A UAV MISHAP TAXONOMY FOR RANGE SAFETY REVIEWS

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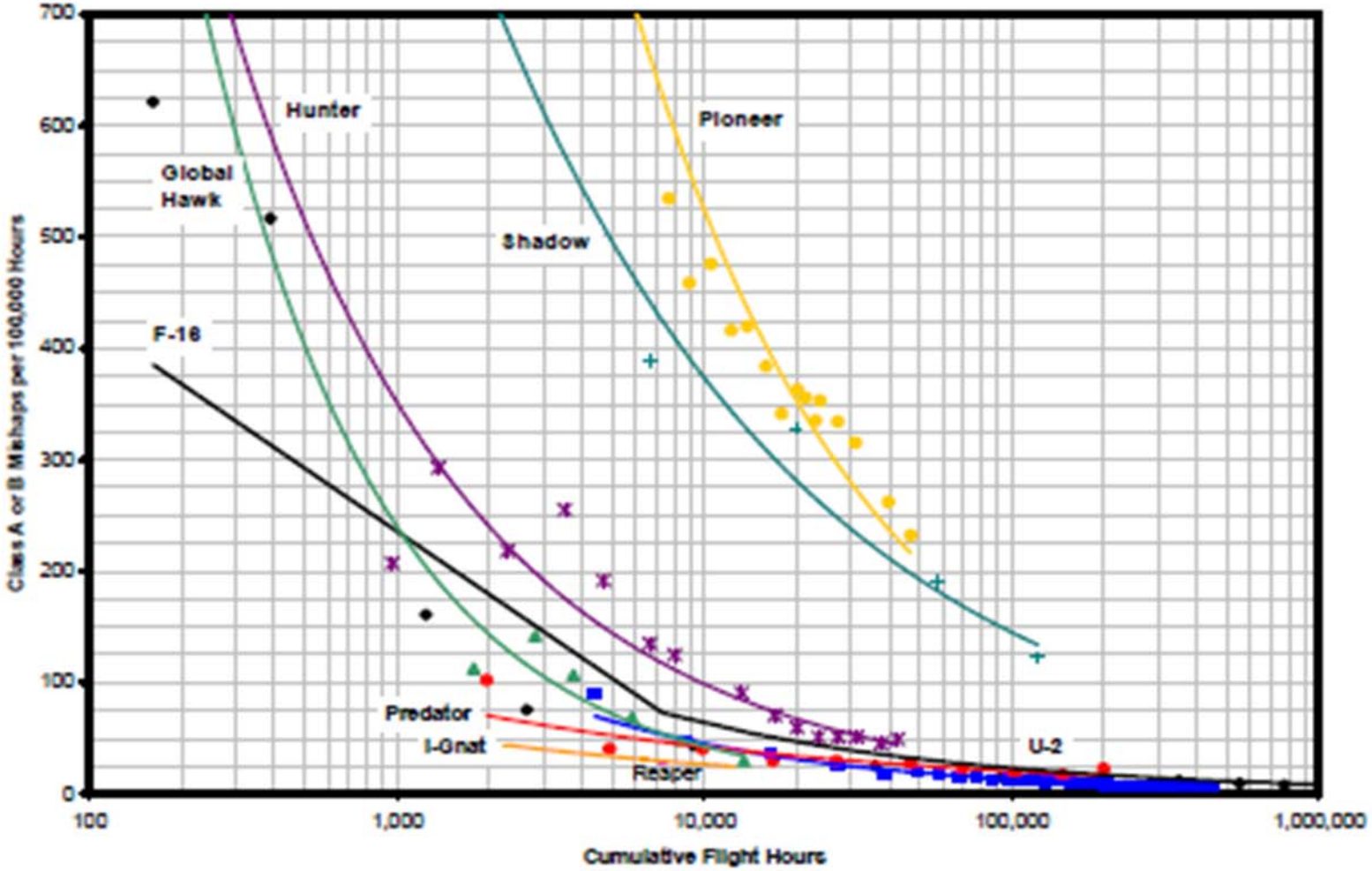
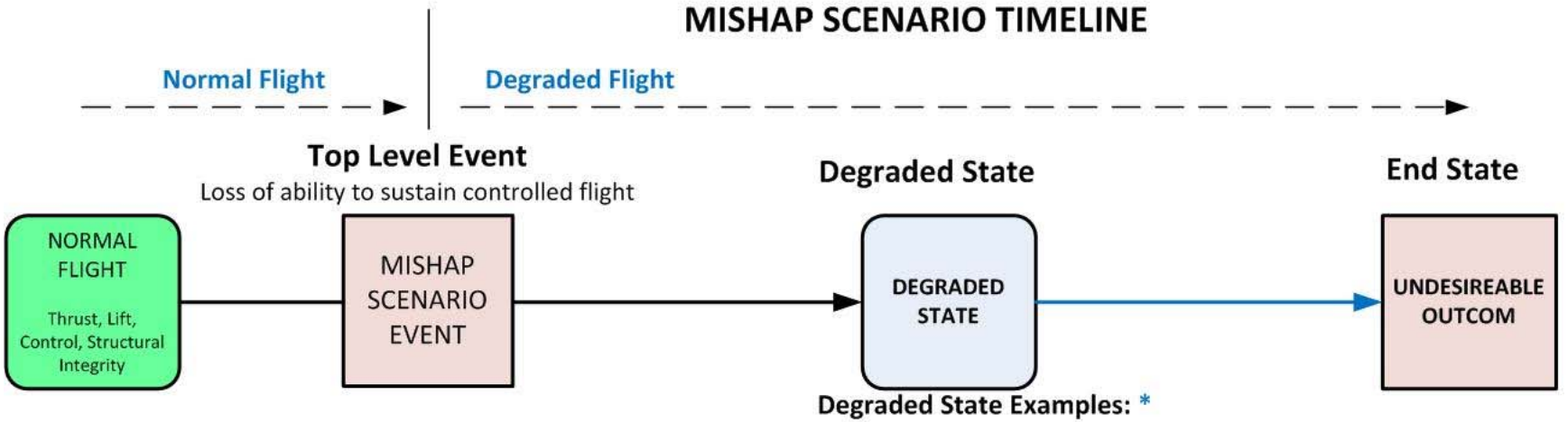
Mishap Rate Comparison

U.S. Military Aircraft and UAS Class A Mishap Rates (Lifetime), 1986-2006



Risk of encountering unknown hazards is more significant early in life

Source OAS UAS Roadmap 2005



Degraded State Examples: *

Cause scenario category
- Material failure,
- Operator vehicle interaction,
- Airfield facility,
- Environment,
- Multiple users,
- Aircraft separation

Degraded States
- Precautionary RTB
- Lost Link
- Glide
- Deploy Parachute
- In flight fire

Worsening Condition
- Undirected Glide
- Ditch / Forced landing

Terminal Degraded States
- Depart Controlled Flight
- In Flight Breakup
- Parachute Failure
- Uncontrolled crash
- Controlled crash / FTS

End State Examples:
- Vehicle loss or damage
- Property damage
- Death or injury,
- Midair, NMAC, airspace risk
- Security compromise
- International incident

* Not all inclusive

"All models are wrong; some are useful."
George Box, Statistician

UAV Mishap Taxonomy as a Range Safety Tool

A mishap taxonomy is useful in dividing the large question:

"**Is this vehicle safe to test on this range**?"

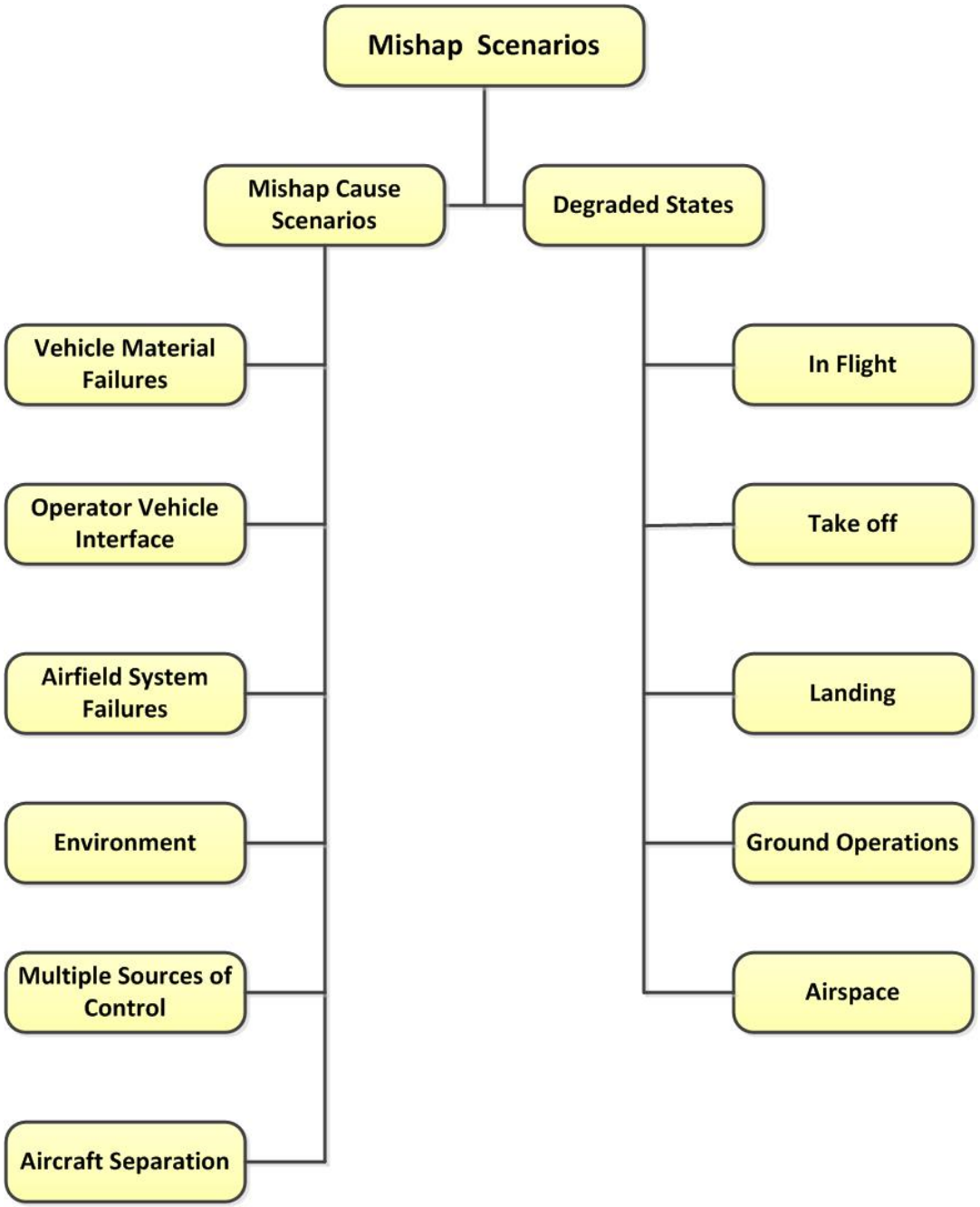
into a series of smaller, more manageable questions:

- What are the hazards that might be encountered?
  - Is there a list of all hazard scenarios? Can this list be tailored?
  - What hazards are already addressed by the Designer and Test team?
  - Do local conditions (population, unique property and airspace) add risk?

- If a hazard is encountered and the vehicle is no longer capable of normal flight, is the Range prepared for the outcome?

A mishap taxonomy also:

- Explicitly provides support for safety reasoning
- Makes the Range Safety process transparent
- Organizes and categorizes mishap data in a useful way


Mishap Scenarios
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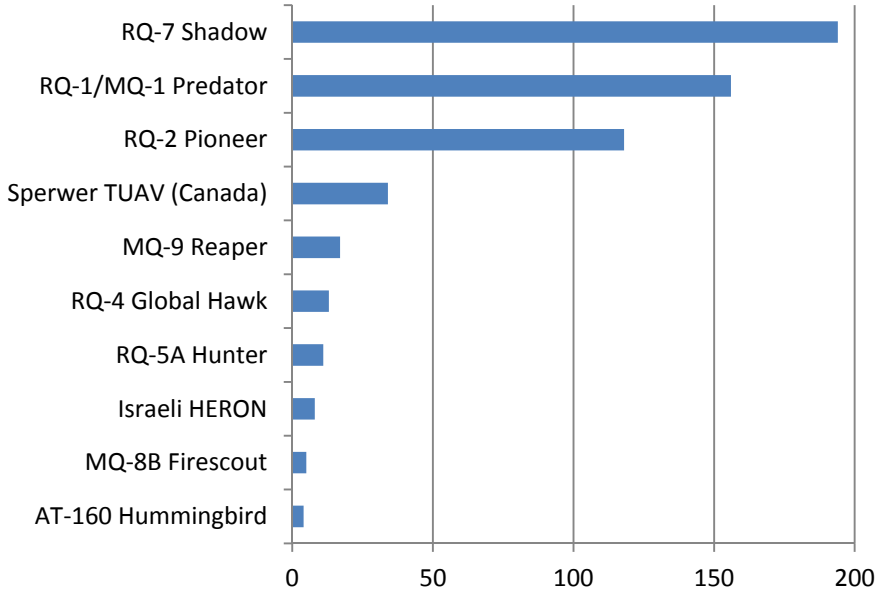
Ground Operations
Airspace

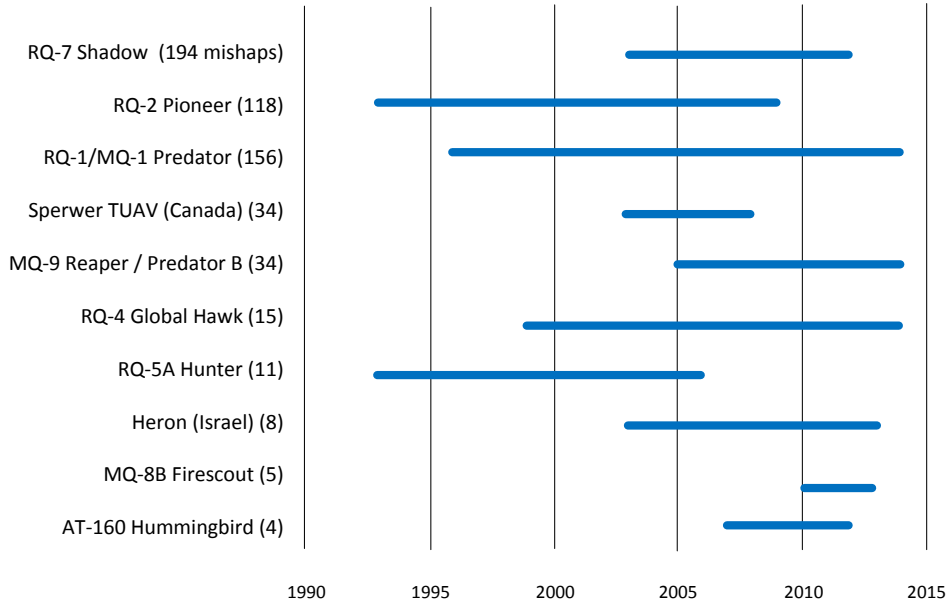
Mishap Data Used

1991-2013

Mishaps by Type Vehicle



Data availability by vehicle and year

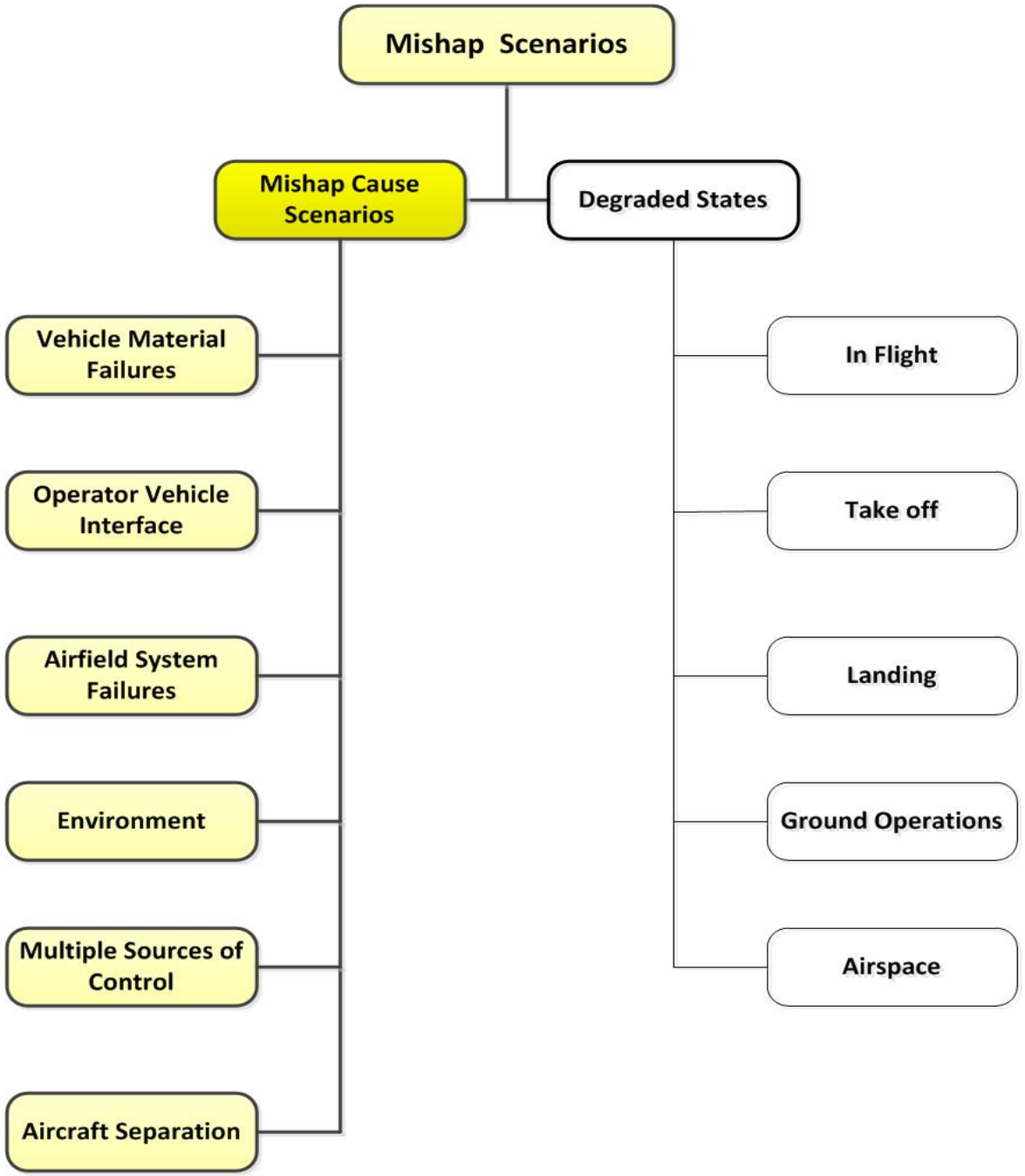


Two mishaps each for RQ-21 Integrator, Turkish ANKA, MAVUS, CL-227 Sentinel, and NASA Perseus

One mishap each for Bell Eagle Eye, Belgian B-Hunter, BQM-147 Exdrone, CL-327 Guardian, CL-427 Puma, Global Observer, H450 Hermes, NASA Helios, KMAX, German Luna, MQ-1C Grey Eagle, P-175 Polecat, NASA Perseus A, Raytheon Cobra, RQ-3A Darkstar, S-100 Camcopter, and NASA Theseus.

Distribution is a reflection of availability of data as well as specific vehicle mishap rates

Data is from DOD Safety Centers, NASA Dryden, NTSB, and news reports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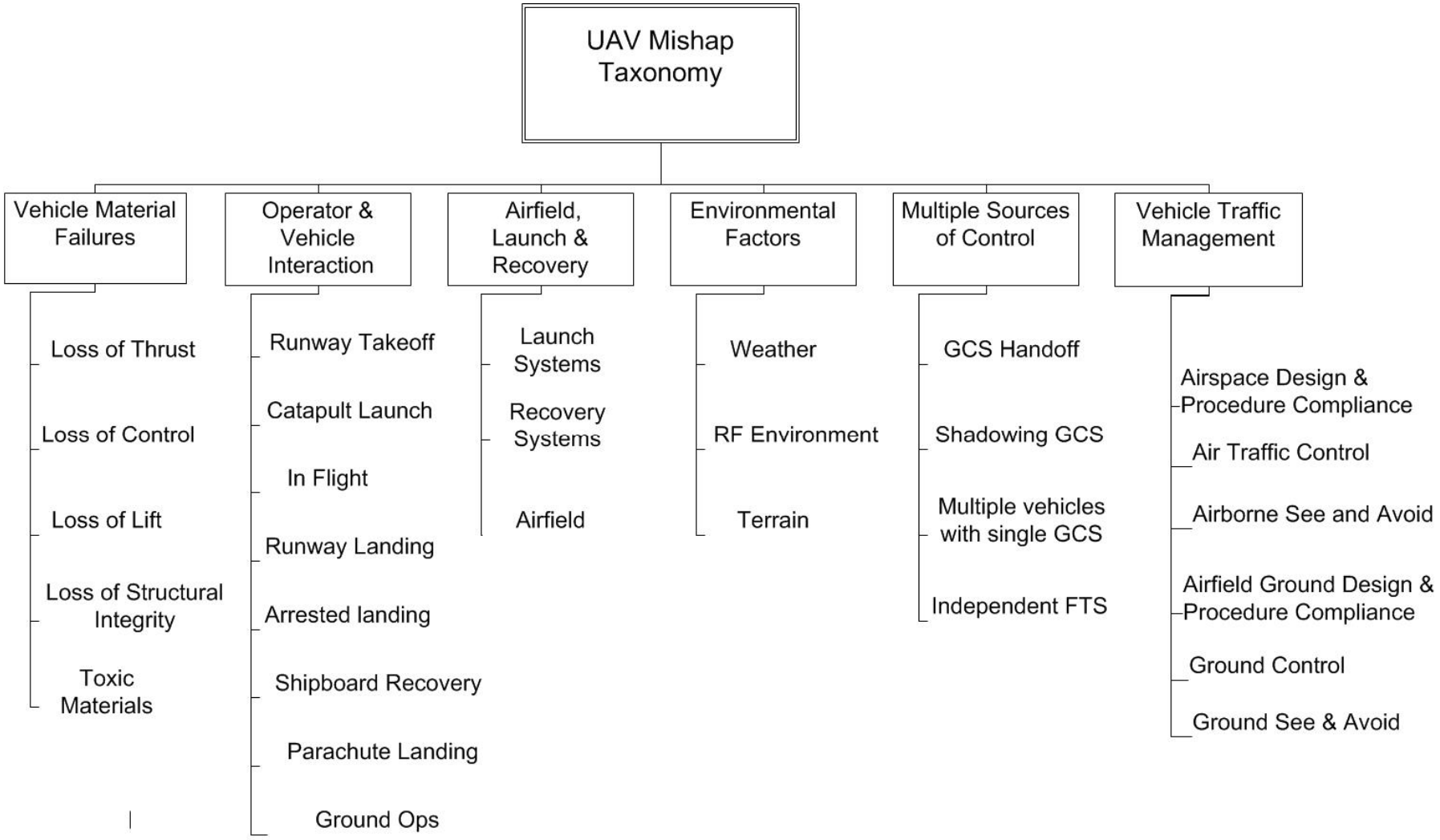
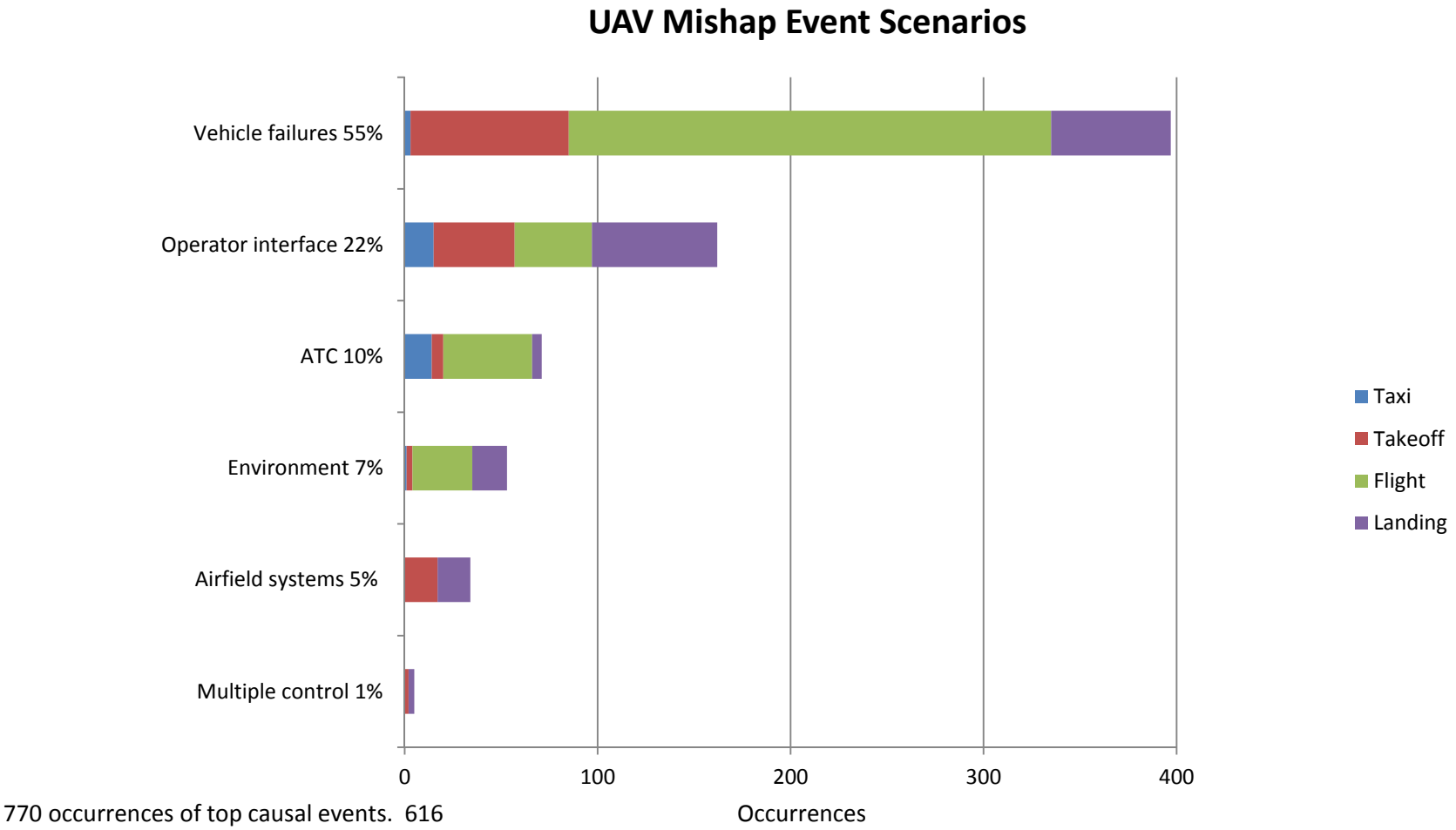
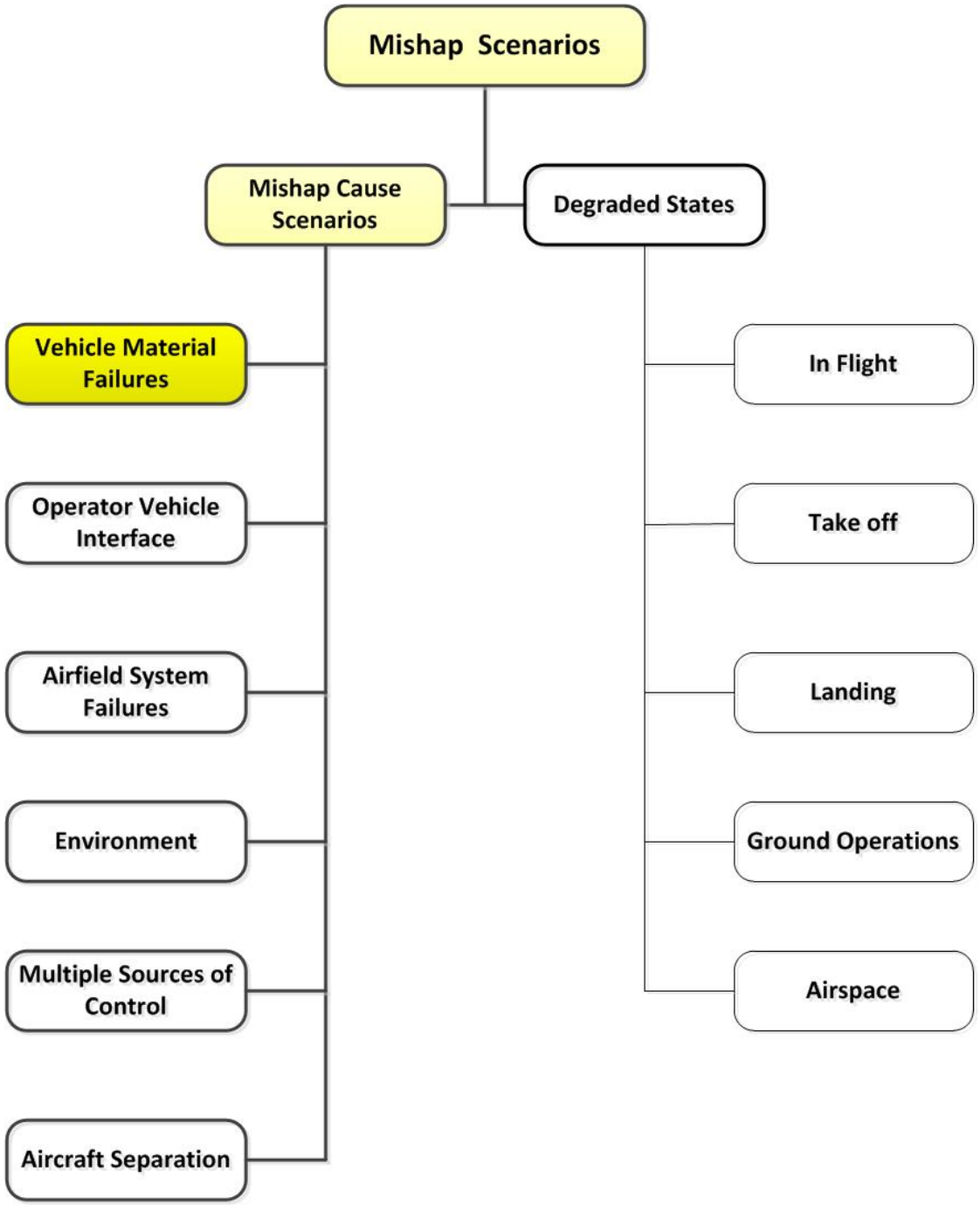
Categories of UAV Mishap Event Taxonomy



Top Level Event Scenarios by Category and Phase of Flight



770 occurrences of top causal events. 616 mishaps total. Some mishaps had multiple key causal scenarios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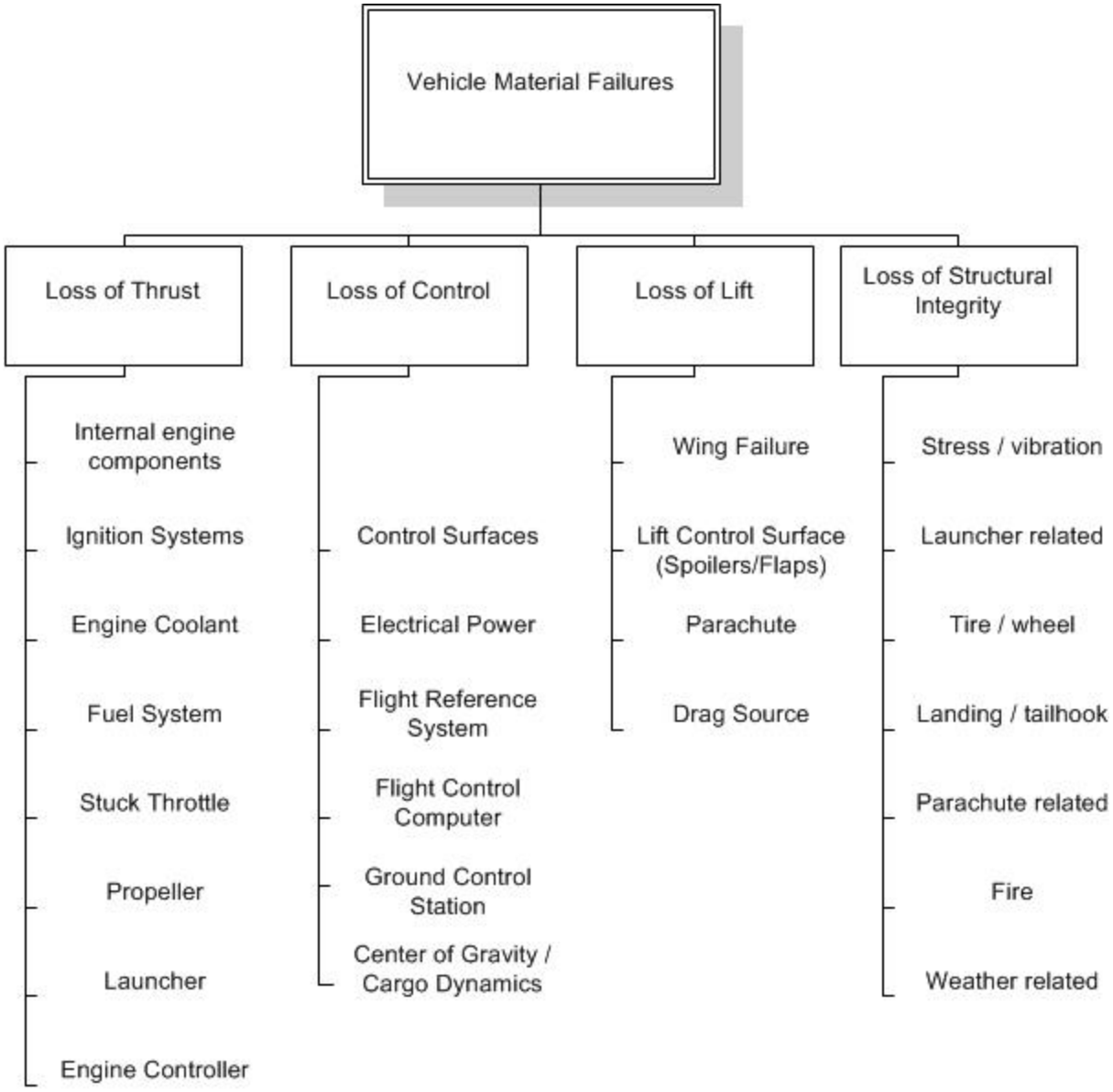
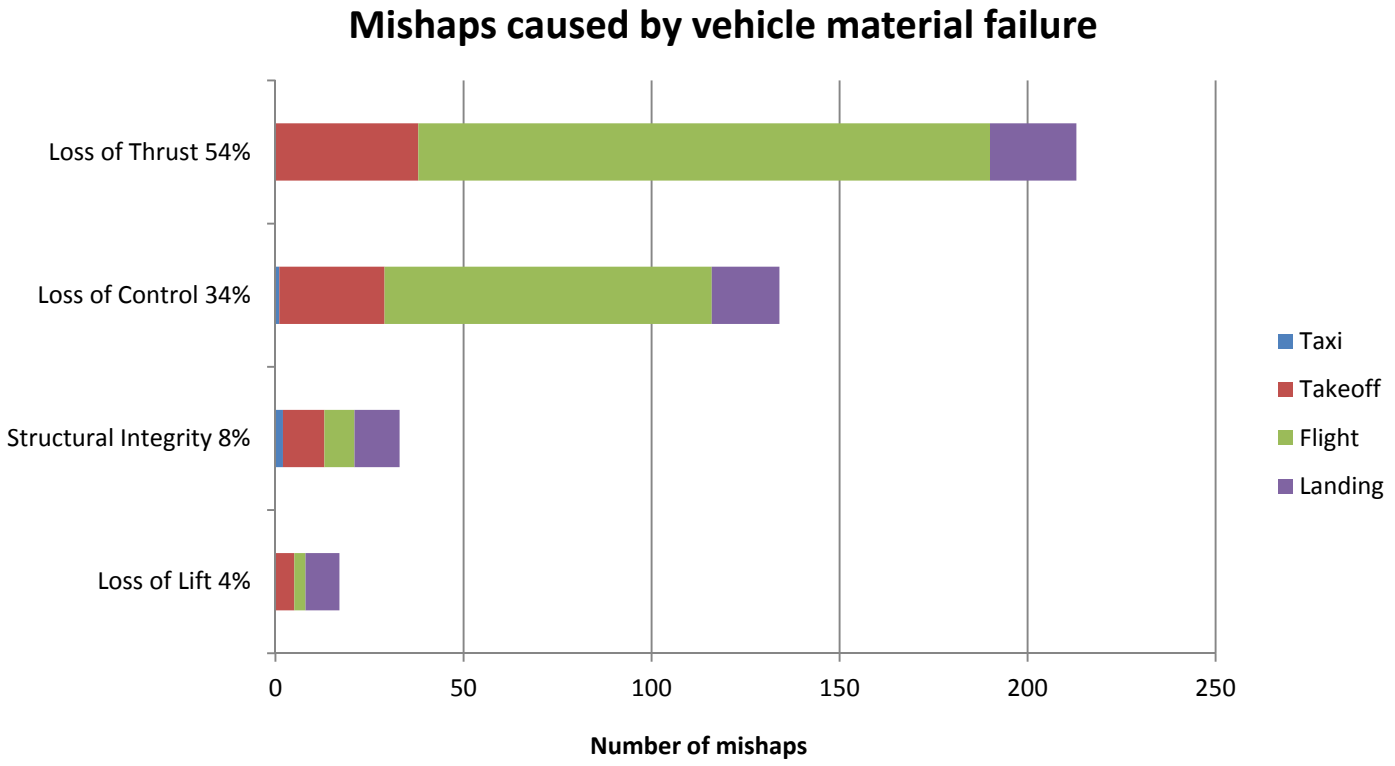

Vehicle Material Failures
Loss of Thrust
Loss of Control
Loss of Lift
Loss of Structural Integrity
Internal engine components
Ignition Systems
Engine Coolant
Fuel System
Stuck Throttle
Propeller
Launcher
Engine Controller
Control Surfaces
Electrical Power
Flight Reference System
Flight Control Computer
Ground Control Station
Center of Gravity / Cargo Dynamics
Wing Failure
Lift Control Surface (Spoilers/Flaps)
Parachute
Drag Source
Stress / vibration
Launcher related
Tire / wheel
Landing / tailhook
Parachute related
Fire
Weather related

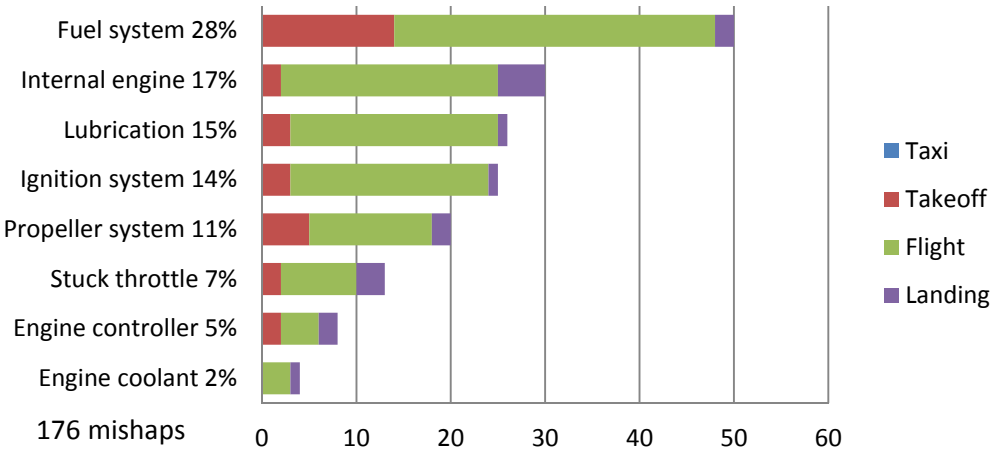


"Sustained flight is only possible when the structure of the aircraft is intact and the forces of lift, thrust, and control are sufficient to maintain the desired altitude, speed, and attitude. Consequently, the essential functions of flight are structural integrity, and lift, thrust, and control [x]"

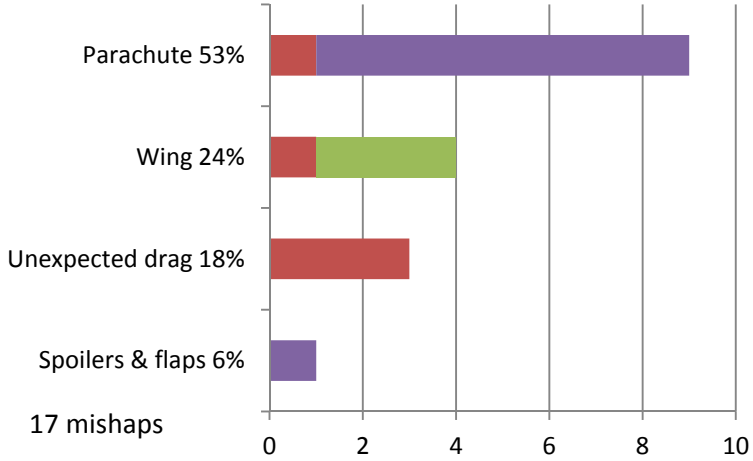
(x) Ball, Robert E., THE FUNDAMENTALS OF AIRCRAFT COMBAT SURVIVAILITY ANALYSIS AND DESIGN, SECOND EDITION, AIAA 2003

Categories of material failures

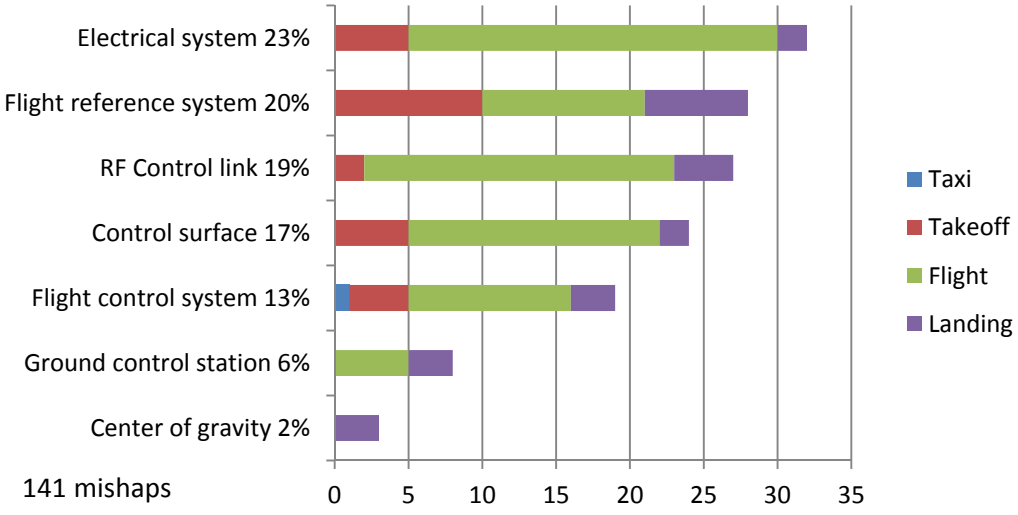
Loss of thrust failures



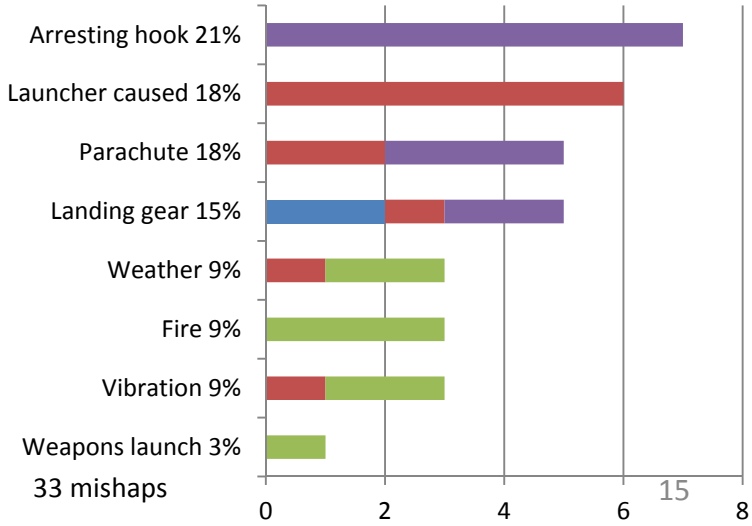
Loss of lift



Loss of control failures



Loss of structural integrity



Example scenario narrative: Loss of Lubrication

Scenario:
Loss of engine lubrication results in reduced engine performance or engine failure and loss of thrust.

There were 22 mishaps in our sample which can be characterized as loss of thrust due to loss of engine lubrication, affecting six different types of vehicles.

Typical lubrication-related mishaps involved oil starvation (engine no longer supplied with lubricating oil). Oil starvation caused engine temperatures to rise, reduced engine RPMs and corresponding thrust to be reduced, or if the engine seized lost thrust.

- Failure to service the oil system before flight
- Failure to check the oil level before flight
- Oil leak (loose bolts, oil filter, or oil seal failure)
- Oil flow blockage (oil filter clogged, thermo control valve installed incorrectly)
- Scavenge pump failure
- Oil pump drive belt failure
- Oil tube to engine came loose during pneumatic launch

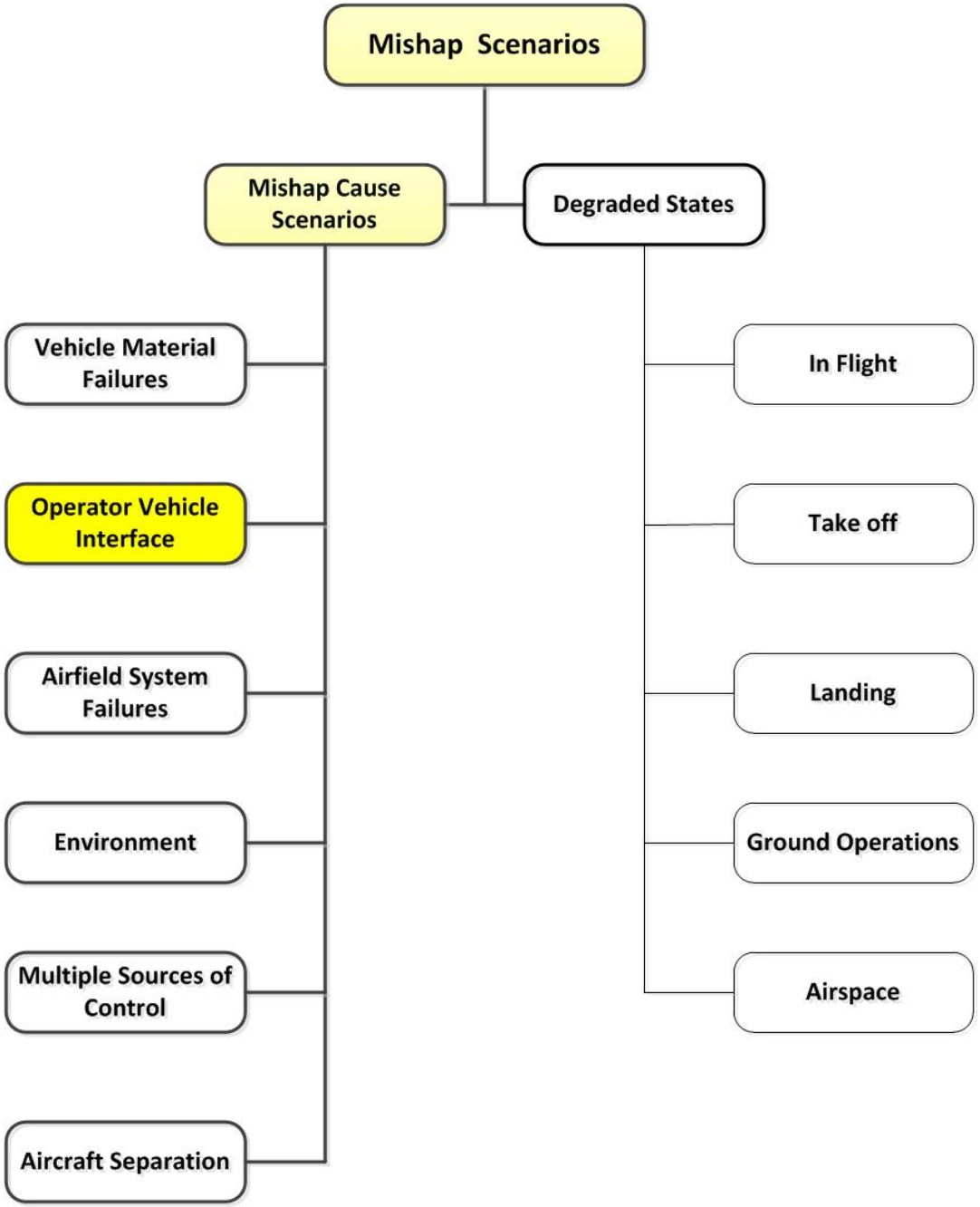
Lubrication-related damage to engines was experienced on some vehicles by unfiltered air mixing with oil in a dust-filled environment. The particles in the oil acted like “liquid sandpaper,” damaging the moving internal engine parts.

Examples of vehicle material failures

GCS Failure

Structural failure and in-flight breakup

Undirected glide after lost link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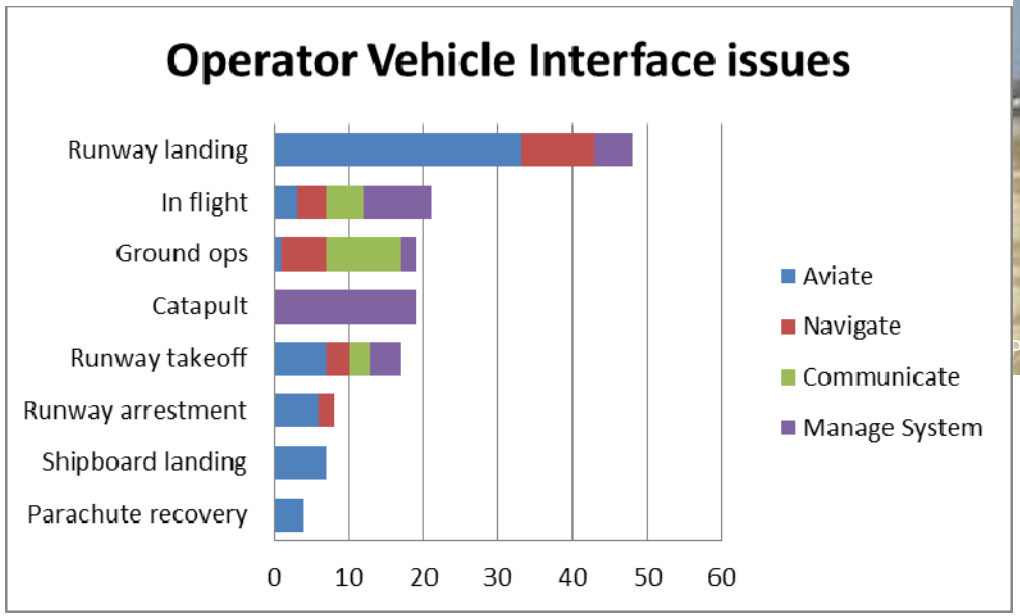
Operator Vehicle Interface

UAV operator decisions and tasks that have led to a hazardous situation or mishap.

- **Aviate tasks**: Takeoff rotation, night ops, landing technique, mode confusion, switch selection errors, proficiency and total experience
- **Navigate tasks**: Takeoff distance calculation, emergency mission planning, automated mission planning errors, and battery power remaining vs. distance to base
- **Communicate tasks**: non-standard terminology, non-compliance with ATC, foreign controllers
- **Manage system tasks**: Checklist errors, wrong mission plan, and switch setting errors



Takeoff distance calculation error resulted in late takeoff abort and forced landing in populated area. One fatality and two severe burn injuries.

Operator Vehicle Interface (continued)

Aviate, Navigate, Communicate, And Manage Systems Tasks

Aviate. Control the vehicle's path

- Maintain altitude, heading, air speed, pitch, roll, vertical velocity, etc. within safe limits
- Avoid obstacles in vicinity of flight path
- Detect and avoid other aircraft
- Perform emergency maneuvers, waveoffs, or runway aborts as necessary

Navigate. Direct the vehicle from its origin to its destination; awareness of aircraft position in relation to its desired trajectory

- Plan/update flight plan considering mission, environment, resources, and vehicle health
- Global awareness of the environment from origin to destination, as well as contingency destinations (routes, special-use airspace, boundaries, weather, geographic obstacles, etc.)
- Local guidance (i.e., to the next waypoint)
    - Current position
    - Runway site survey, runway selection for current wind conditions
- Make performance calculations as necessary
    - Takeoff distance
- Plan/update contingency routes for emergencies or lost link

Communicate. Provide data and requests; receive instructions and flight-related information

- Communicate with airspace authority (i.e., civil or military Air Traffic Control)
- Monitor weather information for route and destination
- Communicate with other GCS for turnover

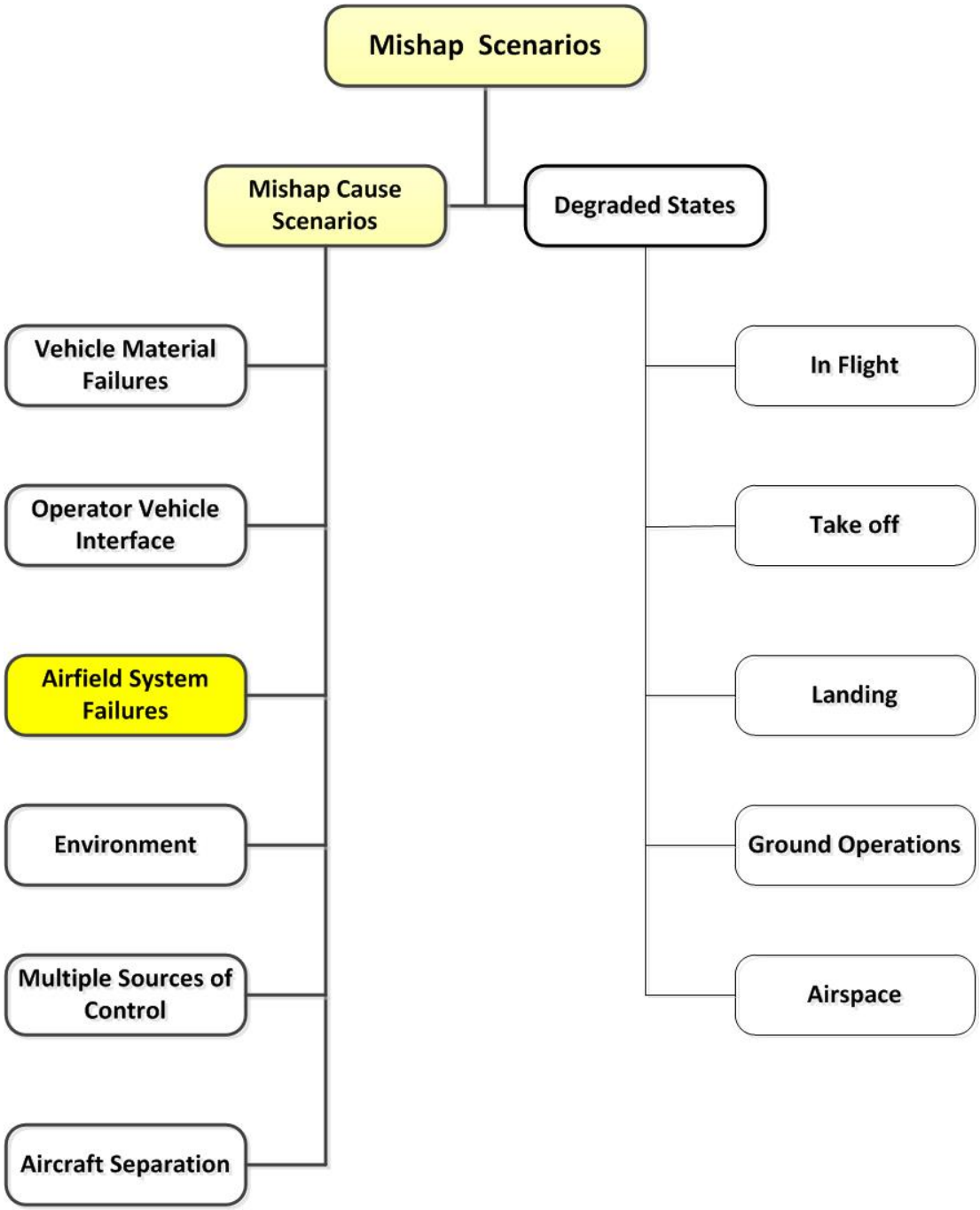
Manage Systems. Manage the configuration and resources available

- Update vehicle configuration for phase of flight
- Monitor vehicle health status
- Monitor fuel quantity

Operator Vehicle Interface (continued)

Additional Issues

- Missing performance information on new systems
- Training gaps
- Student pilot experience
- Experienced pilot negative training
- Checklist issues – skipping steps
- Mode confusion
- Lack of sensor feedback
- System latency
- Pilot induced oscillation
- Unique situations task difficulty
  - External pilot, night, wind, ship
- Lack of “air sense” feedback
  - No “seat of the pants” sense
  - Touchdown, engine sounds
- Checking of automated mission planning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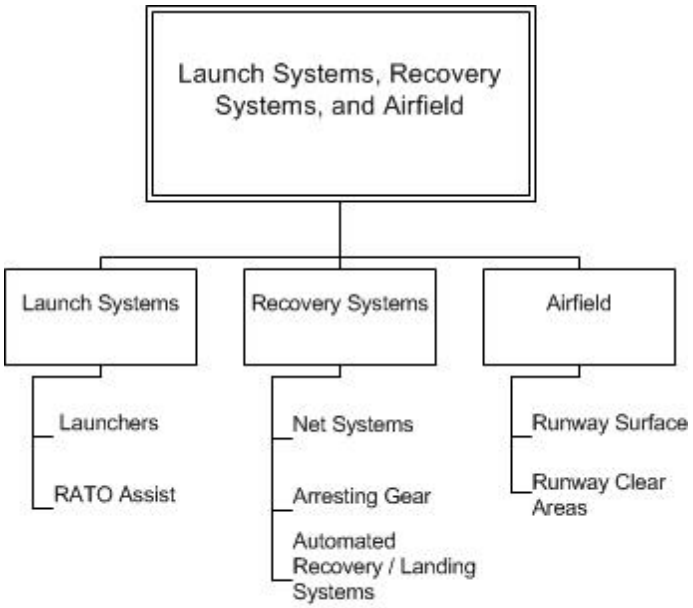
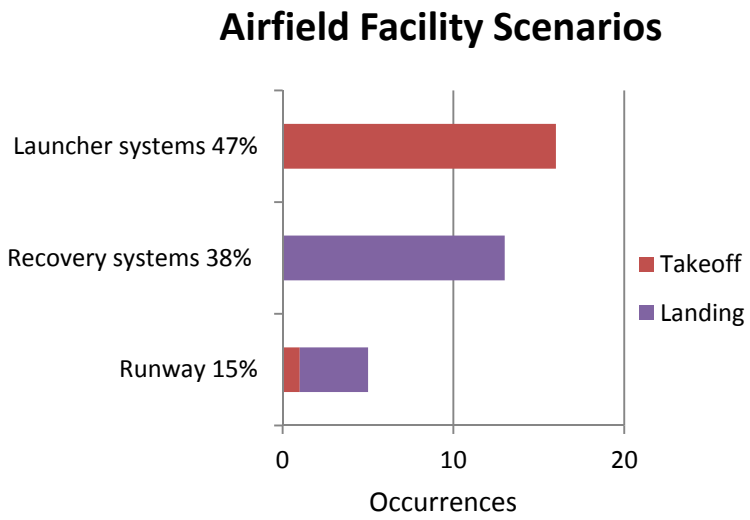
Airfield and Support Equipment Related Mishaps

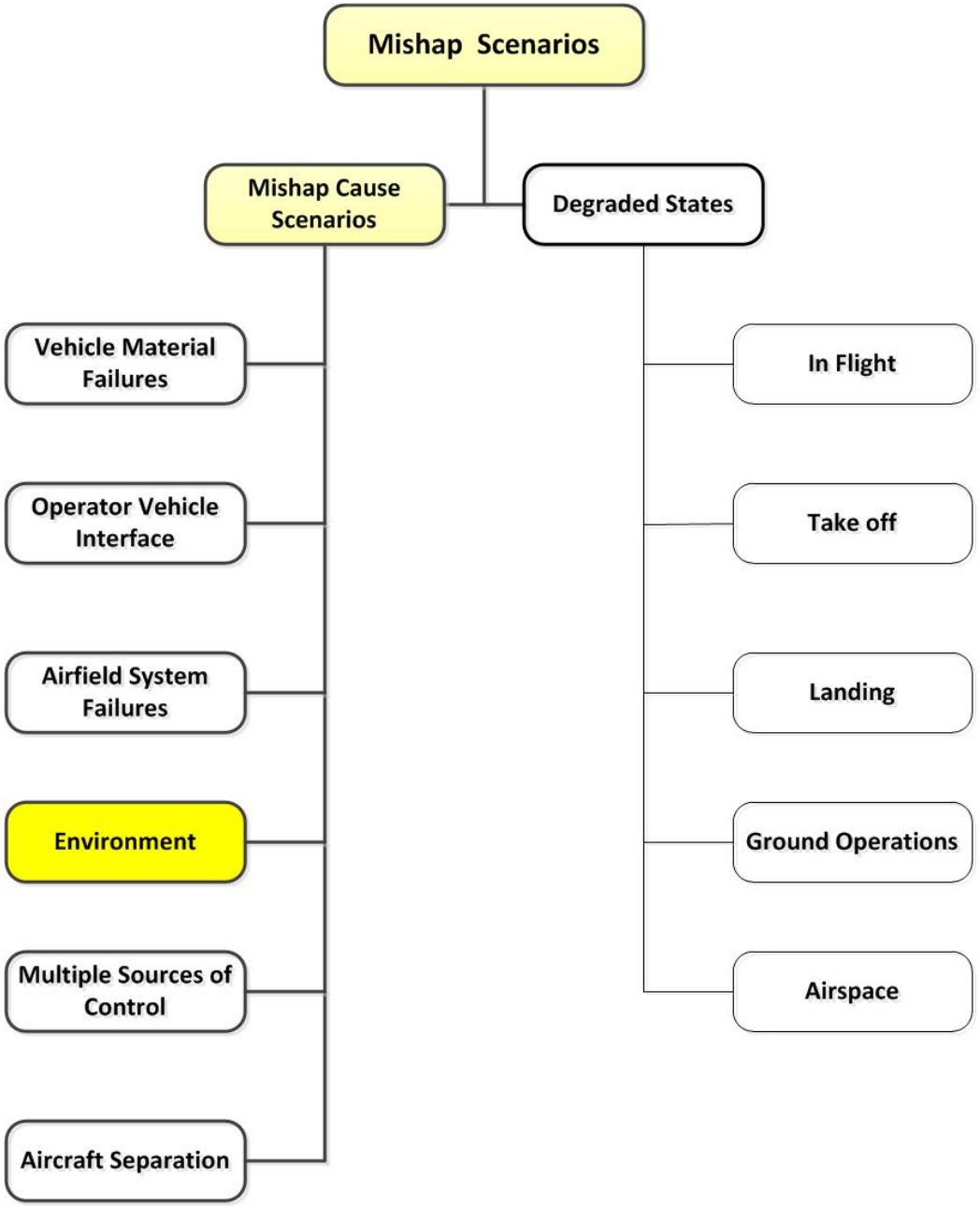
Some UAV mishaps were due to failures of launch or recovery equipment, airfield obstacles in the flight path, or the quality of the runway surface.





Takeaways:

- Ensure launch and recovery paths are clear of obstacles and populated areas
- Launch and recovery systems need to be considered on preflight as well as the vehicle
- Runway surface for manned vehicles may not be adequate for smaller wheels and tailhooks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Environment

Weather

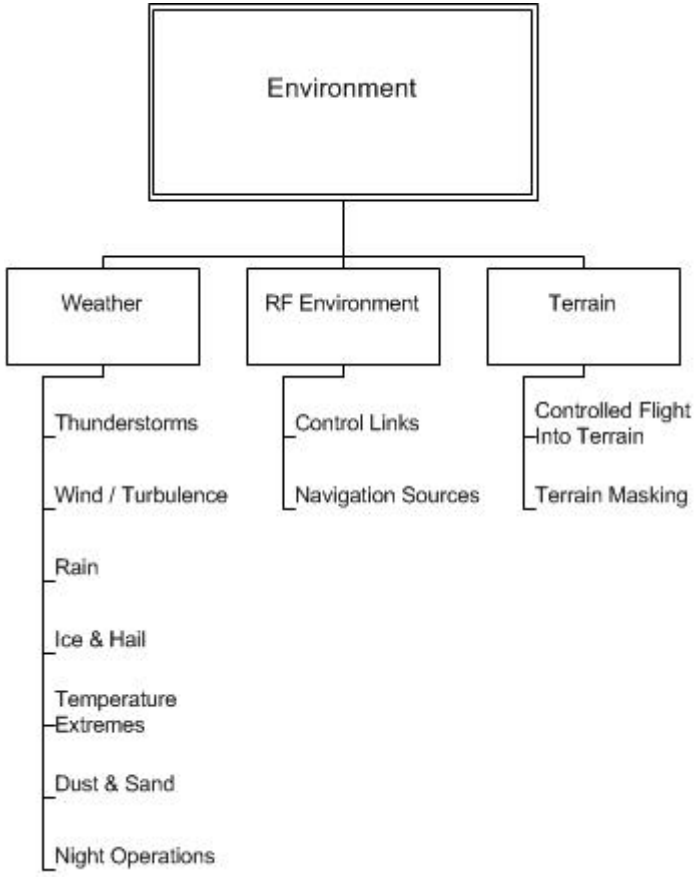
- The local weather damages or destroys the vehicle

RF environment

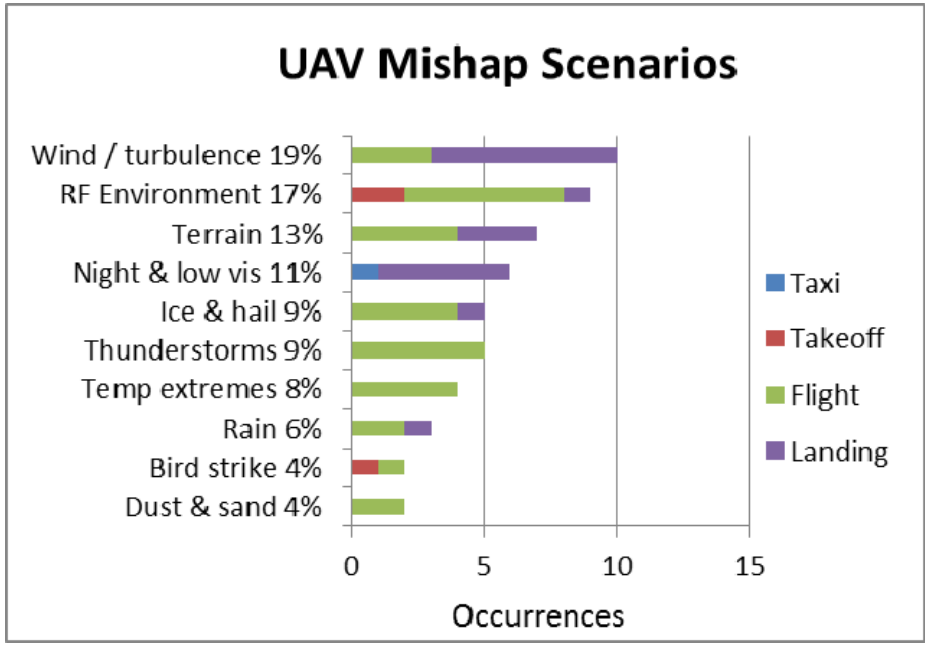
- Other RF transmitters interfere with the vehicles control, navigation, or ability for crews to communicate with other crews

Geography

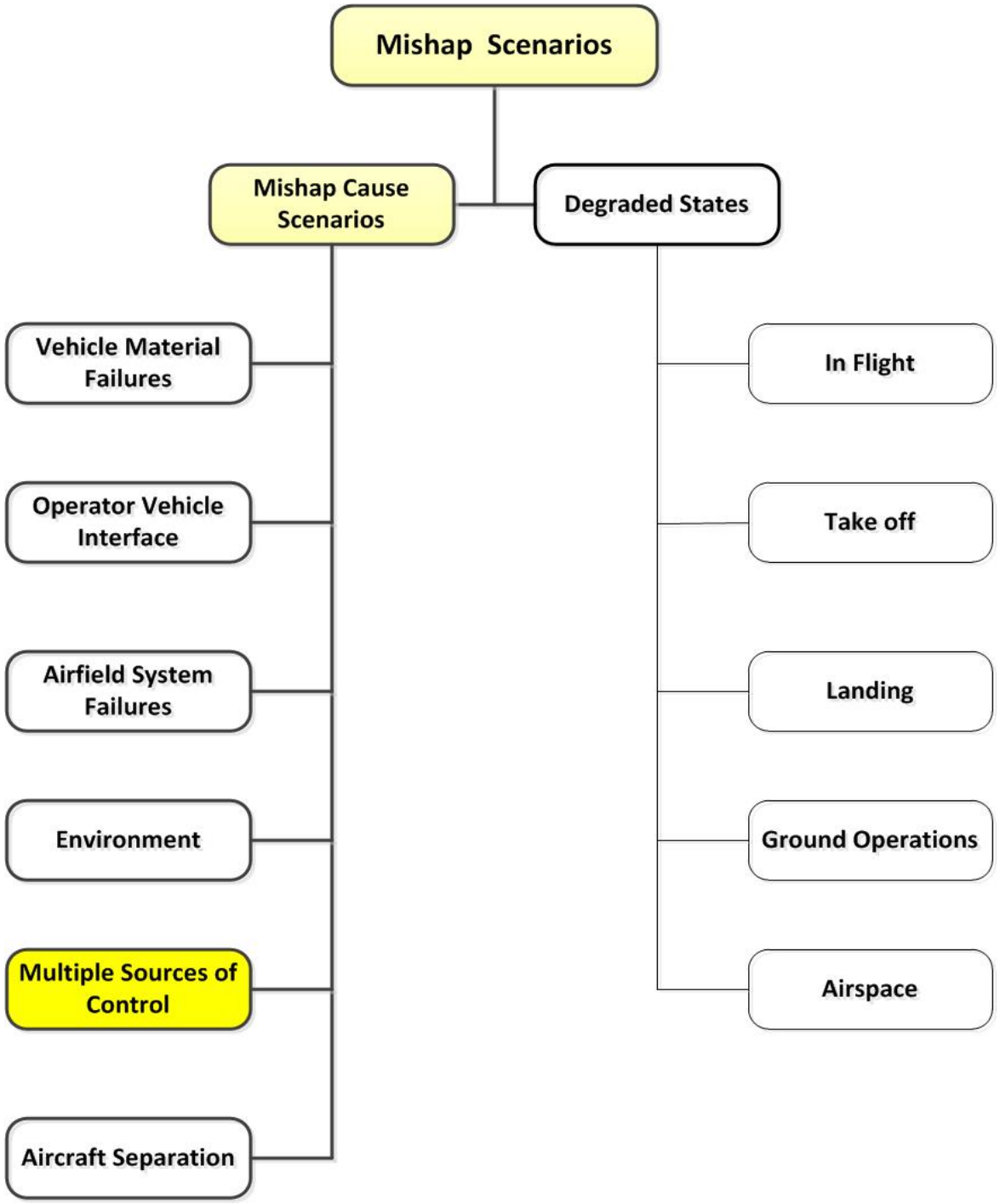
- Mountains or hills block RF line of sight
- Navigation route does not account for mountains or towers



Environment Mishap Scenarios



RF environment caused Camcopter loss of control, impacted GCS, and one fatality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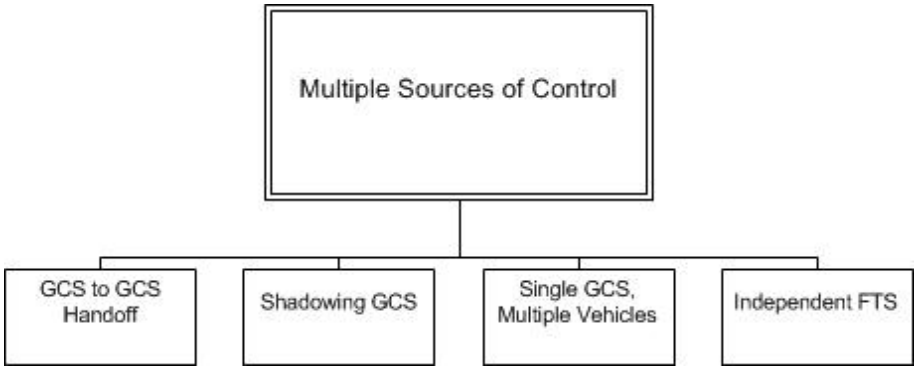
Multiple sources of control



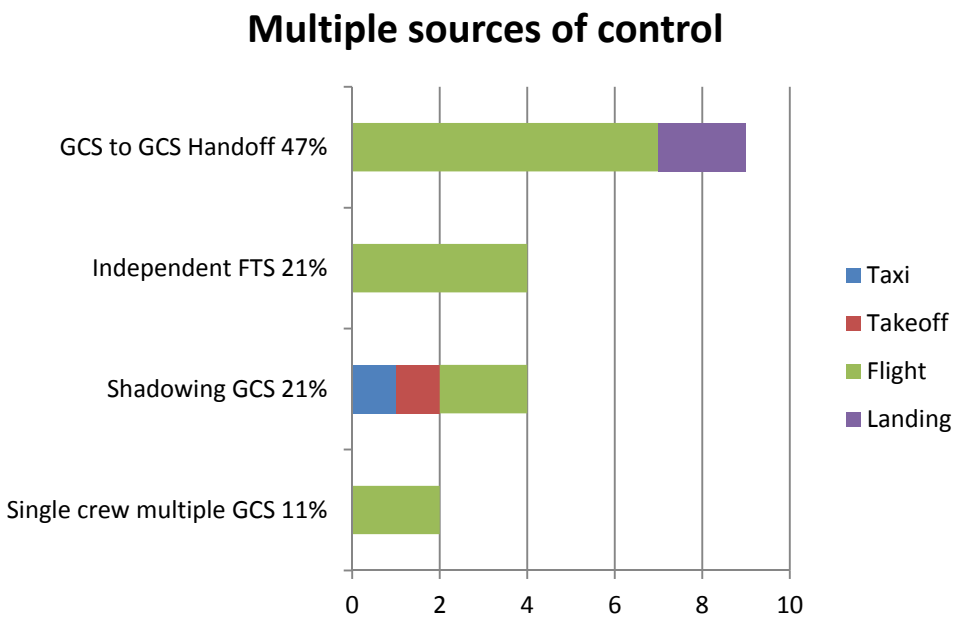
GCS to GCS Handoff
Handoff of vehicle from one ground control station to another creates a hazard if the information is incomplete or erroneous.

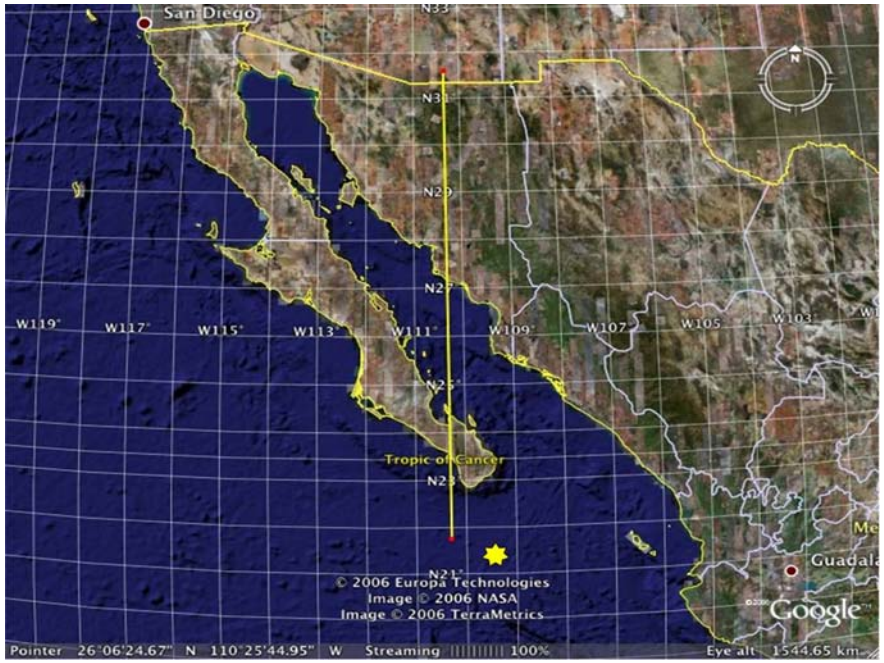
Shadowing GCS
A second ground control station creates a hazard if it jams or accidentally takes control of the UAV.

Single crew with multiple UAVs
A single GCS attempting to control multiple UAVs by time-sharing the monitoring and control function creates a situation where one UAV is airborne but not being monitored.

Independent FTS
An independently controlled flight termination system can create a hazard by accidentally terminating a vehicle.

Multiple sources of control

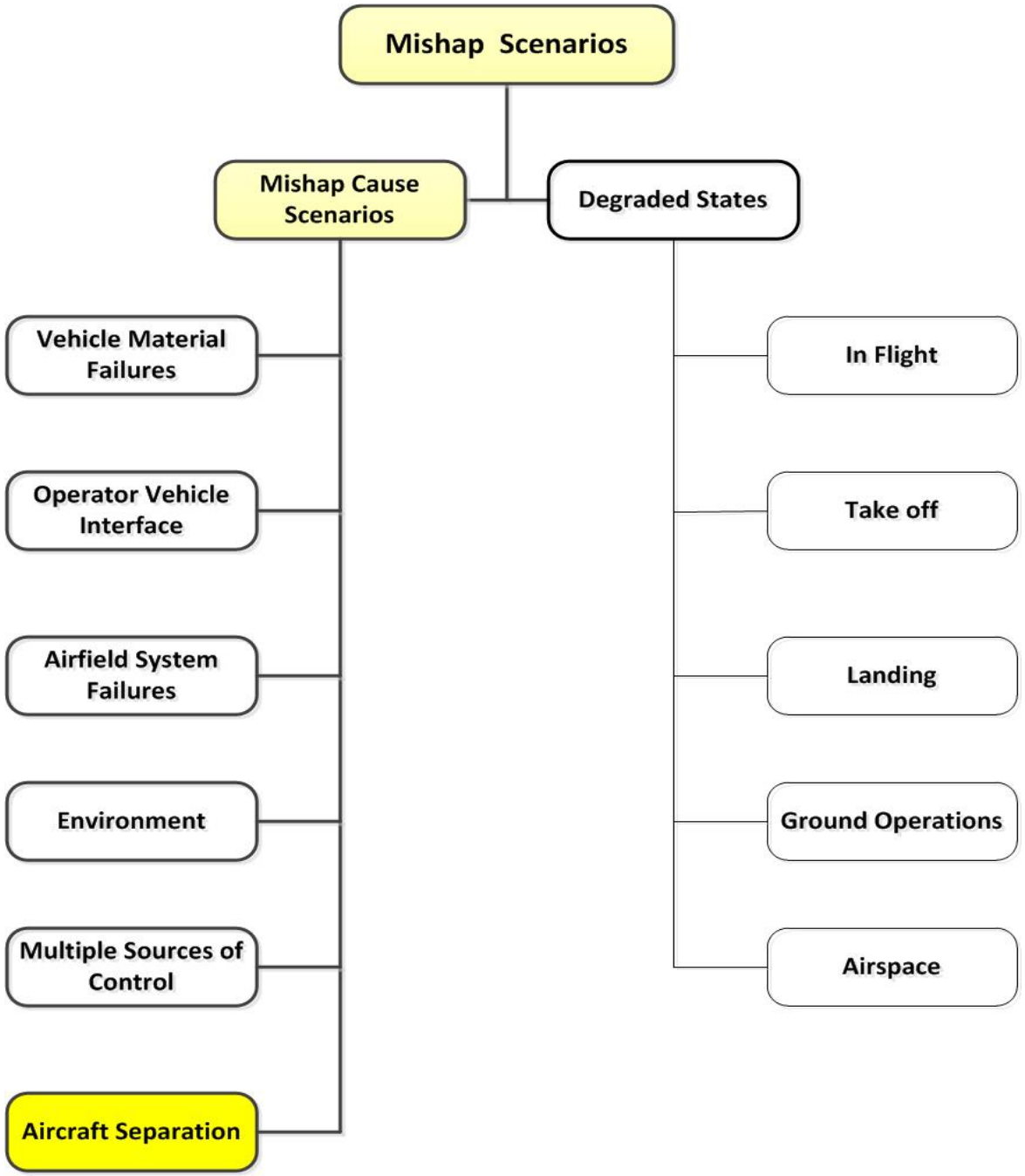




Route accidentally taken when trying to control multiple UAVs

Some incidents:

- Shadowing GCS left on for safety / backup purposes left the transmitter on. Shadowing GCS took control away from the controlling aircrew during taxi and the UAV crashed into a fence.
- During demo of single GCS with multiple UAVs, the fly home location was entered with 10 degree error in latitude. When GCS switched to control the second UAV, the first UAV flew to an erroneous fly home location 600 miles to the south.
- A UAV in flight and under test received FTS ARM and TERMINATE commands from another range performing ground tests on a different vehicle. The UAV was lost.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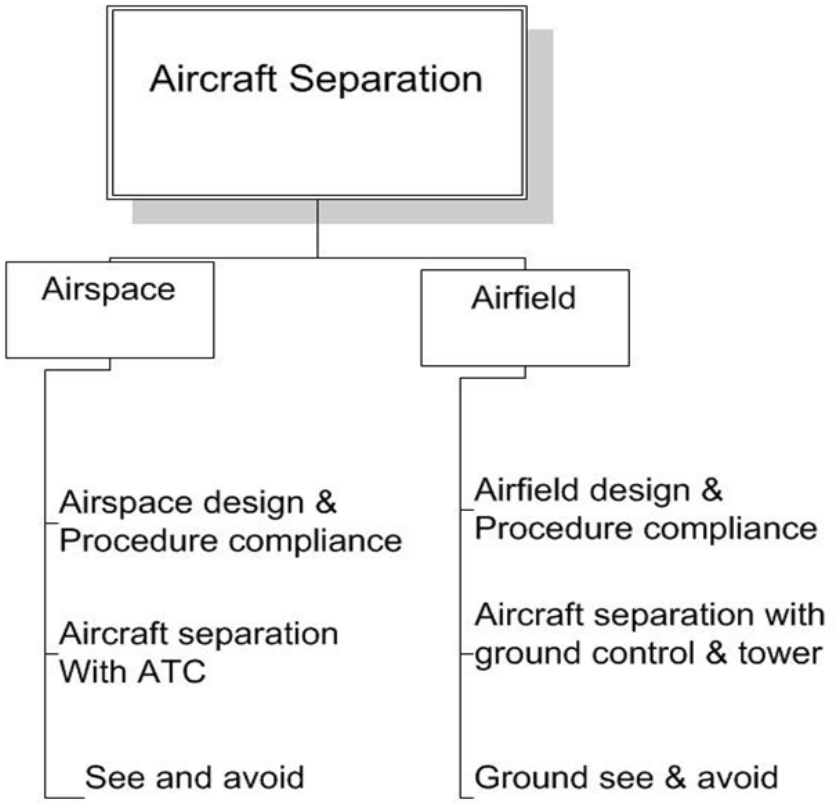
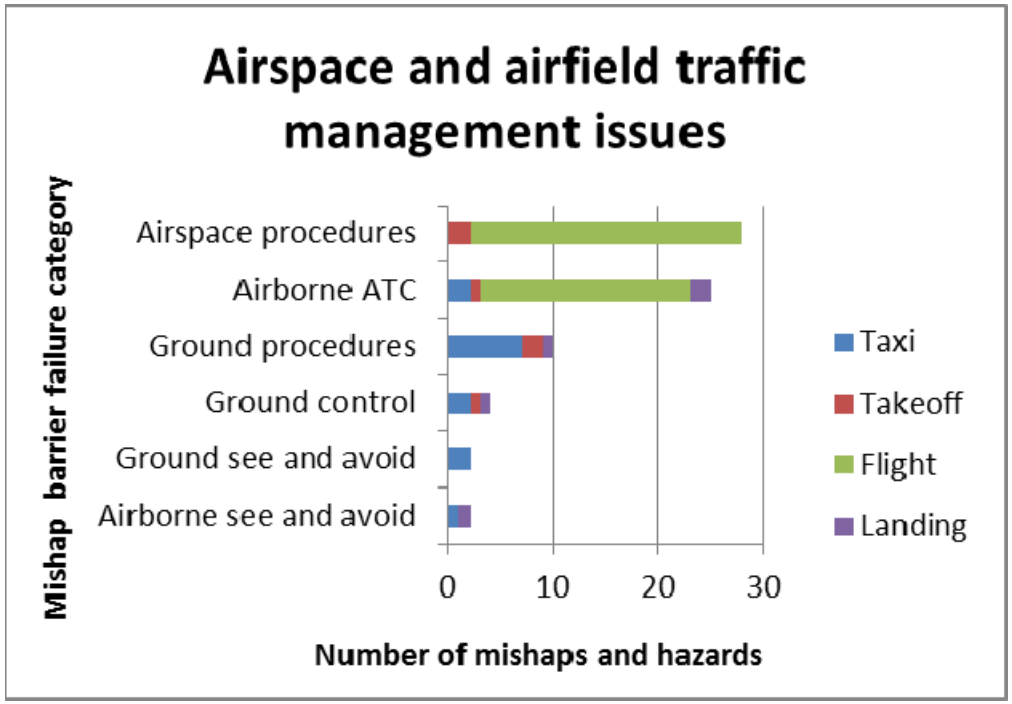
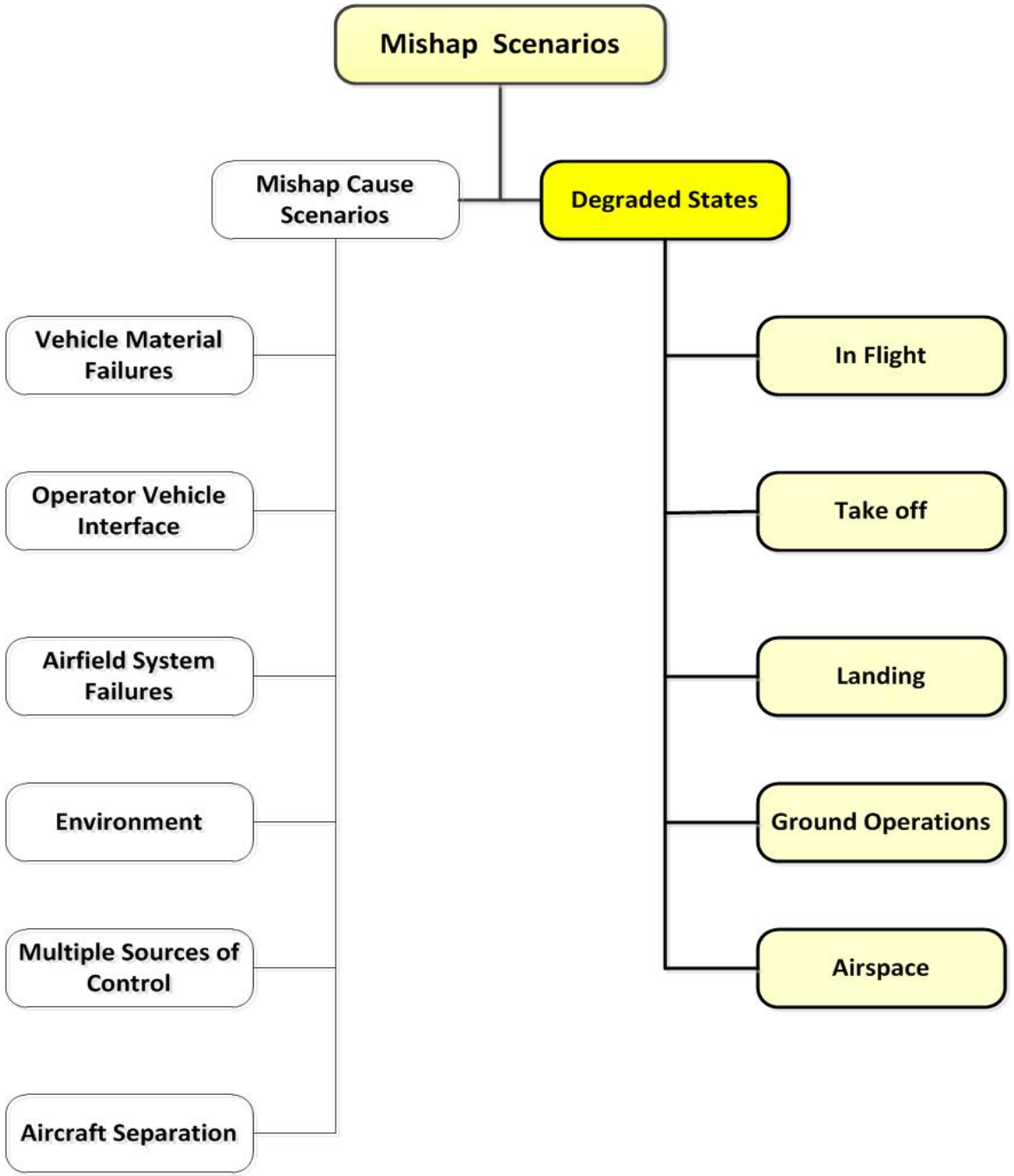
Aircraft Separation



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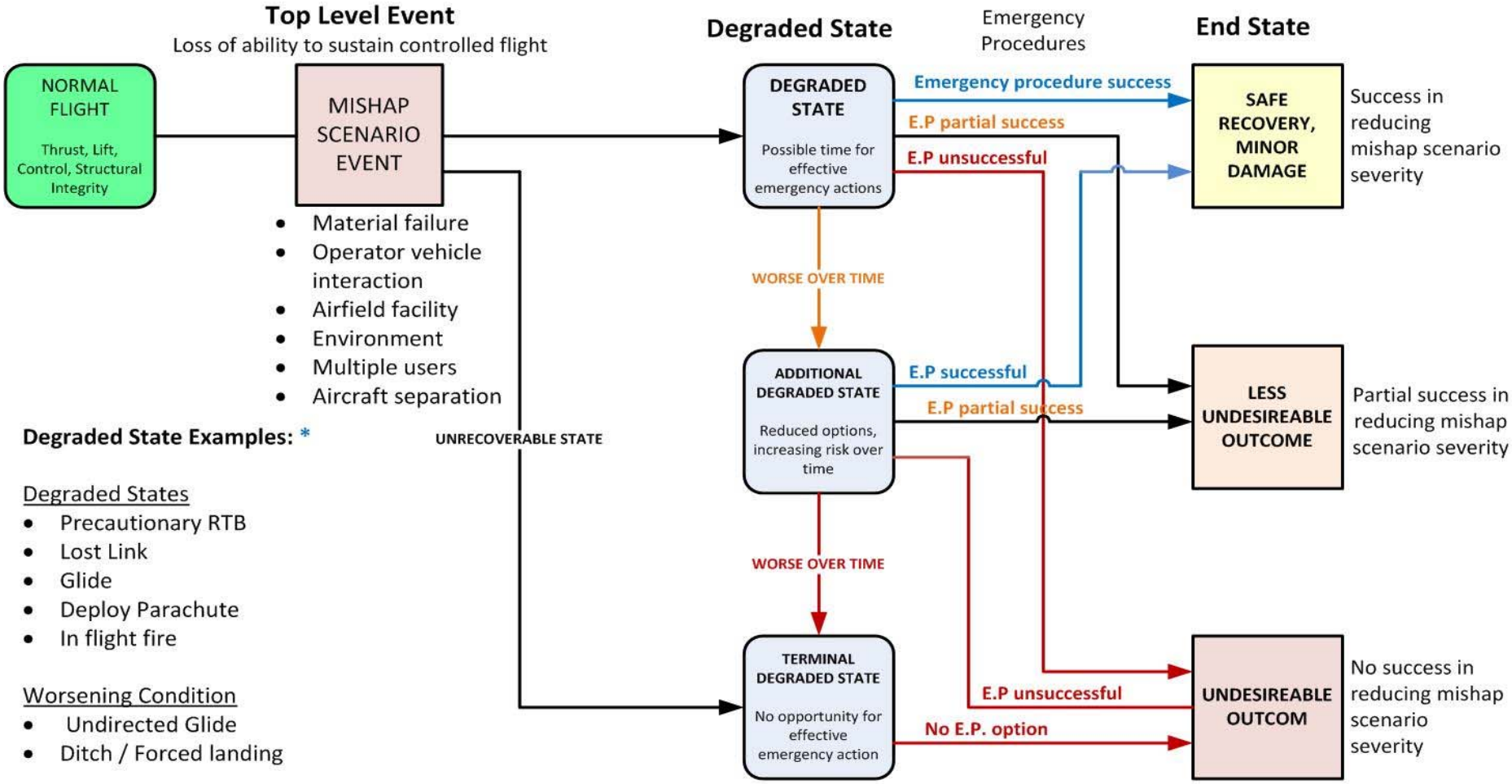
MISHAP SCENARIO TIMELINE



- Material failure
- Operator vehicle interaction
- Airfield facility
- Environment
- Multiple users
- Aircraft separation

Degraded State Examples: *

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- Precautionary RTB
- Lost Link
- Glide
- Deploy Parachute
- In flight fire

Worsening Condition
- Undirected Glide
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- Controlled crash / FTS

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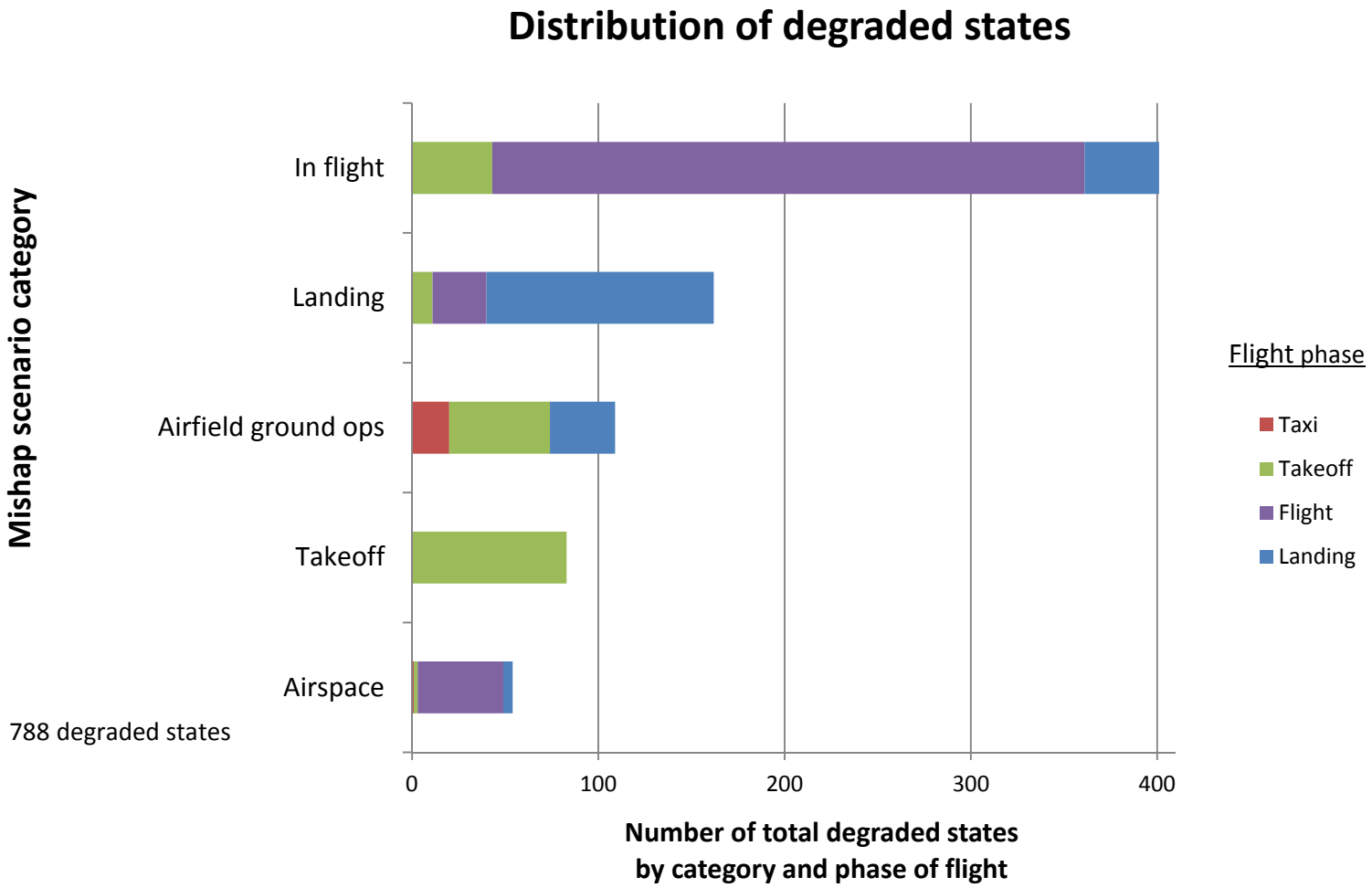
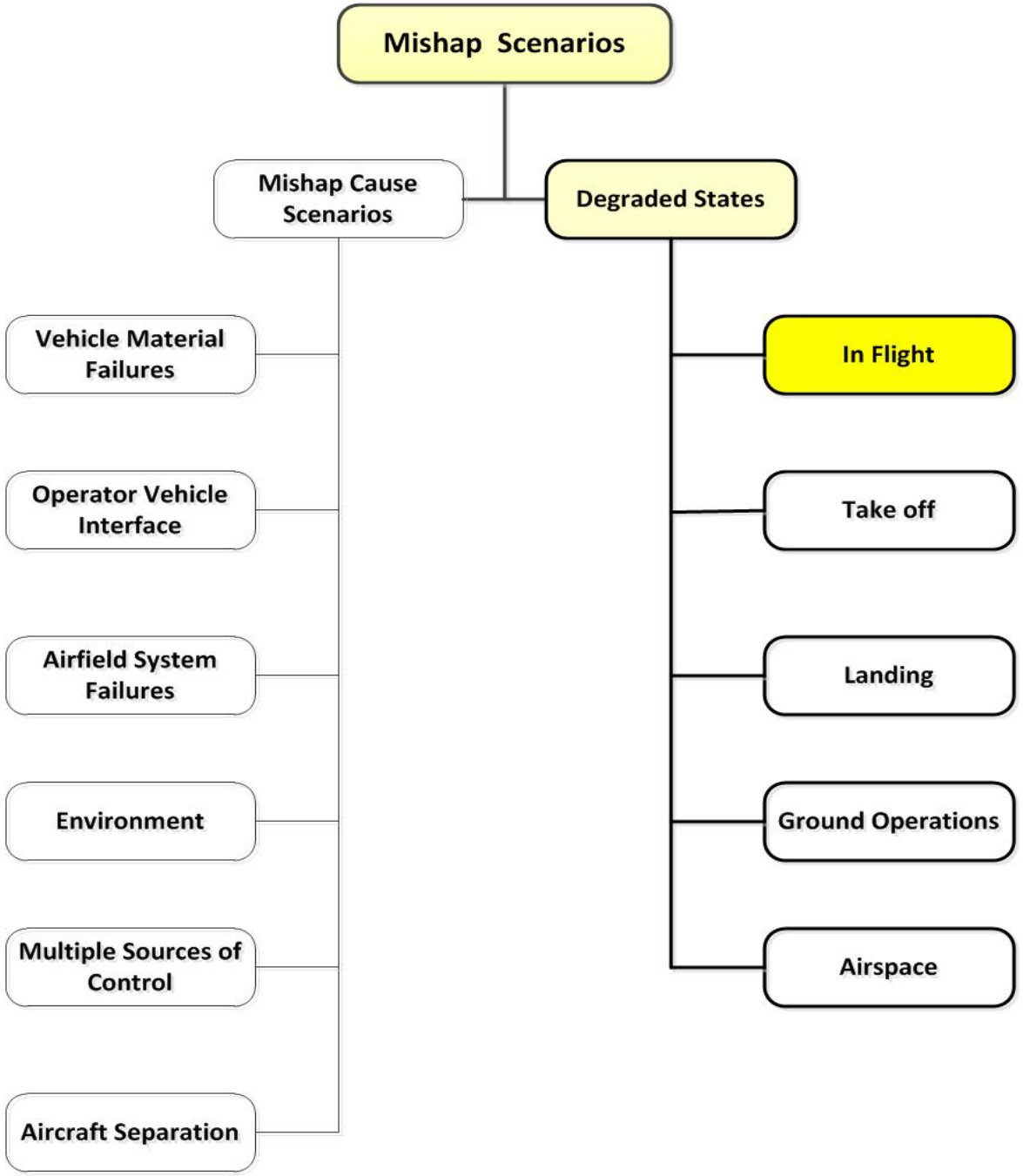
- Death or injury
- Midair, NMAC, airspace risk
- Security compromise
- International incident

* Not all inclusive


Distribution of degraded states
Mishap scenario category
In flight
Landing
Airfield ground ops
Takeoff
Airspace
788 degraded states
0
100
200
300
400
Number of total degraded states
by category and phase of flight
Flight phase
Taxi
Takeoff
Flight
Landing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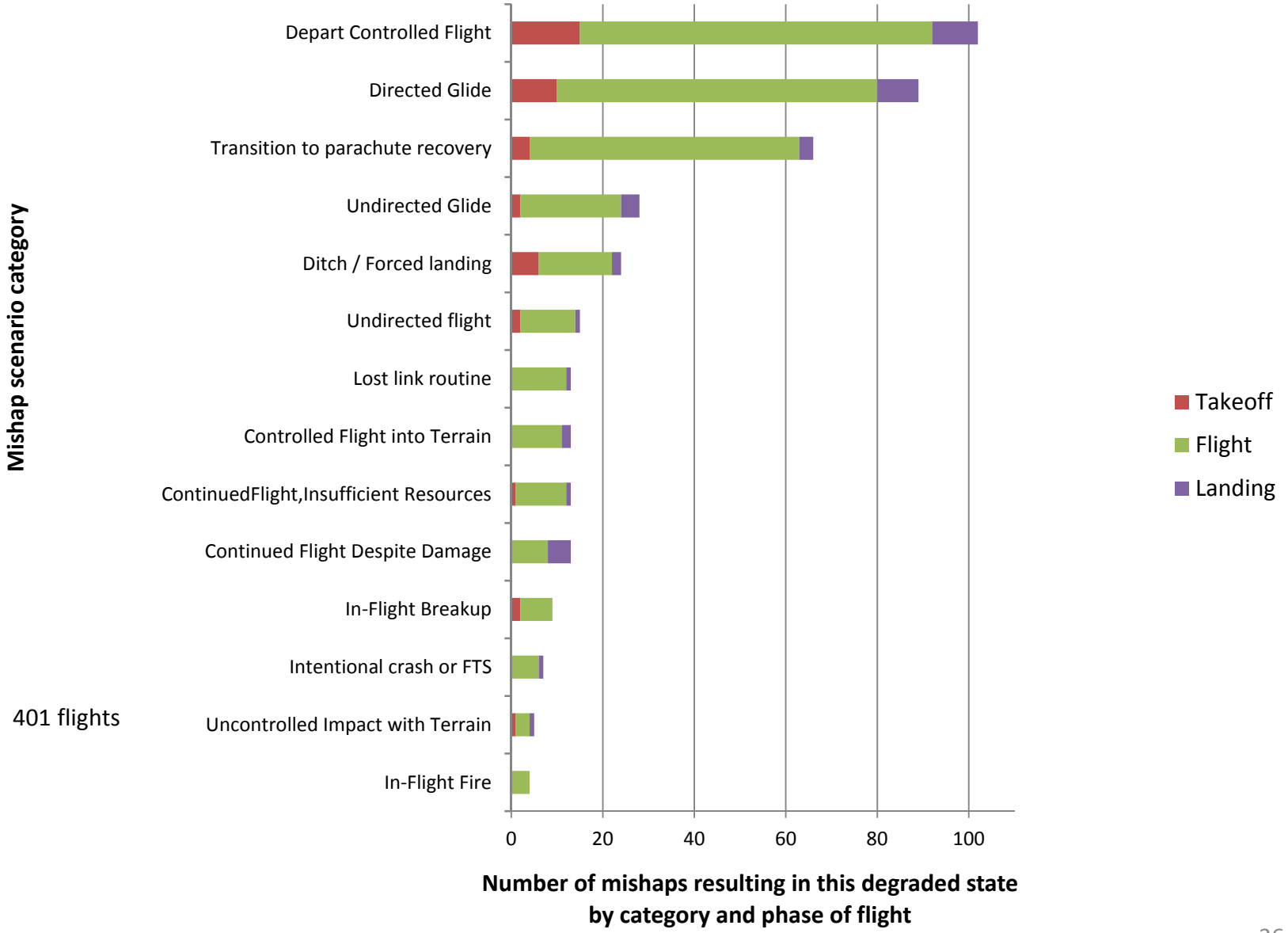
Airspace

In-flight degraded states

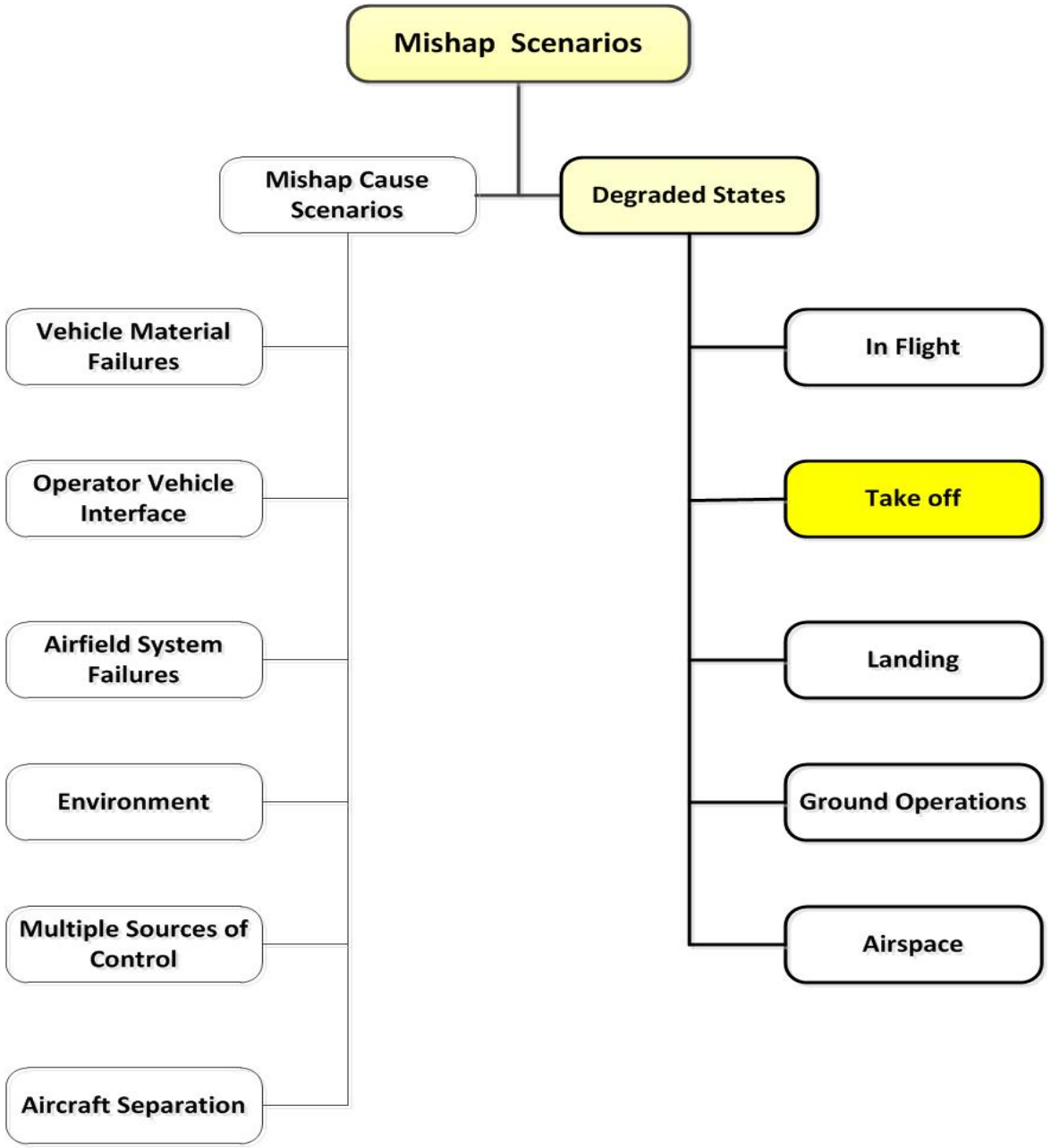


401 flights

Correlating Degraded State With Mishap Event Scenarios

Mishap Scenario	Takeoff	In Flight	Landing	Total
Total – Undirected Flight (Fly Away)	6	26	1	33
Total - Loss of Control	2	10	1	13
• Radio Frequency (RF) Control Link	1	7	1	9
• Electrical System	0	1	0	1
• Flight Reference System	1	0	0	1
• Ground Control Station	0	1	0	1
• Unspecifice Control Failure	0	1	0	1
Total - Operator	1	2	0	3
• Catapult launch	1	0	0	1
• In flight	0	2	0	2
Total-Environment	1	3	0	4
• Rain	0	1	0	1
• RF interference – Nav system	1	1	0	1
• Terrain masking	0	1	0	1
Total – Other Comms	0	2	0	2
• GCS to GCS Handoff	0	1	0	1
• Single GCS, Multiple UAVs	0	1	0	1
Degraded States	2	9	0	11
• Continued flight, insufficient resources	0	1	0	1
• Controlled flight into terrain (CFIT)	0	2	0	2
• Collision during takeoff or landing	1	0	0	1
• Undetermined outcome; possible increased airspace risk	1	4	0	5
• Increased airspace risk	0	1	0	1
• Near midair collision	0	1	0	1

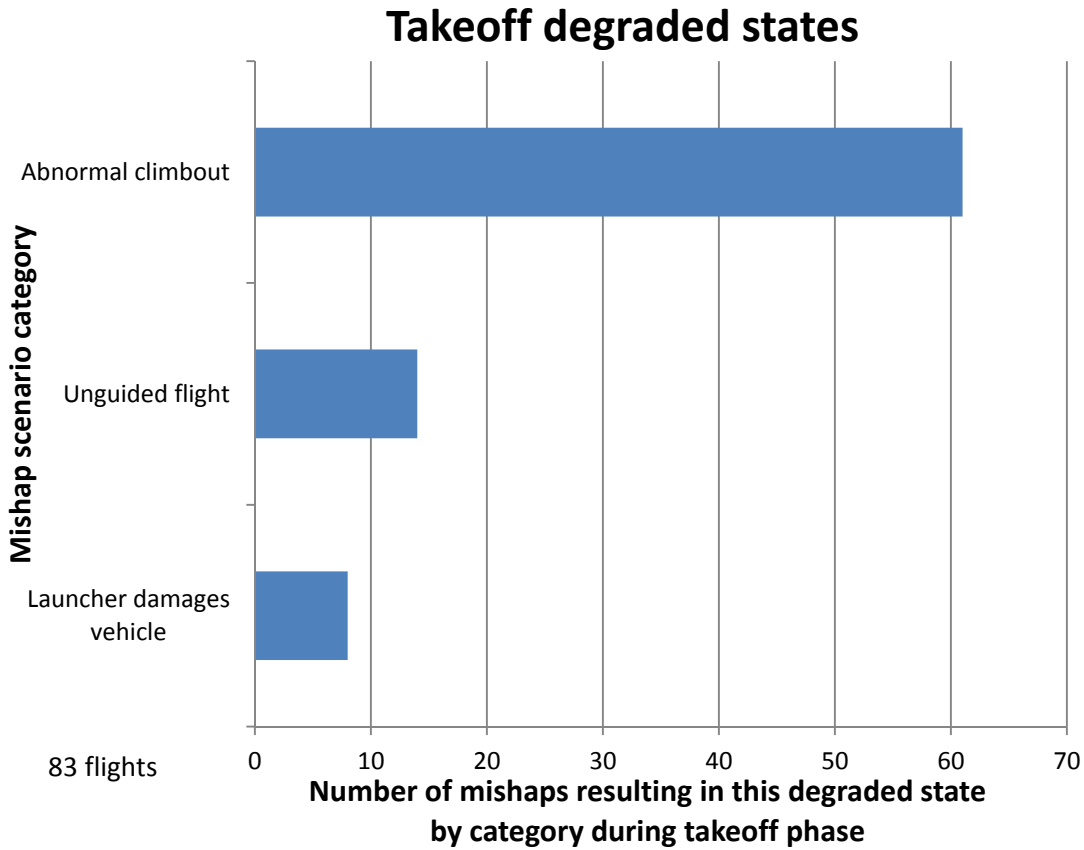
If the Range has no control or protection from the degraded state then one option is to review prevention controls on the associated mishap event scenarios. Other options include risk acceptance by the Decision Authority, or limit or cancel the test.

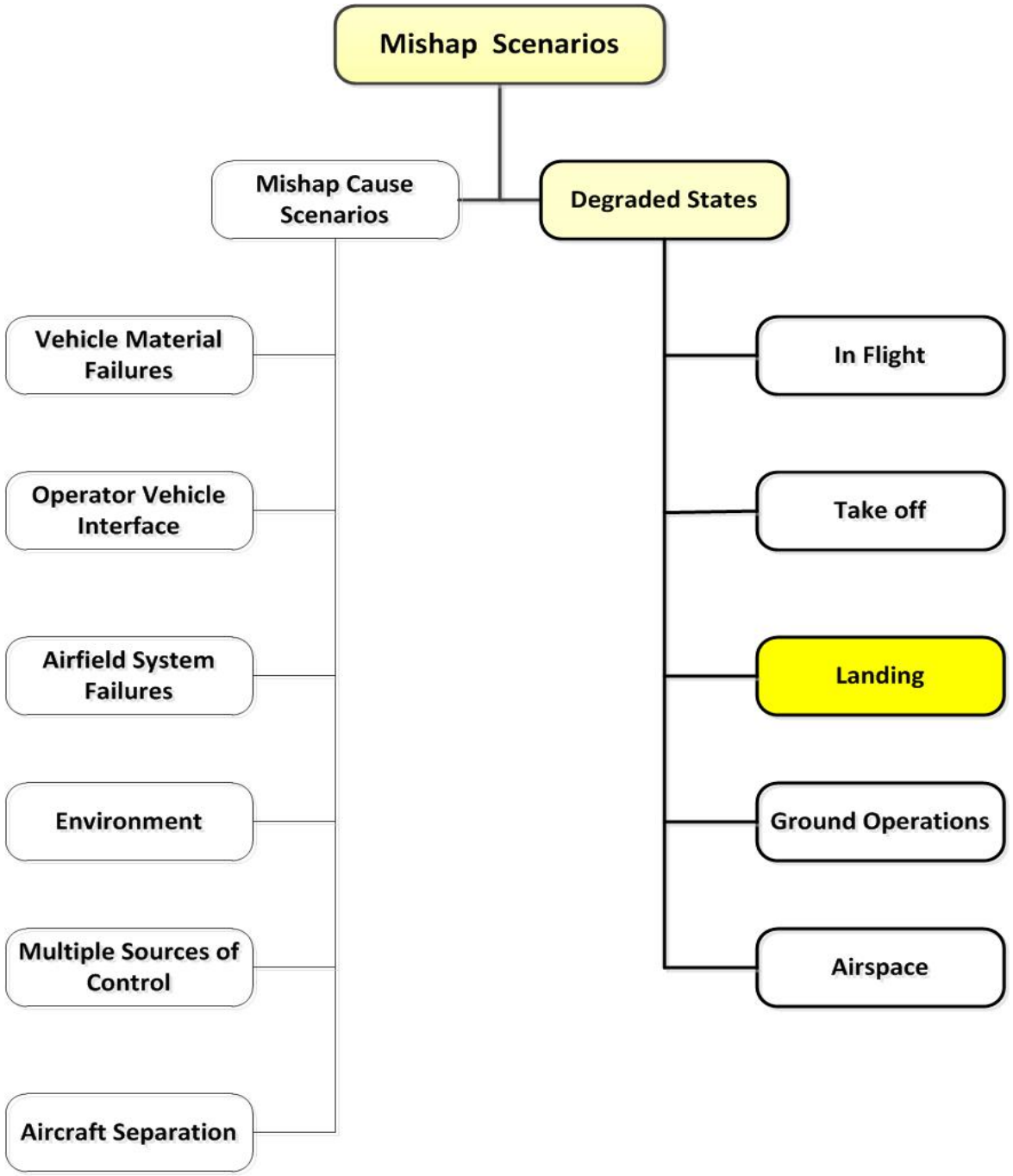

Mishap Scenarios
Mishap Cause Scenarios
Degraded States
Vehicle Material Failures
Operator Vehicle Interface
Airfield System Failures
Environment
Multiple Sources of Control
Aircraft Separation
In Flight
Take off
Landing
Ground Operations
Airspace

Takeoff Degraded States

Abnormal Climbout example

Source: DARO Annual Report, 1996

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Landing
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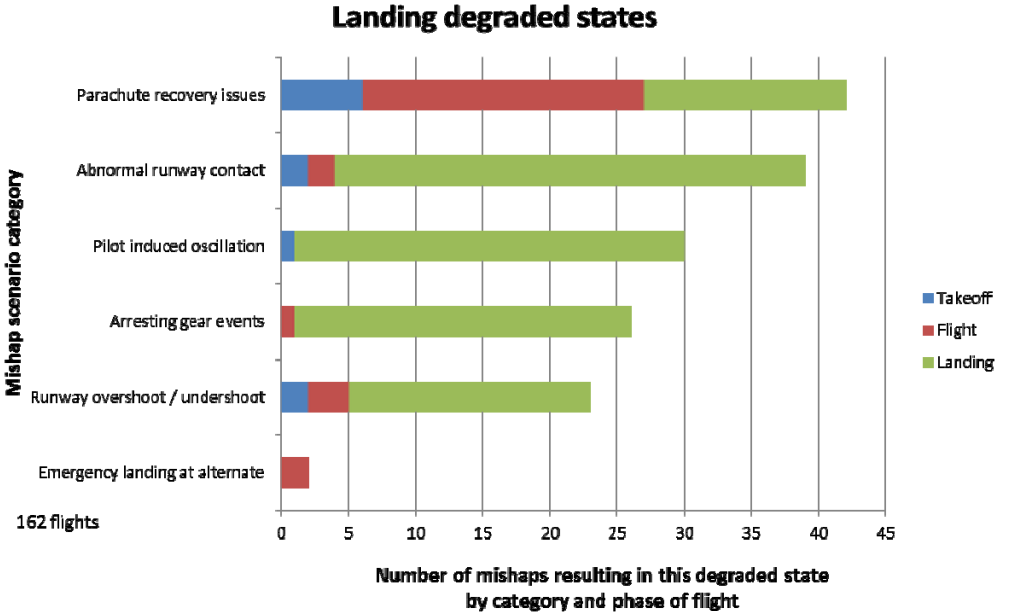
Airspace

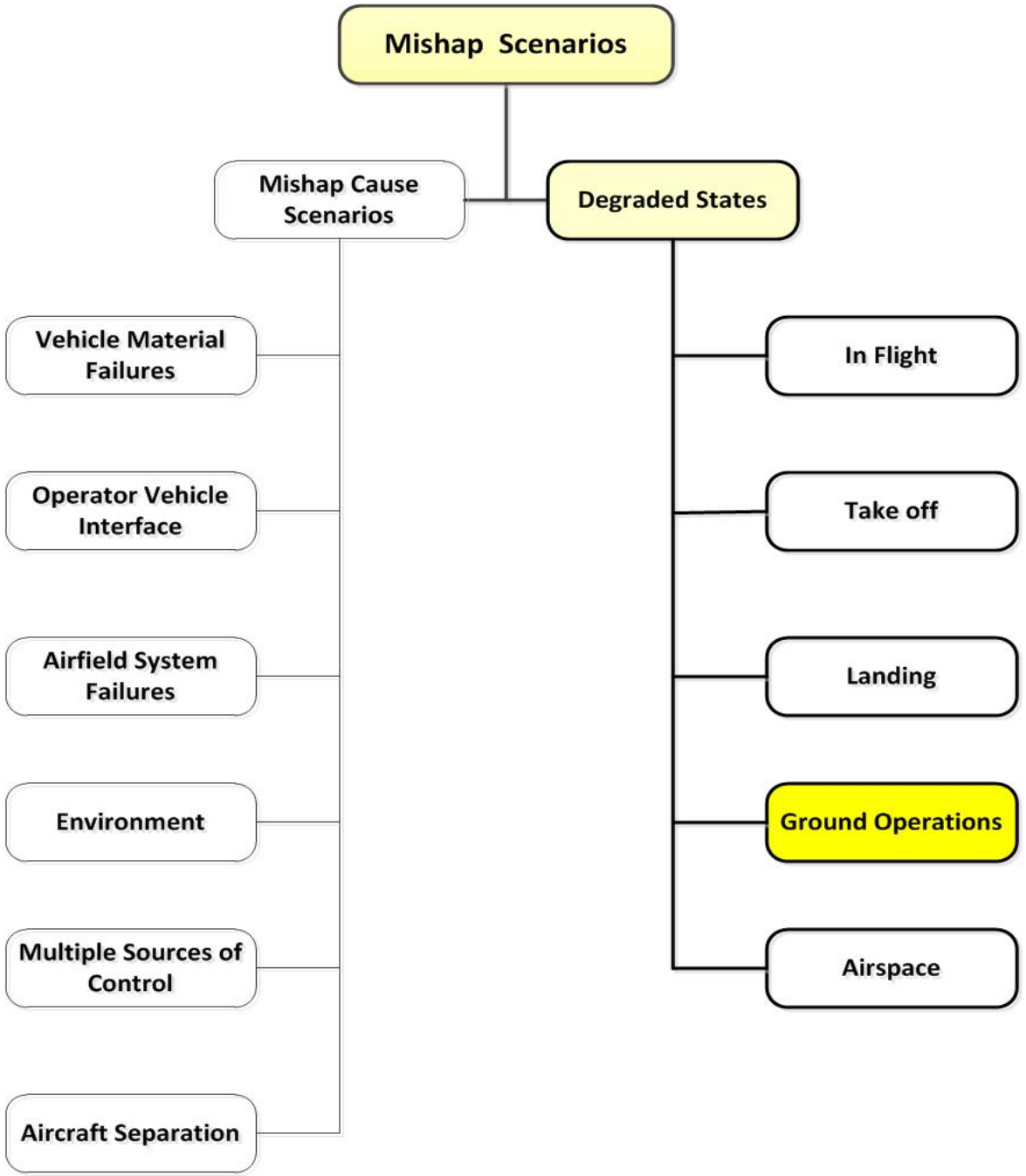
Landing Degraded States

Abnormal runway contact



Runway undershoot

Runway overshoot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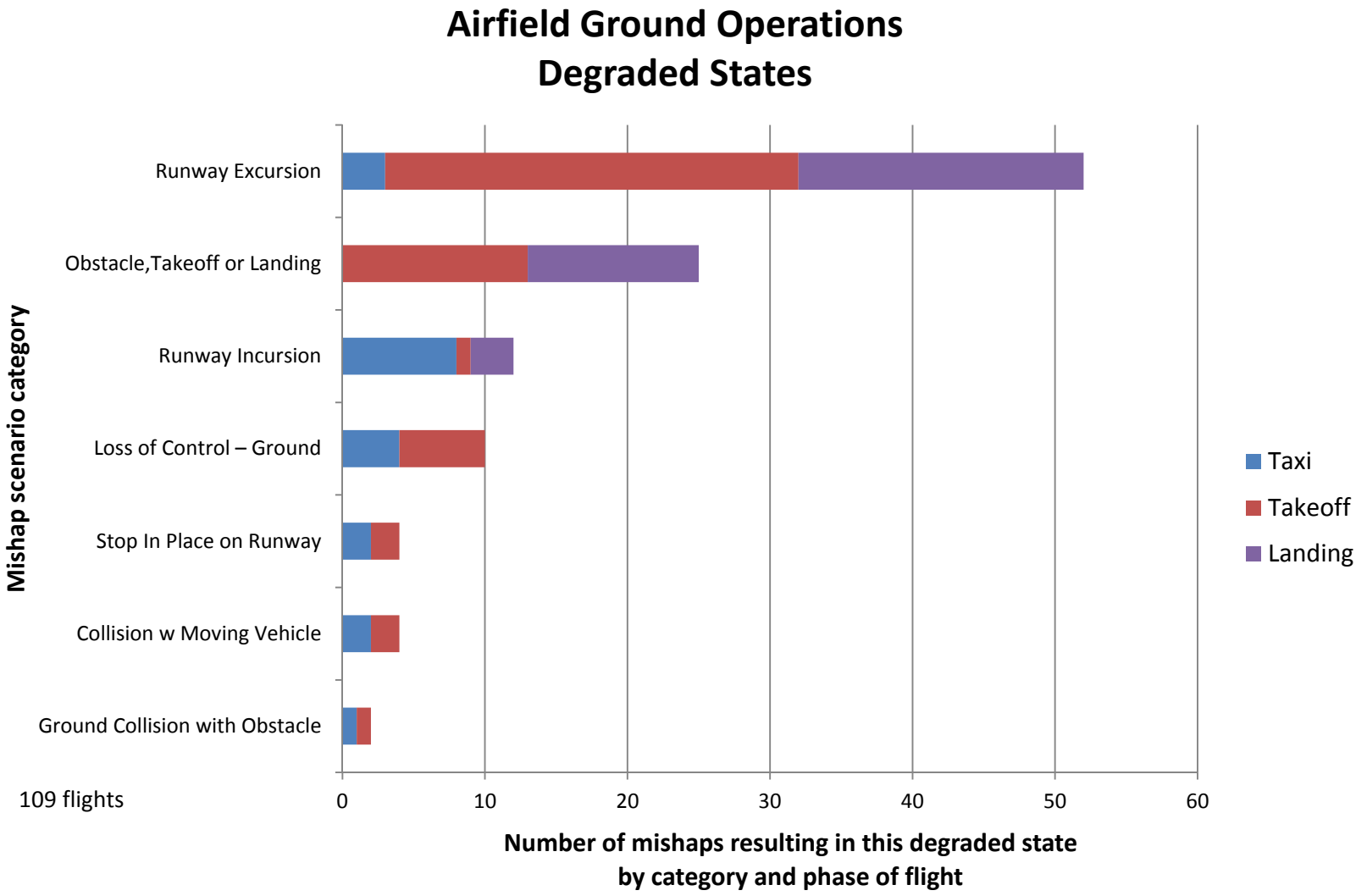
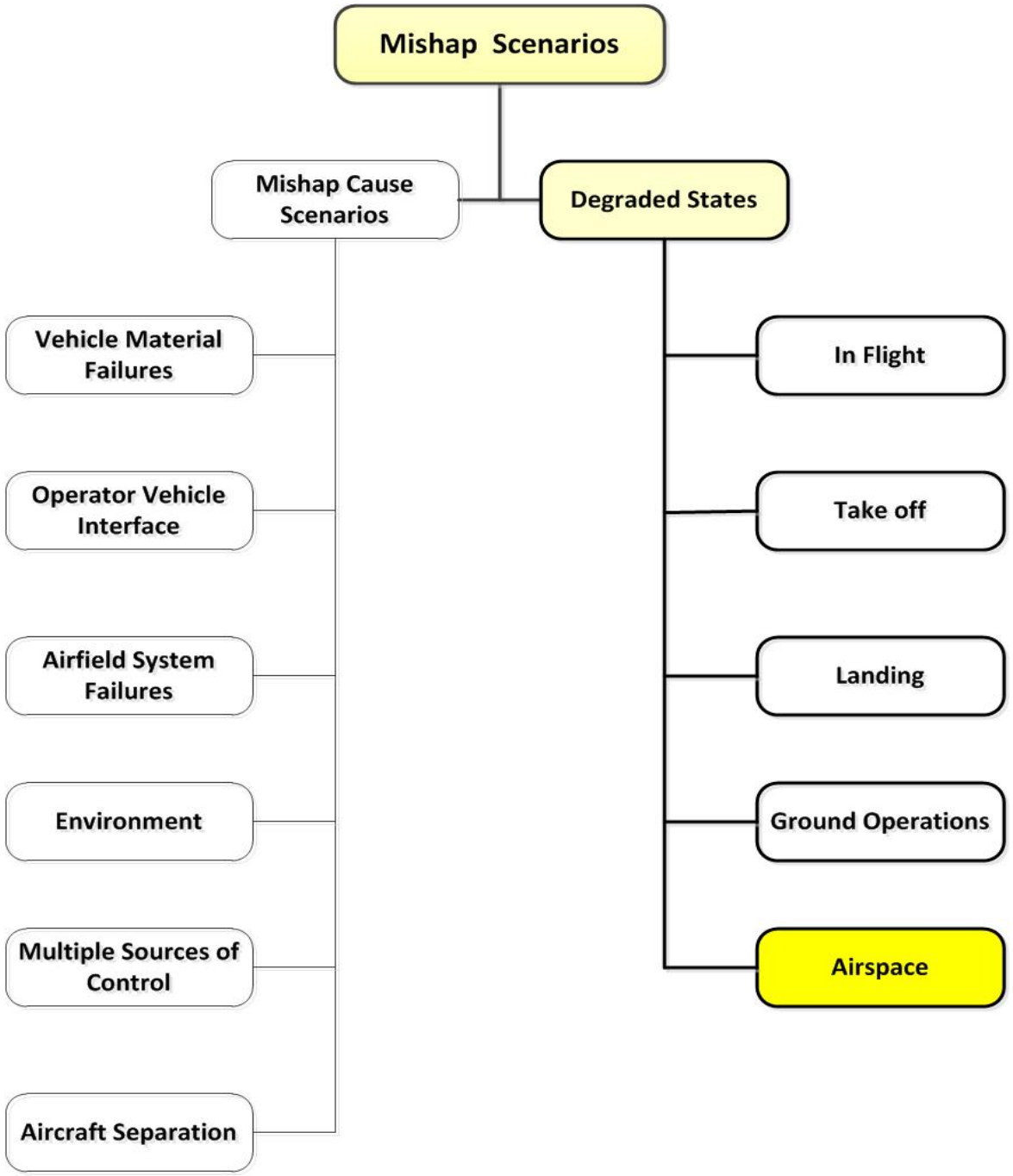
Airfield Operation Degraded States


Airfield Ground Operations
Degraded States
Mishap scenario category
Runway Excursion
Obstacle,Takeoff or Landing
Runway Incursion
Loss of Control – Ground
Stop In Place on Runway
Collision w Moving Vehicle
Ground Collision with Obstacle
109 flights
0
10
20
30
40
50
60
Number of mishaps resulting in this degraded state
by category and phase of flight
Taxi
Takeoff
Landing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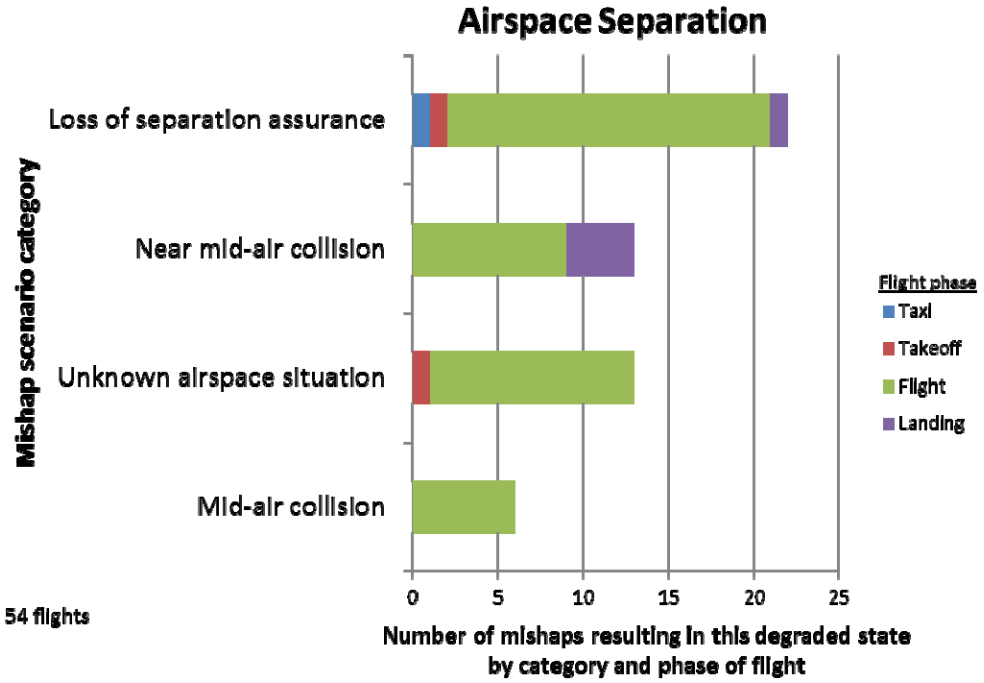
Airspace Degraded States

Unknown airspace outcome (some risk of collision) 29 events
- Lost contact with the UAV, it was never found
- What unrecognized additional airspace risks were created?
- Air proximity issues possible, but not recognized

Loss of airspace separation assurance (some risk of collision) 40 events
- Vehicle violated some separation provision
  - Not on an assigned route or in an assigned area
  - Not close enough to other aircraft to meet near mid-air criteria

Near mid-air collision (high risk of collision) 10 events
- Unplanned proximity within 500 feet
- TCAS resolution advisory

Mid-air collision (a mishap has occurred) 8 events
- Loss or damage to one of the vehicles



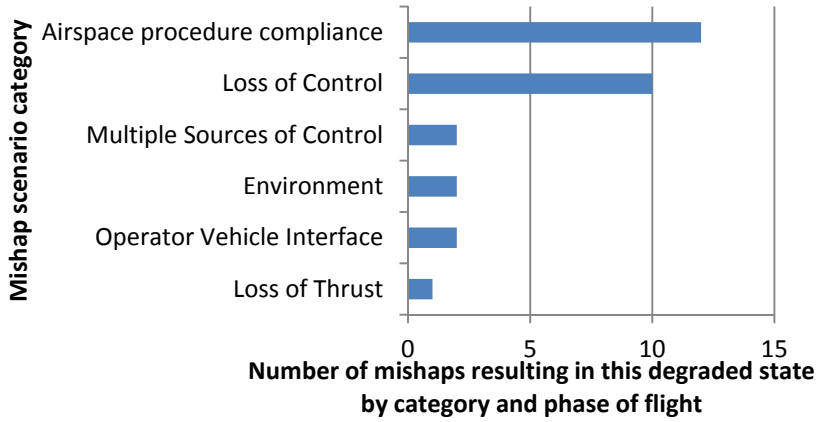
PSA Flight 182, San Diego

Wing leading edge damage after UAV collision

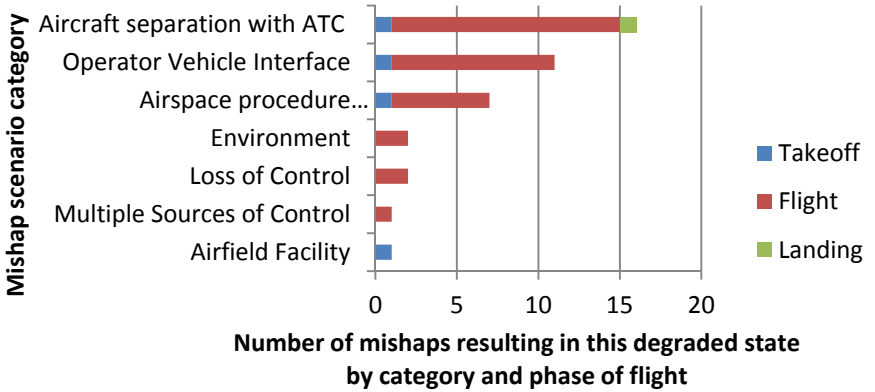
Near mid-air collision

Airspace Degraded States

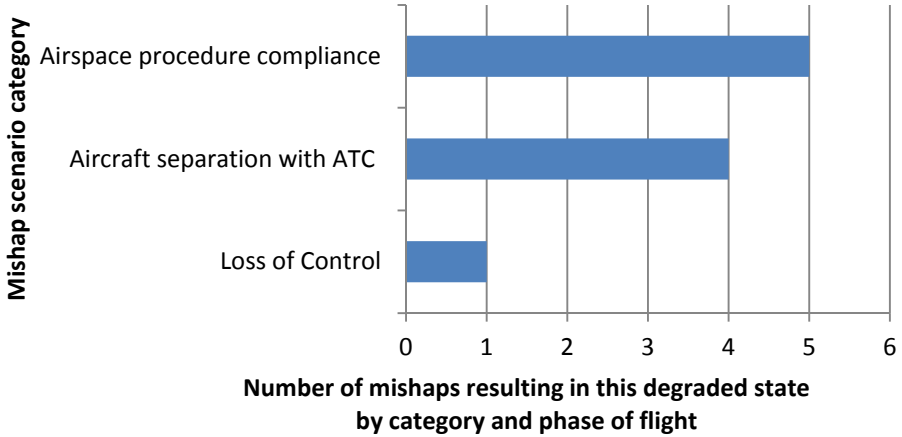
Unknown airspace outcome



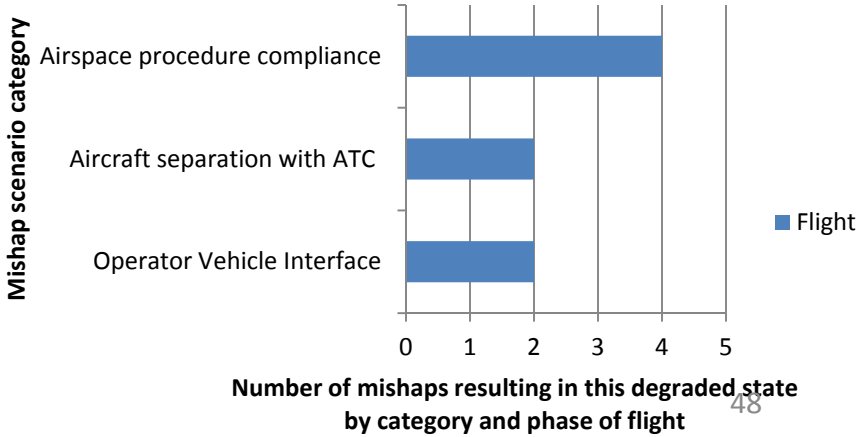
Loss of airspace separation assurance



Near mid-air collision



Mid-air collision



Conclusion:

Taxonomy benefits to Range Safety:

- **Foundation for in-depth risk management**
  - Creating a body of knowledge from mishap lessons learned accessible to safety personnel.
- **Framework for consistent range safety support**
  - Consistent starting point – list of what might happen based on what has happened.
  - Basis for estimating probability and severity.
- **Identify and prioritize long range safety improvement**
  - Recognize evolving trends, advocate long term solutions (policy, procedures, training, equipment etc.).