Integrated Safety for eVTOL
Crashworthiness: From Conceptual Design to Certification

| Gerardo Olivares Ph.D. | Director Crashworthiness and AVET Laboratories | April 13th 2021 | NASA-FAA eVTOL Crashworthiness Workshop # 4
Agenda

Integrated Safety for eVTOL Crashworthiness

- Introduction to eVTOL Integrated Safety Approach
  - eVTOL Safety Challenges
  - Integrated Safety Concept
- Digital Engineering Methods from Conceptual Design to Certification
- Overview FAA Funded Research Programs:
  - FAA-JAMS Crashworthiness
  - FAA-ASSURE AAM/UAM
- Conclusions
Introduction to eVTOL
Integrated Safety Approach

Integrated Safety for eVTOL Crashworthiness
Aerospace Safety

Non-Integrated vs. Integrated Safety

- Structural design for airplane safety combines *airworthiness* and *crashworthiness* design objectives to varying degrees.

- **Airworthiness** design objectives pertain to the ability of the airframe to withstand design loads, or to maintain safety of flight of the airplane relative to the operational environment.

- **Crashworthiness** design objectives pertain to safety of the occupants relative to the airplane.

- **Occupant Safety** must be an integral part of the overall technical and management processes associated with the design, development and operation of Urban Air Transport Systems. Nowadays the crashworthiness design for aerospace applications under 14 CFR *561 and *562 only addresses the dynamic response of the seat and restraint system during emergency landing conditions. In order to improve the survivability rate of occupants an integrated safety approach is required.
# 14CFR *.562 Dynamic Test Requirements

Non-Integrated vs. Integrated Safety

<table>
<thead>
<tr>
<th>DYNAMIC TEST REQUIREMENTS</th>
<th>PART 23</th>
<th>PART 25</th>
<th>PART 27</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>TEST 1</strong></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Test Velocity – ft/sec</td>
<td>31 (9.5 m/sec)</td>
<td>35 (10.7 m/sec)</td>
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<tr>
<td>Seat Pitch Angle – Degrees</td>
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<td>60</td>
</tr>
<tr>
<td>Seat Yaw Angle – Degrees</td>
<td>0</td>
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<td>0</td>
</tr>
<tr>
<td>Peak Deceleration – G's</td>
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<td>14</td>
<td>30</td>
</tr>
<tr>
<td>Time to Peak – sec</td>
<td>0.05/0.06</td>
<td>0.08</td>
<td>0.031</td>
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<tr>
<td>Floor Deformation - Degrees</td>
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<td>None</td>
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<tr>
<td><strong>TEST 2</strong></td>
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<tr>
<td>Test Velocity – ft/sec</td>
<td>42 (12.8 m/sec)</td>
<td>44 (13.4 m/sec)</td>
<td>42 (12.8 m/sec)</td>
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<tr>
<td>Seat Pitch Angle – Degrees</td>
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<tr>
<td>Seat Yaw Angle – Degrees</td>
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<td>±10</td>
<td>±10</td>
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<tr>
<td>Peak Deceleration – G's</td>
<td>26/21</td>
<td>16</td>
<td>18.4</td>
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<tr>
<td>Time to Peak – sec</td>
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<td>0.09</td>
<td>0.071</td>
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<tr>
<td>Floor Deformation - Degrees</td>
<td>10 Pitch/10 Roll</td>
<td>10 Pitch/10 Roll</td>
<td>10 Pitch/10 Roll</td>
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<tr>
<td><strong>COMPLIANCE CRITERIA</strong></td>
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<tr>
<td>HIC</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
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<tr>
<td>Lumbar Load – lbf</td>
<td>1500 (6675 N)</td>
<td>1500 (6675 N)</td>
<td>1500 (6675 N)</td>
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<tr>
<td>Strap Loads – lbf</td>
<td>1750¹/²000²</td>
<td>1750¹/²000²</td>
<td>1750¹/²000²</td>
</tr>
<tr>
<td>Femur Loads – lbf</td>
<td>(7787N/8900N²)</td>
<td>(7787N/8900N²)</td>
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<tr>
<td></td>
<td>N/A</td>
<td>2250</td>
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</table>

¹ Passenger 2 – Pilot

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## 14 CFR * .562 Pulses Crush Requirements

### Non-Integrated vs. Integrated Safety

<table>
<thead>
<tr>
<th>Test I</th>
<th>PART 25</th>
<th>PART 23</th>
<th>PART 27</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time to Peak (s)</td>
<td>0.08</td>
<td>0.05</td>
<td>0.031</td>
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<tr>
<td>Peak - Acceleration Pulse (g’s)</td>
<td>14</td>
<td>19</td>
<td>30</td>
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<tr>
<td>Peak - Z Acceleration (g’s)</td>
<td>12.1</td>
<td>16.4</td>
<td>26.0</td>
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<tr>
<td>Peak - Z Velocity (ft/s)</td>
<td>31.2</td>
<td>26.5</td>
<td>25.9</td>
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<tr>
<td>Peak - Z Displacement (inch)</td>
<td>30.3</td>
<td>16.2</td>
<td>9.6</td>
</tr>
</tbody>
</table>

![Graphs showing acceleration, displacement, and velocity components for different pulse requirements.](image-url)
Aerospace Safety Criteria

Integrated Safety for eVTOL Crashworthiness

- Maintain Survivable Volume
  - Overall Survivable Space Dimensional Check (Peak during Dynamic Event and Post Test Deformations)
  - Avoid Occupant to Interior Structure Contacts during impact

- Maintain Deceleration Loads to Occupants
  - Injury Criteria Limits per 14 CFR 562:
    - 1500 lbf, HIC 1000, Shoulder Strap Loads

- Retention Items of Mass
  - Interior items of mass per 14 CFR 561
  - Occupants and Seat Structures supported throughout the crash event (14 CFR 562)

- Maintain Egress Paths
  - Maintain Aisle Distance (if applicable)
  - Evaluate Plastic deformations of the supporting structure near the exit door
  - Floor Warping
  - Floor Beam Failures – Reduced Strength to support passenger weight
Non-Integrated Safety

Example Aerospace Non-Integrated Safety Development

- **Drop velocity:** 30 ft./sec
- **Composite Fuselage**
  Certified under 14 CFR Part 25 - **Airworthiness**
- **Dynamic Certified Seats**
  per 14 CFR 25.561 and 562 – **Emergency Landing Conditions**
Non-Integrated Safety “Real World” Issues

Example Aerospace Non-Integrated Safety Development
Aerospace Integrated Safety
Integrated Safety for eVTOL Crashworthiness

- Occupant safety must be an integral part of the overall technical and management processes associated with the design, development and operation of eVTOL Urban Air Transport systems.

- The different elements that constitute the integrated safety concept approach are:
  - Pre-crash: Event Recognition.
  - Control Impact Velocity and Attitude: Distributed Propulsion System Redundancy, Parachute Ballistic Recovery Systems, Retro Rockets...etc.
  - Integration of Landing Gear-Airframe Crashworthy Structure, Deployable Energy Absorbing Systems (Vehicle Airbags, Structural EA Devices...etc.)
  - High-energy Absorbing Seats, and Advanced Restraints.
  - Post-crash: Battery Fire Suppression, and Egress

- Energy Absorbing Landing/Take off Sites

- The implementation of Pre-Crash, Active Safety Systems can prevent or mitigate the outcome of eVTOL crashes. The autonomous nature of eVTOL Urban Air Transport systems could potentially provide a significant effect in the reduction of fatalities caused by human error (75% of the cases for GA fixed wing aircraft).
# UAM Architectures

## Integrated Safety for eVTOL Crashworthiness

<table>
<thead>
<tr>
<th>Multicopters</th>
<th>Quadcopters</th>
<th>Hybrid</th>
<th>Tilt Rotor</th>
<th>Fixed Wing Ducted Vectored Thrust</th>
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<tbody>
<tr>
<td>VTOL</td>
<td>VTOL</td>
<td>VTOL or VTOL &amp; CTOL</td>
<td>VTOL or VTOL &amp; CTOL</td>
<td>VTOL or VTOL &amp; CTOL</td>
</tr>
<tr>
<td>Skid System</td>
<td>Skid System</td>
<td>Skid System or LG</td>
<td>Skid System or LG</td>
<td>Skid System or LG</td>
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</tbody>
</table>

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Key Hazards and Risk Severity
Integrated Safety for eVTOL Crashworthiness

- Battery Thermal Runaway
- Battery Energy Uncertainty
- Common Mode Power Failure (Low-/High-Altitude)
- Fly-By-Wire System Failure
- High-Level Autonomy Failure
- Bird Strike

Integrated Safety - Typical Mission Profile

## Integrated Safety for eVTOL Crashworthiness

- **Hover Climb (B) and Hover Descent (J):**
  - **Distributed Propulsion:** Reduce Impact Velocity
  - **Aircraft Systems:** EA Seat, Advanced Restraints, EA Airframe, EA Skid/Landing Gear System, Deployable Energy Absorbing Devices
  - **Take-off & Landing Site:** Energy Absorbing Sites
  - **Impact Parameters:**
    - Max. AGL Altitude: 50 ft (15 m)
    - Max. Vertical Impact Velocity: 56.7 ft/s (17.3 m/s)
    - Max. Horizontal Impact Velocity: ~ 0 ft/s (0 m/s)
    - Max. Time: 1.75 s

- **Transition Climb (C) and Transition Descent (I):**
  - **Distributed Propulsion:** Reduce Impact Velocity
  - **Aircraft Systems:** EA Seat, Advanced Restraints, EA Airframe, EA Skid/Landing Gear System, Deployable Energy Absorbing Devices
  - **Take-off & Landing Site:** Energy Absorbing Sites
  - **Ballistic Recovery System [10% Efficiency up to 150 ft, 50% Efficiency up to 250 ft, ~100% Efficiency 250 ft plus] [Note these are estimates]
  - **Impact Parameters:**
    - Max. AGL Altitude: 300 ft (91.5 m)
    - Max. Vertical Impact Velocity: 139 ft/s (42.3 m/s)
    - Max. Horizontal Impact Velocity: 1.2*Vstall
    - Min. Time: 4.3 s

- **Accel + Climb (E), Decel + Descent (G), Cruise (F):**
  - **Distributed Propulsion:** Reduce Impact Velocity
  - **Aircraft Systems:** EA Seat, Advanced Restraints, EA Airframe, EA Skid/Landing Gear System, Deployable Energy Absorbing Devices
  - **Ballistic Recovery System**
  - **Impact Parameters:**
    - AGL Altitude: 1500 ft (457 m)
    - Max. Vertical Impact Velocity: 310 ft/s (94 m/s)
    - Max. Horizontal Impact Velocity: 220 ft/s (67 m/s)
    - Min. Time: 9.69 s

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### Mission Parameters

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<th>Distance (mi)</th>
<th>Vertical Speed (ft/min)</th>
<th>Horizontal Speed (mph)</th>
<th>AGL Ending Altitude (ft)</th>
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<td>B Hover Climb</td>
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<td>0</td>
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<td>C Transition + Climb</td>
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<td>0 to 1.2*Vstall</td>
<td>300</td>
<td></td>
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<tr>
<td>D Departure Terminal Procedures</td>
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<td>1.2*Vstall</td>
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<td></td>
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<tr>
<td>E Accel + Climb</td>
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<td>1.2*Vstall to 150</td>
<td>1500</td>
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<tr>
<td>F Cruise</td>
<td>0</td>
<td>150</td>
<td>1500</td>
<td></td>
</tr>
<tr>
<td>G Decel + Descend</td>
<td>500</td>
<td>150 to 1.2*Vstall</td>
<td>300</td>
<td></td>
</tr>
<tr>
<td>H Arrival Terminal Procedures</td>
<td>500</td>
<td>1.2*Vstall</td>
<td>300</td>
<td></td>
</tr>
<tr>
<td>I Transition + Descend</td>
<td>500 to 300</td>
<td>1.2*Vstall to 0</td>
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<tr>
<td>J Hover Descend</td>
<td>300 to 0</td>
<td>0</td>
<td>0</td>
<td></td>
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<tr>
<td>K Ground Taxi</td>
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<td>3</td>
<td>0</td>
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<tr>
<td>L Reserves</td>
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Digital Engineering Methods from Conceptual Design to Certification

Integrated Safety for eVTOL Crashworthiness
Engineering and Certification Methods
Integrated Safety for eVTOL Crashworthiness

1 – Experimental – with physical ATDs:
- High Cost and Time.
- Difficulties optimizing the system through physical prototypes.
- Difficult to quantify the Energy Absorbing capabilities of the individual crashworthy design features.
- Deterministic approach: Reduced to one single impact configuration.
- Current ATD’s (HII and FAA HIII) will not capture real world eVTOL occupants injury mechanisms.

2 – Digital Engineering: Computational supported by the building block approach - with Virtual ATDs:
- High Cost of entry: validated methods and tools.
- Reduced development and Certification cycles.
- Non-deterministic approach: Optimized solutions for multiple impact conditions and occupant sizes. Robust Design.
- Virtual ATD’s (HII and FAA HIII) will not capture real world eVTOL occupants injury mechanisms.
Engineering and Certification Methods
Integrated Safety for eVTOL Crashworthiness

- Digital Engineering: Computational supported by the building block approach - with Virtual Human Body Models:
  - High Cost of entry: validated methods and tools.
  - Reduced development and Certification cycles.
  - Non-deterministic approach: Optimized solutions for multiple impact conditions and occupant sizes. Robust Design.
  - Virtual Human Body models will capture real world eVTOL occupants injury mechanisms. Further V&V research is required to evaluate Human body models for non-conventional seating arrangements and aerospace loading applications.
Conceptual Design Process

Urban Air eVTOL Integrated Safety Conceptual Design Methods

1. Define Design Specifications and Performance Requirements
2. Define Design Space
3. NIAR Initial Integrated Safety Calculator
4. Multibody Integrated Safety Optimization Process
5. Integrated Safety Airframe and Safety Systems Optimized Solution
6. Sanity Check with NIAR Integrated Safety Analytical Calculations
7. Check that the optimum solution meets the Design Requirements
8. Final Conceptual Design
eVTOL Design Specifications

Urban Air eVTOL Integrated Safety Conceptual Design Methods

- **MTOW:** 4850 lbs. (2200 kg)
- **Powerplant:** Ducted Electric
- **Battery System:** Sub floor
- **Configurations:**
  - 4 Occupants + Luggage
  - 6 Occupants (no Luggage)
  - Piloted or Autonomous Flight
- **Structural Dynamic Design Performance Requirements:**
  - Landing Gear/Skid Reserve Energy Absorption
    - [Hard Landing]:
      - Impact Velocity: 10.22 ft/s [3.12 m/s]
      - The structure must withstand this test without introducing permanent deformations
  - Crashworthiness [Emergency Landing Requirements]:
    - A change in downward velocity of no less than 30 ft/s [9.1 m/s]
    - Injury Criteria per 14CFR *.562
### Initial Sizing Calculations – NIAR ISSC

Urban Air eVTOL Integrated Safety Conceptual Design Methods

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Seat [Z₁]</td>
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<td>22</td>
<td>41.9</td>
<td>8.00</td>
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<td>30</td>
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<td>2250</td>
</tr>
</tbody>
</table>

* 50% EA Efficiency  
**Peak Pulse Only

- NIAR ISSC: NIAR Integrated Safety Sizing Calculator

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eVTOL Optimization - Sizing Study

Urban Air eVTOL Integrated Safety Conceptual Design Methods

- **18 Design Variables**:
  - Seat Foam Dynamic Characteristic Curves: [1 Variable: Force Scaling Factor]
  - Seat EA Profile: [9 Variables: 5 Force Levels, 4 Displacement Levels]
  - Floor System: [4 Variables: 2 Crush Distance, 2 Crush Force]
  - Skid Systems: [4 Variables: 2 Crush Distance, 2 Crush Force]

- **Monitoring Output Variables**: Occupant Injury, Structural, Accelerations

- **Objective Function**:
  - Minimize Lumbar Load for Emergency Landing Condition (EL)

- **Design Constraints**:
  - Not to exceed the Elastic Limit for the Seat, Floor, and Skid System during Hard Landing Condition (HL)
  - Not to exceed injury criteria to passengers for HL and EL Conditions

- **Reduction of 64% on the Lumbar Load for the Emergency Landing Condition**:
  - Reduction from 2,194 lbf to 778 lbf
  - Design meets all constraints for EL and HL

![Optimization Objective History](chart)
Injury Criteria Summary

Design 1 – Optimization Results

**Emergency Landing**
- Lumbar Load
- Neck Fz Tension
- Neck Fz Compression
- NTF
- NTE
- NCF
- NCE
- Chest Deflection
- Chest 3ms
- Femur Load Left
- Femur Load Right

**Hard Landing**
- Lumbar Load
- Neck Fz Tension
- Neck Fz Compression
- NTF
- NTE
- NCF
- NCE
- Chest Deflection
- Chest 3ms
- Femur Load Left
- Femur Load Right

*Normalized with 14 CFR * .562, and FMVSS208 Limits*
Kinematics – Baseline vs. Optimized

Emergency Landing Results

Emergency Landing - Baseline
Time = 0.000000

Emergency Landing - Design 1
Time = 0.000000
Kinematics – Baseline vs. Optimized

Emergency Landing Results

Emergency Landing - Baseline
Time = 0.000000

Emergency Landing - Design 1
Time = 0.000000

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Kinematics – Baseline vs. Optimized

Hard Landing Results

Hard Landing - Baseline
Time = 0.000000

Hard Landing - Design 1
Time = 0.000000
Kinematics – Baseline vs. Optimized

Hard Landing Results

Hard Landing - Baseline
Time = 0.000000

Hard Landing - Design 1
Time = 0.000000
1. **Detail Conceptual Design Specifications** based on Multibody Model Optimization results.

2. **Virtual Engineering Design – NIAR Building Block Methodologies:** Coupon and Component Level Testing.

3. **Detail Conceptual Design FEA Proof of Concept Virtual Testing.**

4. **Prototype Full Scale Testing.**
EA Seat Design Check HBM

eVTOL Integrated Safety
Seat Prototype Testing – Proof of Concept

eVTOL Integrated Safety

- 6 Month Development
- Concept to Proof Test
- Optimization Methods to cover 5th through 95th Percentile Occupants
- Over 5000 Simulations
- New EA Technology Development - US Patent 9,327,623
- 1st Prototype test meets the Design Requirements
- Lumbar Load Reduction from 2300 lbf down to 895 lbf
Virtual Flight Testing
Integrated Safety for eVTOL Crashworthiness

Flight

Emergency Landing - Crashworthiness

Emergency Landing – System Failure or Operator Error

Simcenter Prescan

Drone states

Ref. Trajectory
LiDAR point cloud

LiDAR Point Cloud
Drone State

Trajectory
Obstacle Detection Algorithm
Safe Trajectory

Avoidance Trajectory Calculation
Safe Trajectory

Simulink

Simcenter Amesim

Avoidance Trajectory Calculation
Safe Trajectory

Safe Waypoints

Emergency Switch

Emergency Stop Trajectory

Crashworthiness Evaluation with Simcenter Madymo

Real World Initial Impact Conditions
Detect and Avoid Virtual Testing
Integrated Safety for eVTOL Crashworthiness

- Point Cloud
- Drone Position
- Original Trajectory
- Avoidance options
- Selected Avoidance Trajectory

Blue dot = drone position
Red dot = detected obstacle along path
Green dot = new (safe) waypoint
Red line = original path
Green line = new (safe) path
Overview FAA Funded R&D Programs

Integrated Safety for eVTOL Crashworthiness
eVTOL Crashworthiness Research
FAA JAMS COE Research

- Metallic Fuselage Drop Test (PMHS Injury Evaluations) – Ongoing
- Effects of Defects in the Energy Absorbing Capabilities of Composite Structures – Ongoing
- eVTOL Crashworthiness Methods – Pending Funding FY 2021
eVTOL UAM Research

FAA ASSURE COE Research

- **A36 Urban Air Mobility**: Safety Standards, Aircraft Certification and Impact on Market Feasibility and Growth Potentials
  - **Working Packages Overview**:
    - WP 1: Evaluation of UAM Market Potential: economic feasibility, potential size and growth, characteristics of population, and ground infrastructure.
    - WP 2: Airworthiness regulations and its applicability to UAM aircraft certification.
    - WP 4: Final Report and Recommendations for future research.
  - **Period of Performance**: 10/5/2020 to 7/1/2022
  - **Universities**: WSU–NIAR, Mississippi State University, Embry Riddle Aeronautical University, South Carolina State University

- **A47 sUAS Mid-Air Collision (MAC) Likelihood (14 CFR 23,25 ,27,and 29)**
- **A3, A16, A17: sUAS Airborne Collision Severity Studies (14 CFR 23,25 ,27,and 29)**
Conclusions

Aerospace Integrated Safety

- In order to successfully operate eVTOL vehicles, occupant safety must be an integral part of the overall technical and management processes associated with the design, development and operation of eVTOL Urban Air Transport systems.

- Current emergency landing conditions requirements specified in 14 CFR *.561 and *.562 do not provide the level of safety required for eVTOL vehicles.

- A successful implementation of the eVTOL market will require the development of Emergency Landing Standards and means of compliance (FAA, EASA, ASTM.. etc.) that address real world safety expectations.

- Emergency landing standards will need to be defined for eVTOL vehicles taking into consideration their unique design features and operation:
  - New and Novel Electric Distributed Propulsion Systems
  - New and Novel Vehicle Architectures
  - Non-conventional seating arrangements
  - Complex Urban environment operations (sharing airspace with other aircraft, sUAS, building infrastructure, people on the ground..etc..)
  - Mixed Modes of Transportation (Air and Ground)
  - Landing Sites crashworthiness design
  - Battery System Protection and post impact fire risk assessment

- Crashworthiness design needs to be implemented from the conceptual design stage of the vehicle, since the crashworthiness optimization of the various structural elements cannot be implemented once the design has been driven only by airworthiness requirements.
Thank you for your attention.