Oriented
Mature Technology	Rapidly Evolving Technology
Pass/Fail	Risk Thresholds
Evaluates System	Evaluates Safety

Airworthiness is one of the Biggest Challenges to the sUAS Community

The Need

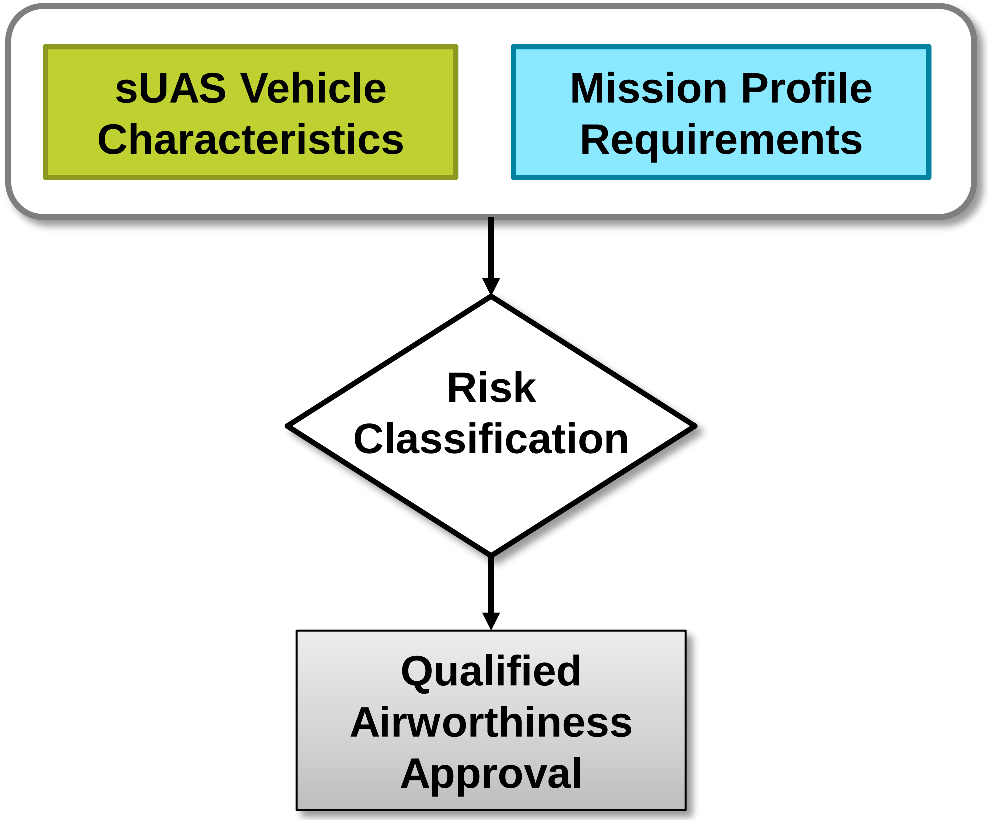


The sUAS stakeholder community needs a streamlined, repeatable approach, designed for the unique risks of sUAS commercial operations

sUAS Risk-Based Airworthiness Safety Model Concept

Research Question

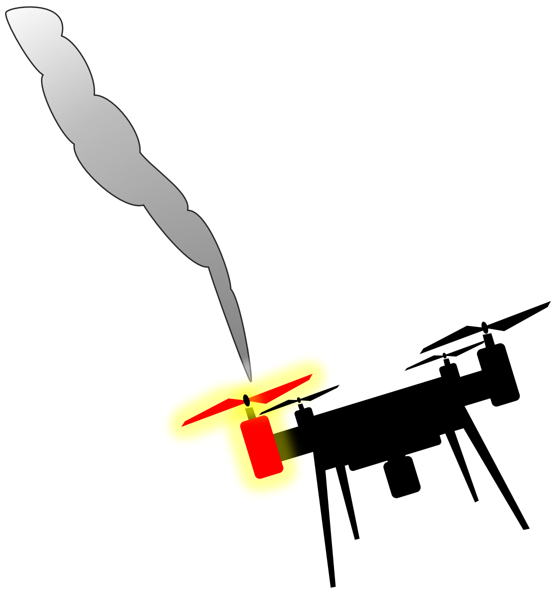
Can a Risk-Based Approach for sUAS airworthiness approval be developed that combines the vehicle and mission characteristics to ensure an acceptable level of safety?



What is a *Risk-Based Approach* ?

Systematic consideration of relevant risks

- Failure modes
- Failure likelihoods
- Failure severity
- Risk tolerance
- Risk mitigation
- Occurrence Probabilities
- Event Results



sUAS Risk Model System

MITRE Innovation Program

sUAS Mission Profile

sUAS Vehicle Profile

Dynamic Inputs

Risk Model

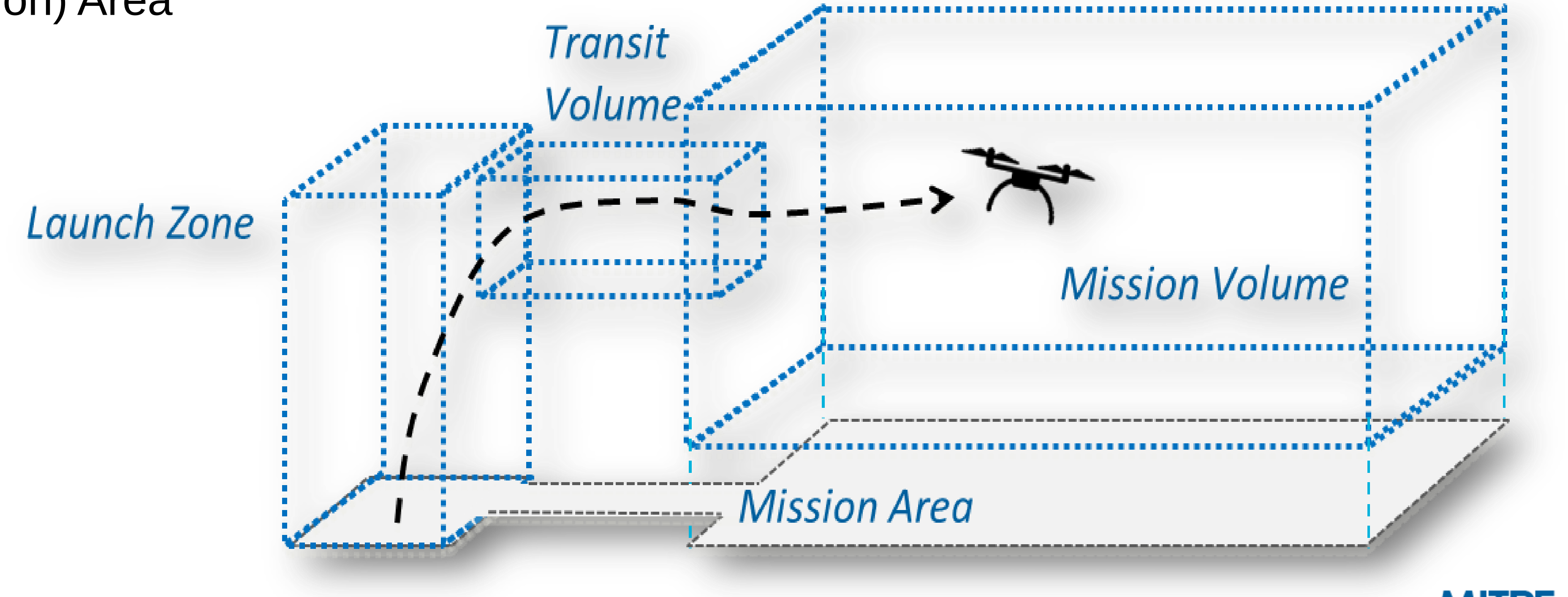
Performance Coefficients Database

- Fatality model coefficients
- Collision detect & avoid coefficients

Mission Profiles

Mission Profile Development

- Three Aspects of the Mission Profile
  - Launch and Recovery Zone
  - Transit Route
  - Operations (Mission) Area



Different missions have different risks to the public

- **Mission Characteristics**
  - Density of people/pedestrians
  - Mission area size
  - Number of launches and landings (e.g., for package delivery)
- **Operational Characteristics**
  - BVLOS
  - Daytime/night time
  - Flight duration
  - Operating altitude
- **Vehicle Characteristics**
  - Size and weight
  - Type (rotorcraft, fixed wing)
  - Speed

Simplify Modeling: Standard Mission Profiles

Sparse Area

Agriculture, Wildlife, Disaster Insurance Assessment, etc.

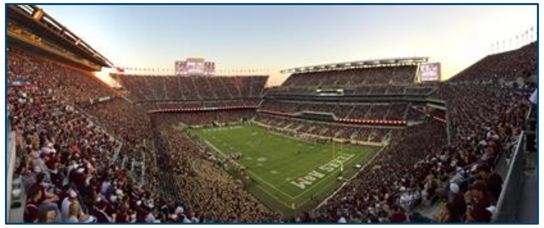
Contained Area

Static Infrastructure Inspection, Real Estate Photography, etc.

Linear Area

Linear Infrastructure, Waterfront Advertising, Traffic, etc.

Public Event



Parades, Sporting Events, Concerts, Static News Coverage, etc.

Network Operations

Small Cargo Delivery, Emergency Response, etc.

Dynamic Area

Police Chases, Media Coverage, etc.

Each of the Mission profiles have different types of operational risks

Sub-Missions – Varying degrees of risk

Sparse

- BVLOS
- BVLOS Ops over People

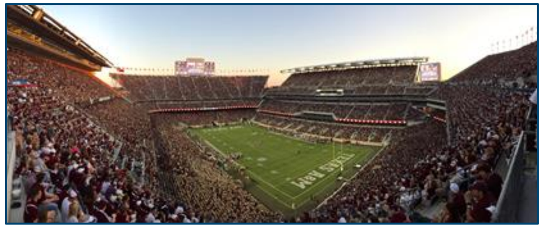
Contained Area

- Ops over People
- EVLOS Ops over People

Linear Area

- BVLOS
- BVLOS Ops over People

Public Event



- Ops over People
- EVLOS Ops over People

Network

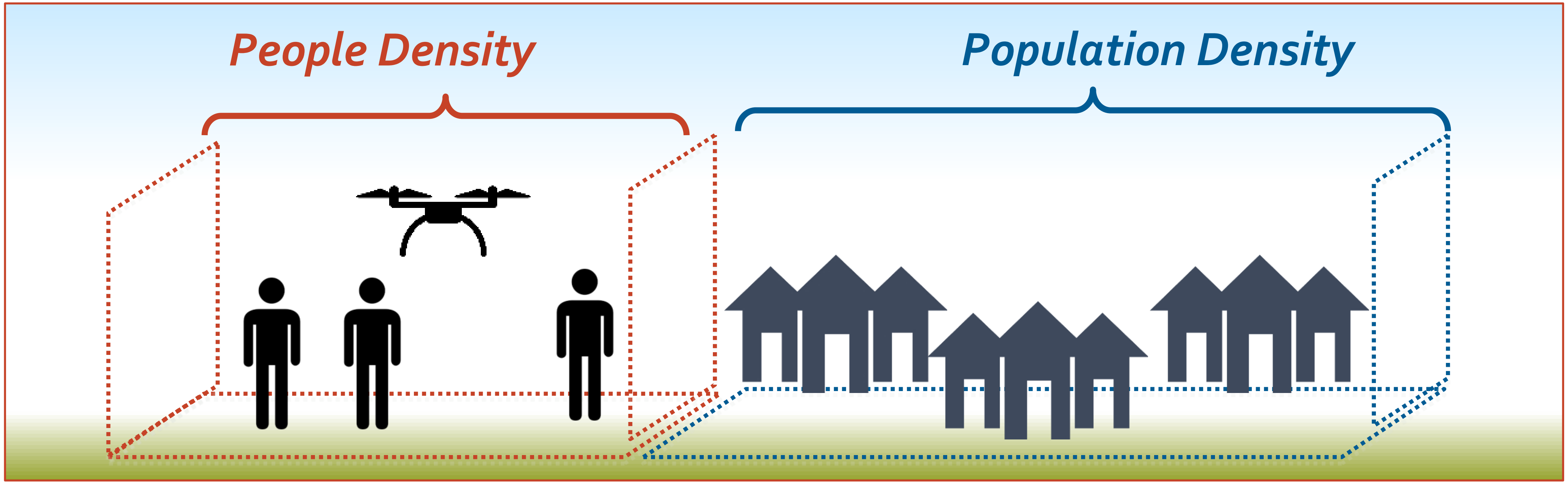
- BVLOS Ops over People - Rural
- BVLOS Ops over People - Urban

Dynamic Area

- BVLOS Ops over People

The Density of People is a *key* component to the Level of Risk

- **People density** is the number of people exposed to the sUAS operation
- **Population density** is based on where people sleep



People Density: LandScan™ Data Analysis

	Category	Breaks	Median (ppl/mi^2)	% Contiguous US Land Area	% US Population
Rural	Low	[0, 335)	0	95.78	10.5
	Medium	[335, 1216)	600	2.04	12.4
	High	[1216, 2500)	1,733	0.98	16.1
Urban	Low	[2500, 12602)	4,050	1.15	29.3
	Medium	[12602, 63190)	17,169	0.051	19.2
	High	[63190, 534827)	85,160	0.0017	7.5
Open Air Assembly	Low	N/A	1,219,882*	N/A	4.4
	Medium	N/A	1,904,935*	N/A	0.7
	High	N/A	2,589,990*	N/A	0

*not median, but chosen people density value

Mission Profile Characteristics

	Mission Profile Parameters		Sparse Area Operations BVLOS	Sparse Area Operations BVLOS/UOP	Contained Area Operations VLOS/UOP	Contained Area Operations EVLOS/UOP	Linear Area Operations BVLOS	Linear Area Operations BVLOS/UOP	Public Event Operations VLOS/UOP	Public Event Operations EVLOS/UOP	Network Operations BVLOS/Rural	Network Operations BVLOS/Urban	Dynamic Ops BVLOS/UOP
Mission Area	Pedestrian Density	Rural - Low	80	20	10	20	60	70			20	10	15
		Rural - Medium	10	50	10	20	20	10			20	10	15
		Rural - High	5	20	10	20	20	10			20	10	15
		Urban - Low	5	10	30	30	10	5	5	2	20	10	15
		Urban - Medium			50	10	10	5	5	2	5	30	15
		Urban -High							40	4	5	30	25
		Open Air - Low							40	40			
		Open Air - Medium							**5**	**50**			
		Open Air - High							5	2			
	Operating Area	Length (km)	5	5	1	1	100	100	1	1	20	20	20
		Width (km)	5	5	1	1	1	1	1	1	20	20	20
	2nd Party	% 2nd party	5	0	95	90	5	50	5	95	1	1	0
	Pedestrian Behavior	% transit	40	50	30	0	80	80	30	30	40	40	40
		% loiter	30	40	40	100	20	20	40	40	30	30	50
		% fixed	30	10	30	0	0	0	30	30	30	30	10
Operations	BVLOS	Yes/No	Yes		No		Yes		Yes		Yes		Yes
	Ops over People	Yes/No	No		Yes		No		Yes		Yes		Yes
	Flight Duration	< 30 mins			X	X			X	X	X	X	X
		30 mins - 1 hour	X	X	x	X			X	X	X	X	X
		1 hour - 3 hours		X			X	X					X
	Fleet size	small (1-10)	X		X		X		X				X
		Medium (10-100)									X		
		Large (> 100)											
	Cruise Speed	Vehicle profile											
	Cruise Altitude % time	< 10 AGL	10	10	70	10							
		10 < 100 AGL	100	25	30	80							
		100 < 400 AGL	0	65	0	10					X		
		> 400 AGL	0	0	0	0							
	Vehicle trajectory (flight states?) % time	% Linear	20	20	0	0	100	100	0	0	90	90	80
		% Grid	80	60	0	25	0	0	20	0	0	0	0
		% Hover	0	20	100	75	0	0	80	100	10	10	20
Vehicle	Vehicle Type	Fixed wing	X	X			X	X					X
		Rotorcraft	X	X	X	X			X	X			X
		Hybrid									X	X	
	MTOW	Micro: < 0.55 lbs											
		Mini: 0.55 - 4.4 lbs	X		X		X						
		Limited: 4.4-20 lbs							X				X
		[illegible]									X		

Vehicle Profiles

Vehicle Characteristics

- **sUAS Type**
  - Rotorcraft
  - Fixed Wing
  - Hybrid

- **Weight Class**
  - Micro (< 0.55 lb)
  - Mini (0.55 < 4.4 lb)
  - Limited (4.5 < 20 lb)
  - Bantam (20.1 < 55 lb)

- **Other Characteristics**
  - Maximum speed
  - Wingspan (width)
  - C2 Range (communication links)
  - Endurance (function of battery)
  - Payload capacity
  - Reliability (MTBF)
  - Mitigations

Hunter King, Latitude Engineering

sUAS Risk – Vehicle Reliability

Vehicle Failed to Maintain Flight

- **Model accounts for vehicle failures**
- **Reliability Model:**
  - Subclasses of System
  - Estimates of Reliability
- **Failure-To-Fall Type Model:**
  - 3 Fall Types Produced
    - Spiral
    - Glide
    - Drop

10: AIRFRAME

- 11:Airframe
- 13: Landing Gear
- 14: Flight Control Surfaces
- 15: Rotor Protection

20: POWER SYS

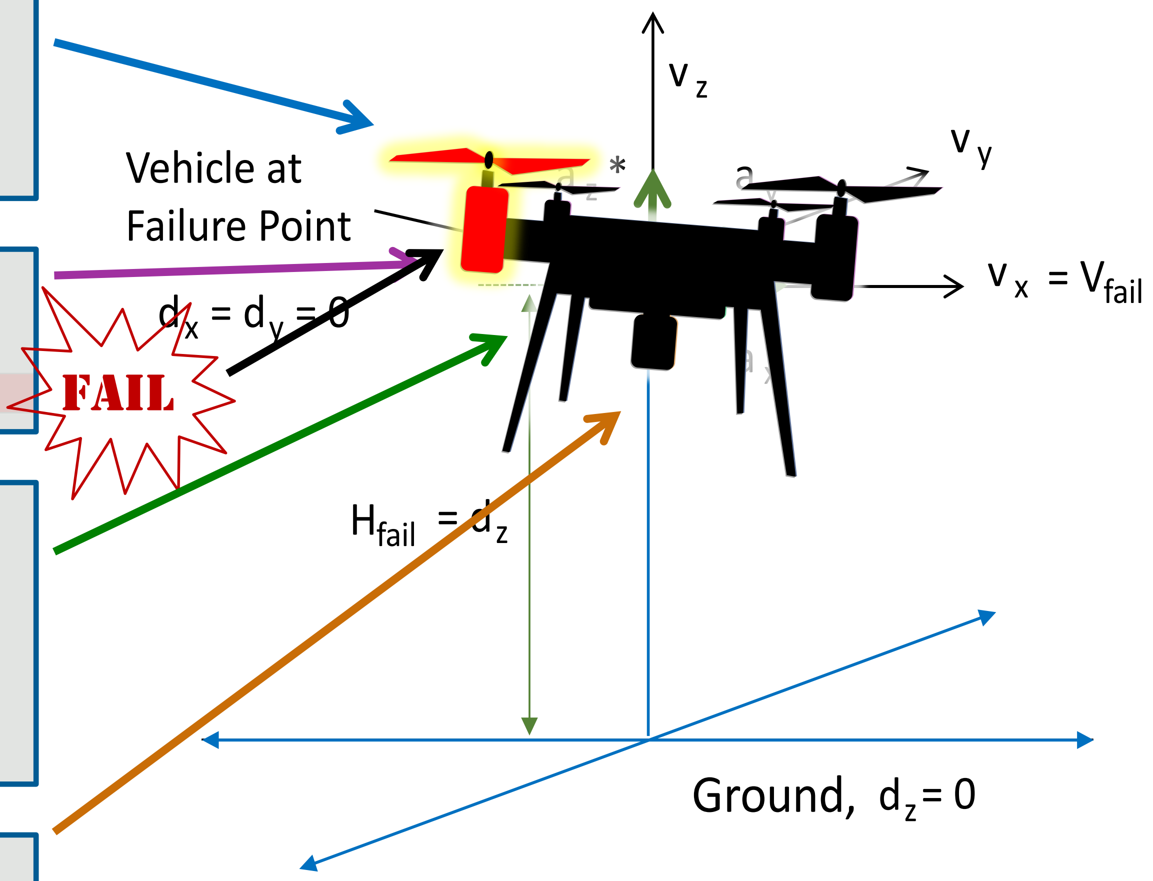
- 21: Recip Engines
- 26: Helo Rotary Wing
- 28: Multi-Rotor Engines

40: FLT PWR SYS

- 42: Electric Systems
- 43: Electric Power
- 44: Lighting Sys
- 46: Fuel System
- 48: Wx Protection Sys
- 49: Misc Utility

50: CTRL INSTRM

- 51: Instrument System
- 52: Autopilot
- 53: Drone Guidance
- 54: Telemetry
- [illegible]: Flight Control System



Generic Vehicle Profile Information

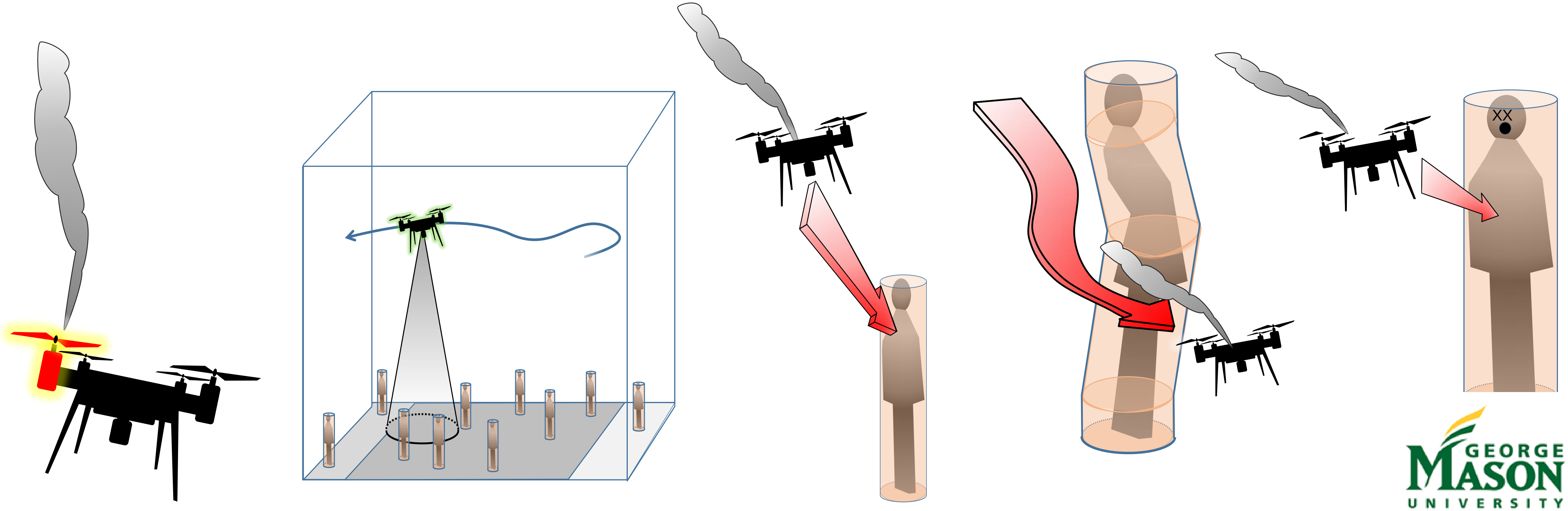
Vehicle	Vehicle Weight Class	Average Weight	Average Linear Speed (Cruise Speed)	Wingspan/ Vehicle Width	Max. Velocity	C2 Range	Endurance (Flight Time)	Payload Capacity	Reliability (MTBF)	Angle of Inclination (degrees)
Micro Generic - Fixed Wing	Micro <.55 lb	0.2 lb	10 mph	13 inches	20 mph	200 ft	8 mins	TBD	TBD	30
Micro Generic - Rotorcraft	Micro <.55 lb	0.1 lb	20 mph	5.5 inches	35 mph	240 ft	7 mins	0.05 lb	TBD	90
Micro Generic - Hybrid	Micro <.55 lb	0.2 lb	15 mph	TBD	30 mph	TBD	10 mins	TBD	TBD	60
Mini Generic - Fixed Wing	Mini .55-4.4 lb	2.6 lb	23.1 mph	3.9 ft	50 mph	3.1 mi	62.5 mins	0.3 lb	TBD	30
Mini Generic - Rotorcraft	Mini .55-4.4 lb	2.8 lb	22 mph	1.6 ft	45 mph	1.5 mi	25.8 mins	0.7 lb	1860 hrs*	90
Mini Generic - Hybrid	Mini .55-4.4 lb	3 lb	30 mph	3 ft	55 mph	TBD	30 mins	TBD	TBD	60
Limited Generic - Fixed Wing	Limited 4.4-20 lb	10.8 lb	28.5 mph	6.3 ft	55.8 mph	4.3 mi	88.8 mins	2.4 lb	TBD	30
Limited Generic - Rotorcraft	Limited 4.4-20 lb	9.3 lb	25 mph	3.3 ft	46 mph	2.4 mi	29.3 mins	8.5 lb	TBD	90
Limited Generic - Hybrid	Limited 4.4-20 lb	9.4 lb	40 mph	6 ft	65 mph	20 mi	67.5 mins	8.3 lb	TBD	60
Bantam Generic - Fixed Wing	Bantam 20-55 lb	33.8 lb	49 mph	10.5 ft	79 mph	41 mi	855 mins	10.8 lb	TBD	30
Bantam Generic - Rotorcraft	Bantam 20-55 lb	30.2 lb	30 mph	4.8 ft	42 mph	2 mi	28.3 mins	12 lb	TBD	90
Bantam Generic - Hybrid	Bantam 20-55 lb	25.7 lb	35 mph	TBD	40 mph	TBD	285 mins	5.8 lb	TBD	60

* Provided by DJI

Risk Based Approach – Development of a Probabilistic Model

sUAS Risk Model – Failure Modes

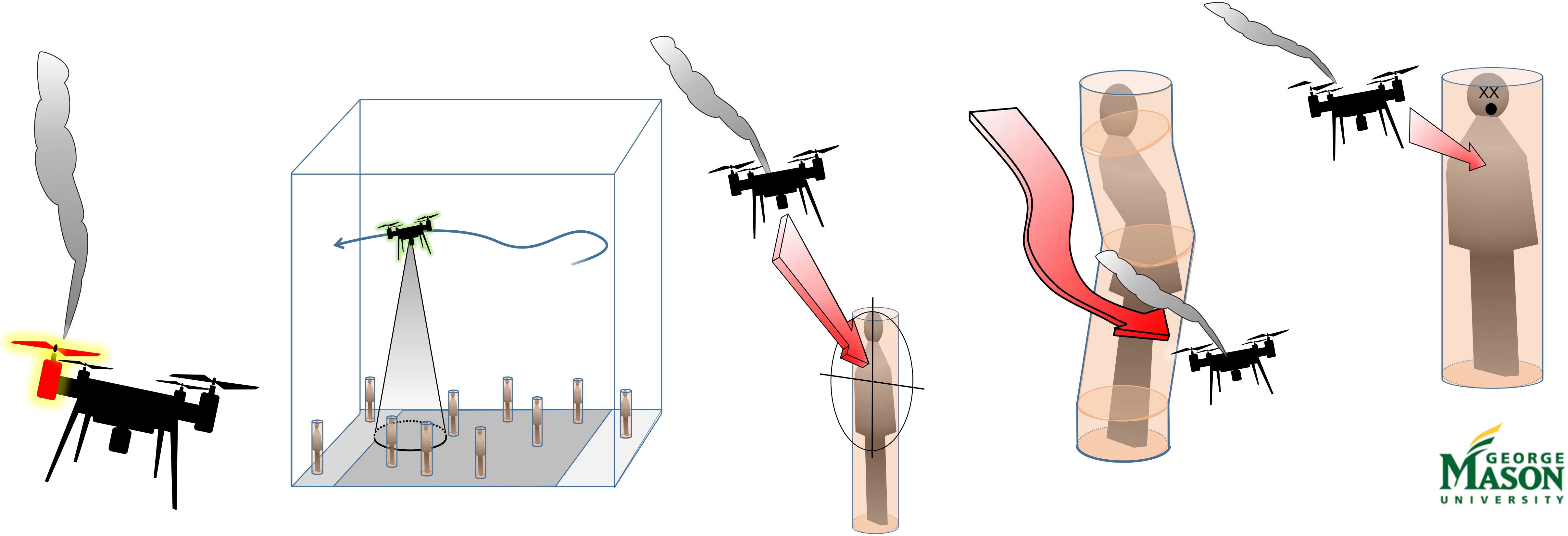
Determine the risk of a sUAS and pedestrian collision, and the possibility of the impact being fatal



sUAS Risk Model

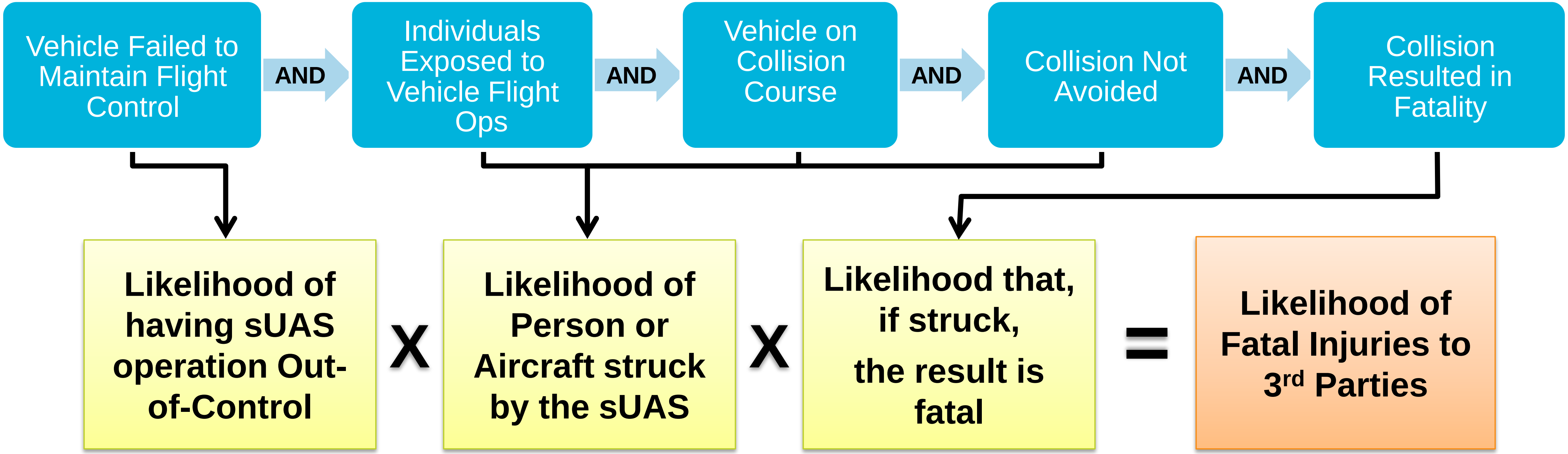
How did we get there?

Does the collision between sUAS and pedestrian provided sufficient kinetic energy to be lethal.



sUAS Risk Model

Modeling Each Node

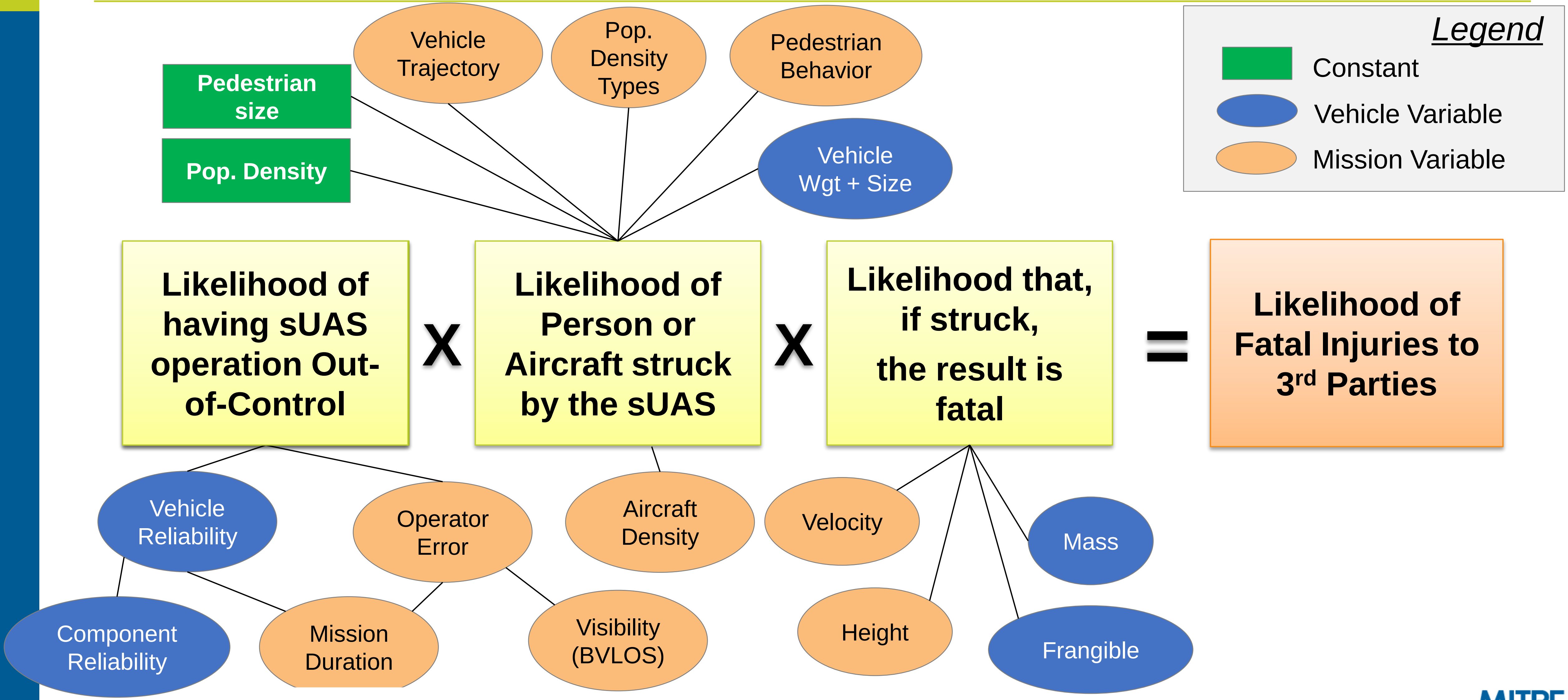


These events are uncorrelated and thus the chances of each may be multiplied together

Quantifying the Risk Model

sUAS Risk Model Overview

Integrating Attributes and Parameters



Model Inputs: Constants, and Attributes Vehicle Profile, and Mission Profile

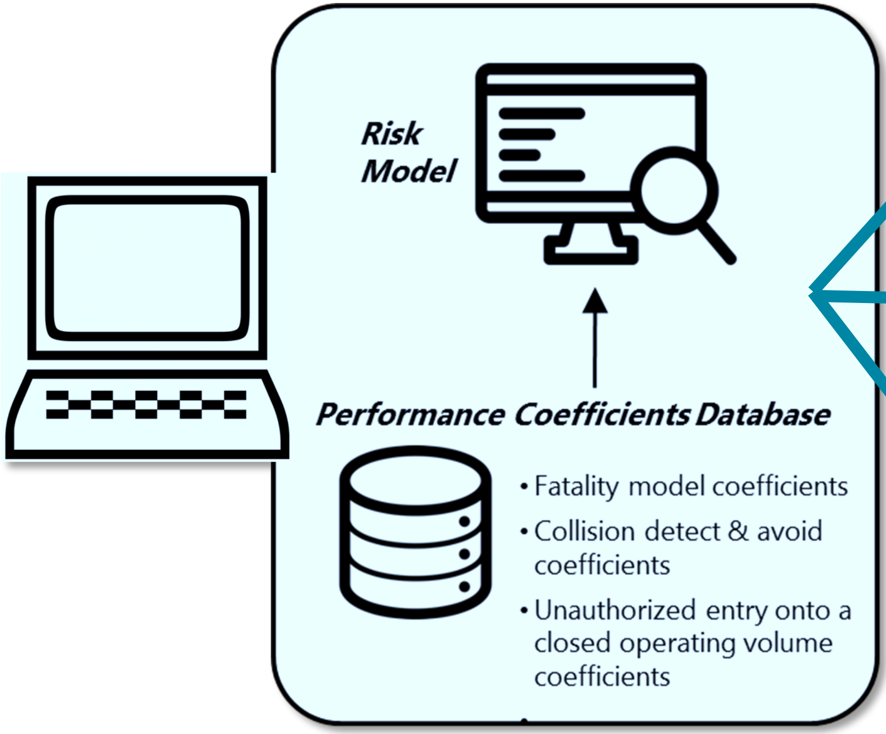
Vehicle Profile Input Variables	Units
Vehicle	
Vehicle Type	
Vehicle Weight Class	
Average Weight	kg
Vehicle Length	m
Vehicle Width	m
Average Transit Speed	m/s
Average Grid Speed	m/s
Average Hover Speed	m/s
Max. Velocity	m/s
C2 Range	km
Endurance (Max Flight Time)	min
Payload Capacity	kg
Reliability MTBF	hrs
Angle of Inclination	deg
Drag Coefficient	
Lift Coefficient	

Model Constants	*Units*
Population Density Categories	
People Density-Rural Low	*ppl/sq. km*
People Density-Rural Medium	*ppl/sq. km*
People Density-Rural High	*ppl/sq. km*
People Density-Urban Lo	*ppl/sq. km*
People Density-Urban Md	*ppl/sq. km*
People Density-Urban Hi	*ppl/sq. km*
People Density-Open Air Low	*ppl/sq. km*
People Density-Open Air Medium	*ppl/sq. km*
People Density-Open Air High	*ppl/sq. km*
Pedestrian Dimensions	
Avg. Pedestrian Radius	*m*
Avg. Pedestrian Height	*m*

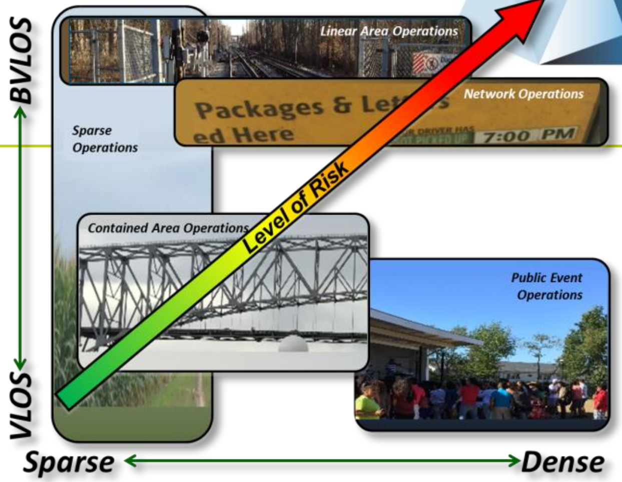
Mission Profile Input Variables	*Units*
People Density-Rural Low	%
People Density-Rural Medium	%
People Density-Rural High	%
People Density-Urban Lo	%
People Density-Urban Md	%
People Density-Urban Hi	%
People Density-Open Air Low	%
People Density-Open Air Medium	%
People Density-Open Air High	%
Mission Area-Length	*mi.*
Mission Area-Width	*mi.*
Second Party	*%*
Flight Duration	*min*
Mission Speed	*kts*
Mission Altitude	*ft*
Pedestrian Transit	*%*
Pedestrian Loiter	*%*
Pedestrian Fixed	*%*
Vehicle Transit	*%*
Vehicle Grid	*%*
Vehicle Hover	*%*

sUAS Risk Model Output & Application

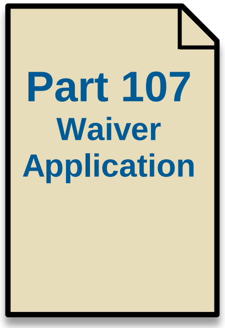
Risk Model Has Multiple Purposes



Assessing relative risk of Standard Mission Profiles



Evaluating risk of waiver applications

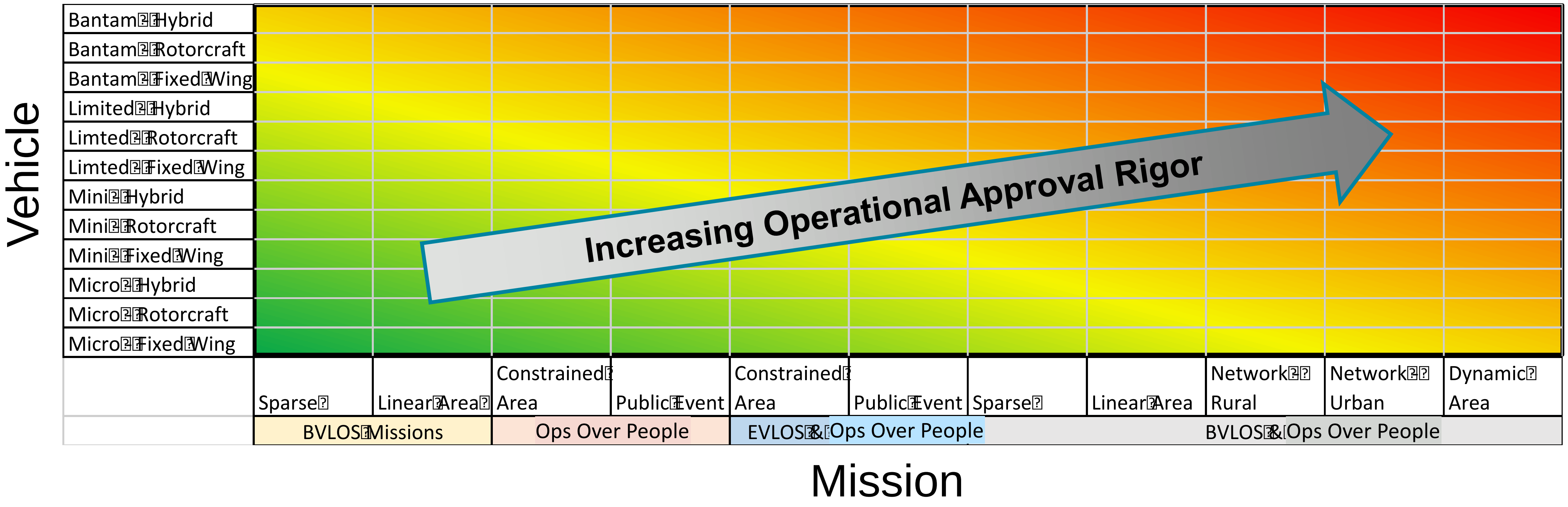


Informing sUAS performance standards and policy

Risk Framework Concept

– Risk is a function of **mission** profiles and **vehicle** profiles

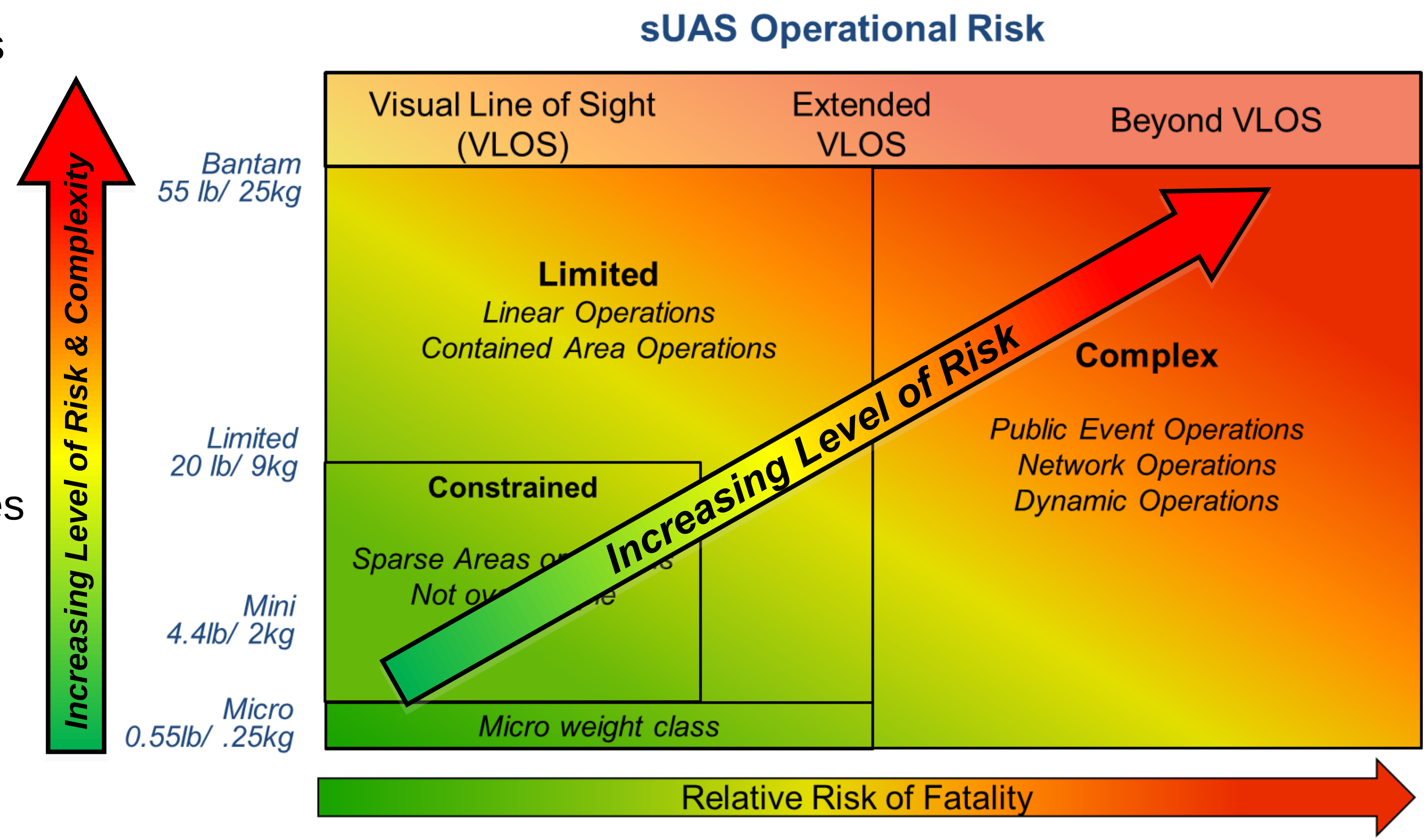
– This type of framework can streamline the sUAS approval process



Notional

Standard Mission Profiles Application

- FAA can classify applications based on standard mission profiles.
- Risk is a function of vehicle profiles and complexity of operation.
- Once relative risk of mission profiles is better understood, the FAA can expand the types of operations that don't need waivers, which will significantly streamline the approval process.



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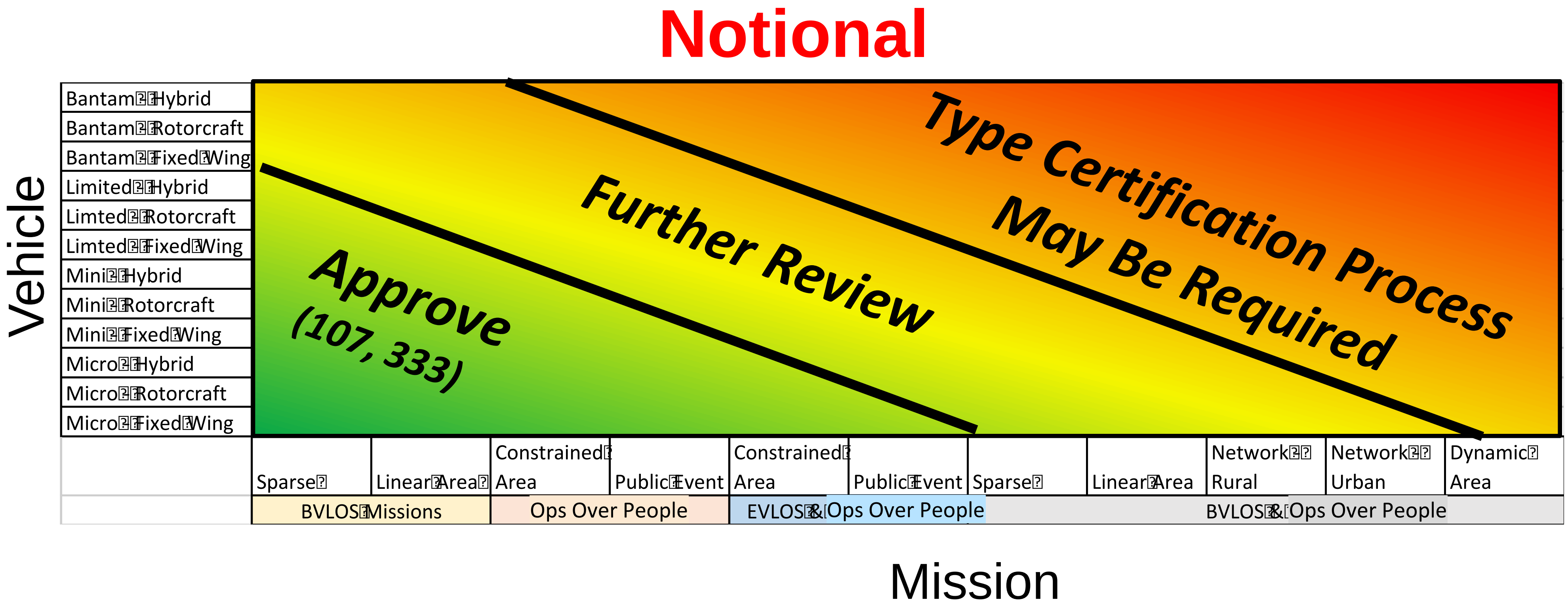
Concept Application –
Vehicle and Mission Risk Comparison

- Classify applications based on standard mission profiles and vehicles
- Risk is a function of vehicle profiles and complexity of operation
- Streamlined Approval Process based on defined risk analysis



Risk Model Interface

Profile Selection

Mission Profiles

- [ ] Dynamic BVLOS
- [ ] Contained EVLOS
- [x] Sparse VLOS
- [ ] Linear BVLOS
- [ ] Linear VLOS
- [ ] Public Event EVLOS
- [ ] Public Event VLOS
- [ ] Sparse BVLOS
- [ ] Contained VLOS

Vehicle Profiles

- [ ] Hybrid Mini
- [ ] Fixed Wing Mini
- [ ] Rotorcraft Limited
- [x] Fixed Wing Limited
- [ ] Rotorcraft Micro
- [ ] Fixed Wing Bantam
- [ ] Rotorcraft Mini
- [ ] Hybrid Limited
- [ ] Hybrid Micro
- [ ] Fixed Wing Micro
- [ ] Hybrid Bantam
- [ ] Rotorcraft Bantam

Load Custom Profile | Load Selected Profiles

sUAS Airworthiness Assessment Tool

Risk Assessment Input Parameters

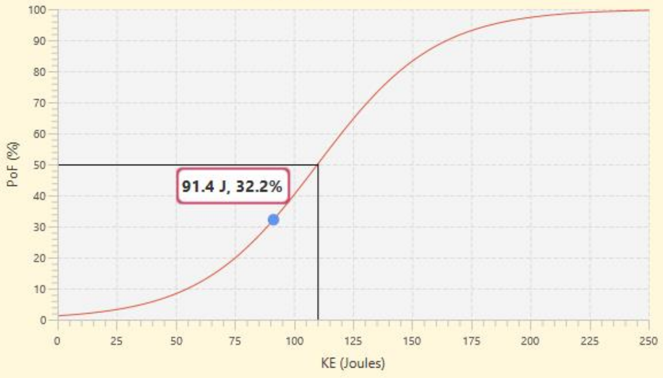
Field	Value	Unit
Type	Sparse	
Subtype	VLOS	
Mission Area Length	5	KM
Mission Area Width	5	KM
Loiter	40	%
Fixed	30	%
Transit	30	%

Mission Profile | Segments | Vehicle Profile | Coefficients

Reset | Load | Save

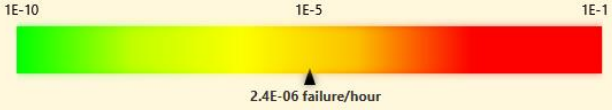
Calculate

Probability of Fatality



50% Probability of Fatality at 110 Joules

Risk Meter



Sensitivity Analysis

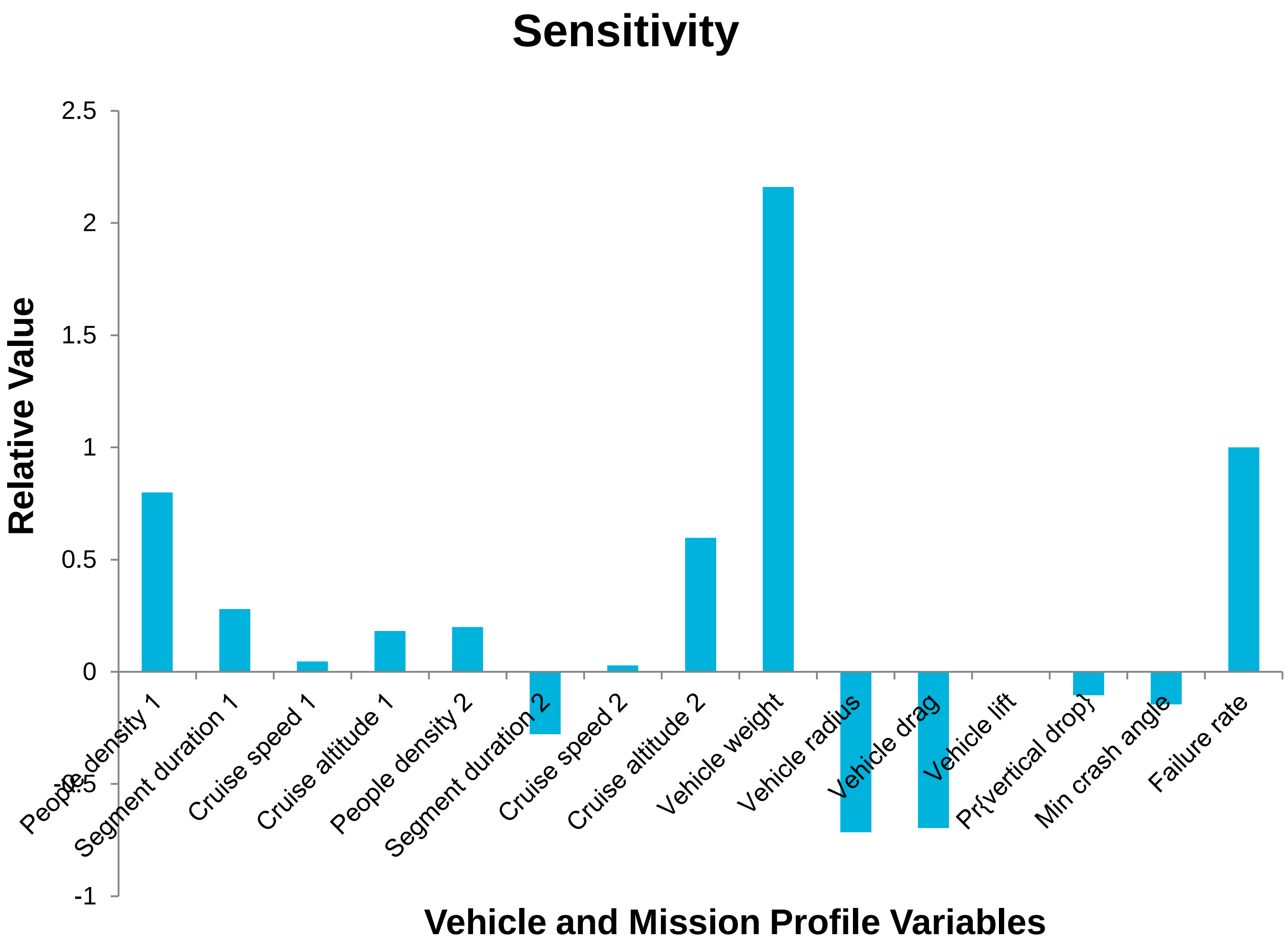
Sample Mission Image
Sparse

Sample Vehicle Image
Fixed Wing Limited

Notional

Mission Profile/Vehicle Variable Sensitivity Analysis

- **Sensitivity Analysis**
  - Identifying the critical variables that have the most impact in driving the level of risk of the operation
  - Provide focus on areas that can provide the highest safety return
  - Exploring the addition of the Kinetic Energy value (Joules) in sensitivity analysis



Notional

Next Steps

Phased Research Approach *Moving to Real-Time Risk Management*

Phase 1 – Near-Term	Phase 2 – Mid-Term	Phase 3 – Far-Term
Standard Mission Profiles	Planned Mission Profiles	Active Mission Profiles

Pre Approval (long lead time) → *Real-time Approval (Just before mission)*

Long-Term Application Concept

- **Manufacturers design vehicles to meet published performance standards**
- **Vehicles indicate approved uses**
- **Operators purchase vehicle for intended mission**
- **Enforcement based on approved missions**

Approved Missions

Ongoing Collaboration

- Concept Approach
- Risk Model Development
- Vehicle and Mission Profile Attributes and Data
- Concept Applications
- Standards Development

Questions

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September 26th, 2017

MITRE Corporation