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Review

Urban Air Mobility, Personal Drones, and the Safety of Occupants—A Comprehensive Review

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Abstract: Urban air mobility (UAM) is expected to provide environmental benefits while enhancing transportation for citizens and businesses, particularly in commercial and emergency medical applications. The rapid development of electric vertical take-off and landing (eVTOL) aircraft has demonstrated the potential to introduce new technological capabilities to the market, fostering visions of widespread and diverse UAM applications. This paper reviews state-of-the-art occupant safety for personal drones and examines existing occupant protection methods in the aircraft. The study serves as a guide for stakeholders, including regulators, manufacturers, researchers, policymakers, and industry professionals—by providing insights into the regulatory landscape and safety assurance frameworks for eVTOL aircraft in UAM applications. Furthermore, we present a functional hazard assessment (FHA) conducted on a reference concept, detailing the process, decision-making considerations, and key variations. The analysis illustrates the FHA methodology while discussing the trade-offs involved in safety evaluations. Additionally, we provide a summary and a featured description of current eVTOL aircraft, highlighting their key characteristics and technological advancements.

Keywords: urban air mobility; electric vertical take-off and landing (eVTOL) aircraft; safety; multibody; finite element method; drone

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1. Introduction

The evolution of urban air mobility (UAM) and personal drones introduces a range of challenges and uncertainties regarding industry maturation, regulatory frameworks, and vehicle integration into existing transportation ecosystems. The development of a novel category of aerial vehicles, such as electric vertical take-off and landing (eVTOL) aircraft, necessitates the establishment of comprehensive operational and safety guidelines. This process is complex, involving both anticipated and unforeseen barriers that must be addressed to ensure safe and scalable deployment.

The rapid advancements in eVTOL technology have demonstrated the feasibility of novel aerial transportation solutions, fostering visions of widespread UAM applications. However, the introduction of new capabilities invariably raises critical safety concerns, some of which align with conventional aviation risks, while others are unique to this emerging domain. Some of these risks are low flight altitude (which reduces the response time of the pilot) or low batteries, which may lead to engine failure.

Manufacturers seeking Federal Aviation Administration (FAA) type certification for eVTOL aircraft must implement rigorous safety engineering methodologies to systematically identify, assess, and mitigate potential hazards associated with these designs.

This study provides a structured overview of the safety and regulatory landscape for eVTOL aircraft within UAM applications, offering valuable insights for stakeholders, particularly new entrants and professionals navigating hybrid roles in the industry. Additionally, we present a functional hazard assessment (FHA) applied to a reference eVTOL concept, detailing the methodology, key decisions, and safety considerations specific to eVTOL systems—which illustrates the FHA process while addressing its inherent complexities, trade-offs, and implementation variations.

2. Urban Air Mobility

The high congestion of modern megacities by road transport is a challenge for the contemporary world. The congestion generates air pollution, as evidenced by the TomTom Traffic Index 2021 [1] and the Air Quality in Europe 2021 report by the European Environment Agency [2]. It can be noted that environmental pollution is not the only problem associated with the increase in traffic in the city. Congestion is a growing concern, especially in densely populated urban areas and regions of Western and Central Europe, as well as in North America (Table 1).

Table 1. Congested urban areas in the global congestion impact ranking 2024 [3].

2024 Impact Rank (2023 Rank)	Urban Area	Country	2024 Delay per Driver (hours)	2023 Delay per Driver (hours)	Change from 2023
1 (6)	Istanbul	TUR	105	91	15%
2 (1)	New York City, NY	USA	102	101	1%
3 (5)	Chicago, IL	USA	102	96	6%
4 (2)	Mexico City	MEX	97	96	1%
5 (3)	London	GBR	101	99	2%
6 (4)	Paris	FRA	97	97	0%
7 (10)	Jakarta	IDN	89	65	37%
8 (7)	Los Angeles, CA	USA	88	89	−1%
9 (9)	Cape Town	ZAF	94	83	13%
10 (12)	Brisbane	AUS	84	74	14%
11 (14)	Bangkok	THA	74	63	17%
12 (8)	Boston MA	USA	79	88	−10%
13 (13)	Philadelphia, PA	USA	77	69	12%
14 (11)	Miami FL	USA	74	70	6%
15 (16)	Dublin	IRL	81	72	13%
16 (15)	Rome	ITA	71	69	3%
17 (19)	Houston, TX	USA	66	62	6%
18 (20)	Brussels	BEL	74	68	9%
19 (21)	Atlanta, GA	USA	65	61	7%
20 (28)	Warsaw	POL	70	61	15%

Excessive use of a ground vehicle results in increased travel time, reduced vehicle reliability, and increased fuel consumption. A person could use the time spent in a traffic jam at work to increase the country's economic benefits or spend more time with family and thereby improve their emotional state. In metropolitan cities such as Los Angeles and New York, an average commuter spends over 90 min in traffic resulting in an increase in stress and anxiety [4]. In this context, local authorities are looking at smarter, greener, more integrated, and more sustainable mobility solutions [5,6]. It is reported that UAM can meet these needs. Air transport of goods and people is no longer a form of distant future but will soon become a reality in the cities of the European Union. Adding a new dimension to urban transport will enable the transport of goods and people by air and can also help make the leap towards more innovative and sustainable cities. Urban air mobility is expected to bring environmental benefits as well as benefits to citizens and businesses, especially for commercial or emergency/medical purposes.

Major parties and corporations have started to support this transportation concept. For example, aviation giant Airbus presents its vision of urban air transport in [7]. Uber has also introduced air taxi models in their business plans. Announced in 2020, Joby Aviation will acquire Uber Elevate. The two parent companies have agreed to integrate their respective services into each other's applications, enabling seamless integration between ground and air travel for future customers. This agreement allows Uber to deepen its partnership with Joby, accelerate the time to market for these technologies, and move the Elevate team to Joby [8].

Despite all the advantages of UAM, it is a concept that needs more study. Urban air mobility is limited by many factors associated with certain regulations, infrastructure, air traffic control, and environmental impact. At the moment, a lot of research is spouting on the topic of studying UAM [9–13]. An interesting study was carried out in the article authored by [14]. An online analysis surveyed 221 respondents about their attitudes towards UAM. Using the exploratory factor analysis, many variables were clustered into groups with high explanatory power, thus reducing the dataset's dimensionality. These included the affinity to automation, safety concerns, data and ethical concerns, the value of time savings, and social attitudes such as environmental awareness, as well as the affinity to social media, online services, and sharing. Research shows that trust and security are critical components of UAM implementation. Humanity's trust in new technologies has always been an obstacle to the rapid implementation of new modern ideas. However, this only proves the importance of safety for potential users of urban air mobility, which requires special attention. Thus, urban air mobility is regarded as the future of urban mobility, which requires deep study from infrastructure to aircraft. Importantly, vehicles—personal drones, which will later be used for the urban air mobility system, are primarily at the prototype stage, and this makes it possible to forecast potential drawbacks of such vehicles at an early phase in the field of safety, which will contribute to the prompt confidence potential for new types of transport.

3. Personal Drones—Insight

Although the concept of urban air transport has existed for decades in limited availability in the form of conventional helicopter transport, it has not been widely available to society due to high operating and maintenance costs. In addition, there are negative factors such as environmental pollution and high noise levels. With the development of technology, this concept has received a new breath. Significant electrical storage and capacity improvements allow the use of electrically powered aircraft, which reduce costs, reduce noise, and provide enhanced safety. Technical advances led to the development of a new type of aircraft, called electrical vertical take-off and landing (eVTOL) aircraft, to meet the idea of urban air mobility. These new eVTOL air taxis are expected to be safer, quieter, and less expensive to operate and maintain than existing vertical take-off and landing aircraft, i.e., helicopters. The European Union Aviation Safety Agency (EASA) has received several requests for certifying this type of eVTOL aircraft, which differs from conventional rotorcraft or fixed-wing aircraft [15].

As part of the preparation of an adequate regulatory framework, the EASA (European Union Aviation Safety Agency) conducted a comprehensive study on the societal acceptance of UAM operations across the European Union. During the study, it was found that more than 200 eVTOL designs and concepts are currently being investigated and developed with many prominent ones such as Volocopter [16], Joby [17], Lilium [18], Airbus [7], Kitty Hawk [19], Jetson One, etc. Figure 1 depicts the status of some passenger eVTOL projects. As can be seen from the figure, most of the projects were started around 2020, which shows a greater interest in new air transport in recent years. The process of creating an aircraft takes, on average, 5 years. During this time, eVTOL developers need not only create an aircraft that will meet the technical specifications but also ensure an appropriate level of safety. The authors would like to apply the classification (eVTOL) of aircraft as personal drones.

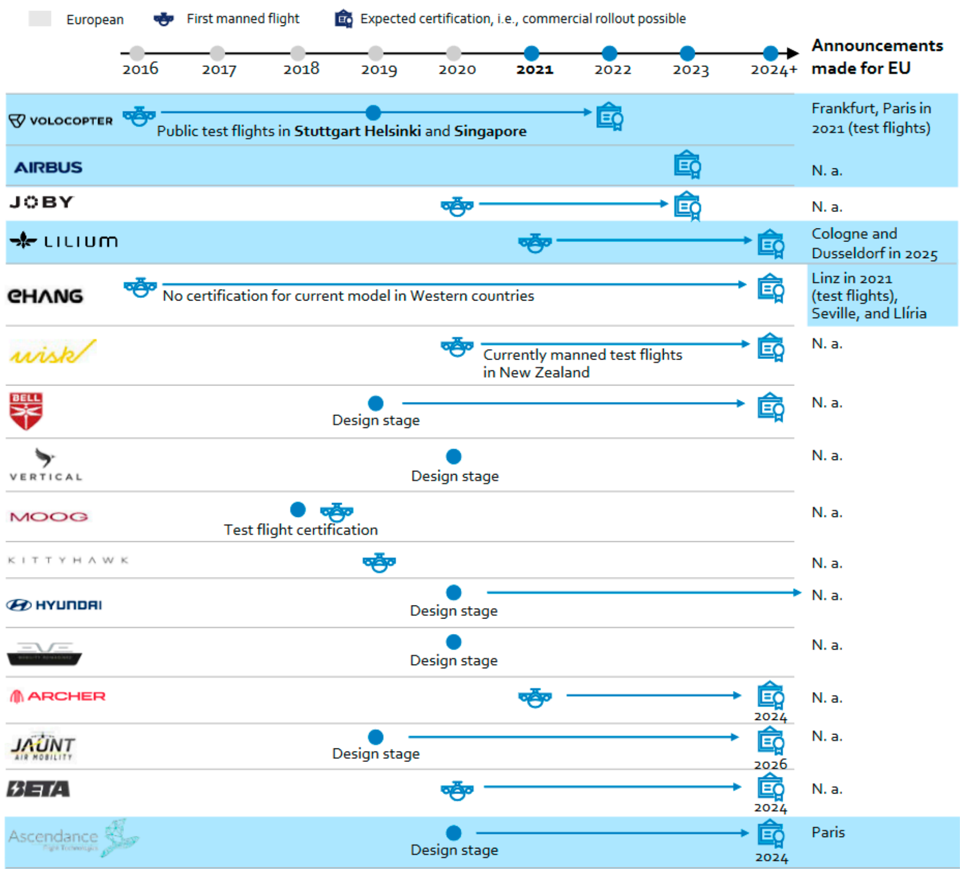


Figure 1. Passenger vehicle certification announcements [5].

Personal drones are typically single- or two-seat vehicles with simple designs (predominately of composite material) focused on practicality using (quickly getting in the vehicle), moving from point A to B or flying for entertainment. To be more practical, these drones have VTOL possibilities. The distinction from conventional aeroplanes is based on the VTOL capability of the aircraft, while the distinction from conventional rotorcraft is based on distributed propulsion, precisely when more than two lift/thrust units are used to provide lift during vertical take-off or landing.

It should be noted that personal drones have different approaches to primary flight controls. Unlike traditional aviation, it does not rely on changing the aerodynamic characteristics of the vehicle by manipulating control surfaces or changing the angle of attack. Instead, they use computational algorithms based on the flight plan or pilot inputs to calculate the rotational speed of each electric motor. This approach has great potential for autonomous flights and the introduction of new ways for airspace management. Unlike traditional aviation, urban areas and low-altitude flights allow the use of close to real-time position and vector reporting, which may change the course of navigation for this group of flying vehicles.

Electric vertical take-off and landing aircraft configurations vary from hover bikes to electric ducted fans. Table 2 shows a market analysis of the different types of personal drones with an actual prototype. The UAM market study, provided by NASA in 2018, classifies personal drones into the following categories [20]: multirotor, tilt rotor, tilt duct, and lift and cruise.

The website Electric VTOL News [21] classifies personal drones almost in the same way: wingless, hoverbikes, vectored thrust, and lift and cruise.

It should be noted that the website Electric VTOL News additionally highlights a separate category, i.e.,:

Hoverbikes [22]—are multirotors that can be flown as riding a motorbike. The pilot sits on a saddle or stands.

Below are some descriptions of the major categories of these types of aircraft:

Multirotor/Wingless—is the most uncomplicated eVTOL design, where lift and propulsive thrust are produced by several rotors distributed across the airframe [23], and lift is created without the wing.

Tilt Rotor/Vectored Thrust—is eVTOL with vectored thrust propulsion uses any of their electric engines for both take-off and cruise. Such eVTOL has tilting elements (wings or only propulsion units) to adjust the propulsion vector to the desired direction (vertical for VTOL and horizontal for cruise) [24].

Tilt Duct—is eVTOL the same as tilt-rotor/vectored-thrust type, but this category has ducted fans that help to keep the flow over the wing attached, enabling controlled flow over the wings throughout the aircraft's flight envelope, which provides improved flight performance [25].

Lift and Cruise—eVTOL that has independent propulsion units (one each for VTOL and cruise) without any vectoring [24].

Finding the best configuration of design of a personal drone depends mainly on the flight mission and technical design specification.

The technical task for the design of a new type of aircraft must contain indicators characterizing the typical conditions of operation, including flight missions. The flight mission scenario is important because many factors depend on the flight mission (such as velocity, load factors, accelerations, etc.). Since there are many different types of personal drones, and they have different designs and technical specifications, it is challenging to organize the load spectrum for this type of aircraft.

It can be assumed that personal drones will use small areas for take-off, such as the roofs of a high-rise block of flats and parking spaces in the yard or the lawn. In such a limited space and built-up environment, personal drones should be able to take off and land vertically (as their main advantage).

Table 2. Electric vertical take-off and landing aircraft (personal drones).

Company	Category	Picture	Technical Specification				
			Occupants	**Range /Flight Time**	**MTOW [kg]**	**Max. Speed [km/h]**	**Frame Material**
Jetson One [26]	Multirotor/ Wingless		1	20 min	181	102	Aluminum
Hover Scorpion [27]	Multirotor/ Wingless/ Hoverbikes		1	21 km	218	69	Carbon fibers
Air One [28]	Multirotor		2	60 min	970	250	Metal and composite
EHang AAV [29]	Multirotor/ Wingless		2	35 km	360	130	Carbon fibers
Passenger Drone (ASTRO) [30]	Multirotor/ Wingless			20–25 min	360	70	Carbon fibers
Whisper [31]	Multirotor/ Wingless		2	30 min	N/A	N/A	N/A
Volocopter VC200 [16]	Multirotor/ Wingless		2	27 min	450	100	Carbon fibers
Airbus Vahana [32]	Tilt Rotor/ Vectored Thrust		1	50 km	815	219	N/A

Table 2. *Cont.*

Company	**Category**	**Picture**	**Technical Specification**				
			Occupants	**Range /Flight Time**	**MTOW [kg]**	**Max. Speed [km/h]**	**Frame Material**
Opener Blackfly [32]	Tilt Rotor/ Vectored Thrust		1	40 km	246	129	Carbon fibers
Wisk Aero Cora [33]	Tilt Rotor/ Vectored Thrust		2	20 min	N/A	160	N/A
Joby eVTOL [17]	Tilt Rotor/ Vectored Thrust		N/A	322 km	1815	322	Composite
Kittyhawk [19]	Tilt Rotor/ Vectored Thrust		1	160 km	N/A	354	Composite
Archer [34]	Tilt Rotor/ Vectored Thrust		1 + 4	96 km	3175	150	N/A
Zuri 2.0 [35]	Tilt Rotor/ Vectored Thrust		1 + 4	700 km	N/A	300	Carbon fibers
Lilium [18]	Tilt Duct/ Vectored Thrust		2	60 min	640	300	N/A
Prosperity I [36]	Lift and Cruise		1 + 3	250 km	N/A	200	N/A

According to the reviewed literature, there are different approaches to personal drones' general flight profile. Shamiyeh et al., in their study [37], divided the flight mission into five segments: take-off, vertical climb, cruise flight, vertical descent, and landing. The sketch is shown in Figure 2.

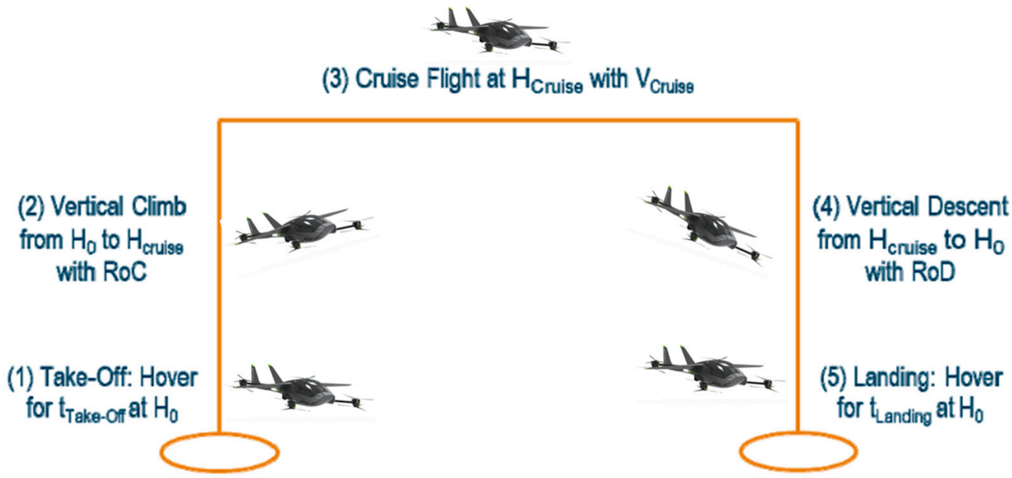


Figure 2. Five segments of the eVTOL vehicle mission. Adapted from [37].

Unlike the usual helicopter, some personal drones (such as tilt rotor/vectored thrust or tilt duct/vectored thrust) need a transitional phase of flight to install thrusters for horizontal flight in cruise mode.

In addition, as was noticed by Bruehl [24], five segments are not enough to describe one flight of eVTOL because it does not consider any forward flight during climb and descent. Thus, Bruehl et al. extended the flight mission profile based on [38,39] and added a taxi segment before take-off and after landing as well as a transition segment in order to change eVTOL configuration from vertical (take-off and landing) to horizontal flight (cruise flight) and vice versa. The proposed complete flight profile is shown in Figure 3.

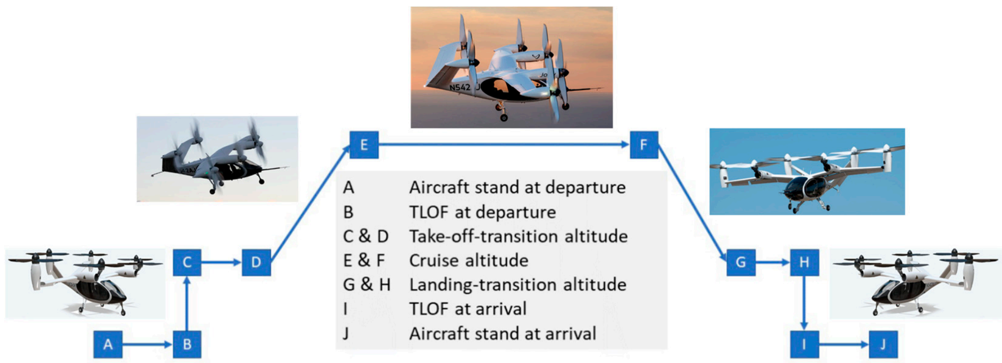


Figure 3. General eVTOL mission profile with transition mode. Adapted from [24].

Since personal drones are unambiguous aircraft with specific technical features, it is difficult to obtain a typical profile for different categories of drones. For example, the typical profile presented in Figure 2 is more suitable for the type of personal multirotor drone. On the other hand, the flight profile, according to Figure 4, is suitable for the type of drone—tilt rotor/vectored thrust or lift and cruise (due to the presence of a transitional mode).

Bacchini and Cestino performed a comparative investigation of different types of eVTOL vehicles [22]. The authors compared five main parameters such as disk loading, total hover time, cruise speed, and practical range. Their investigation shows that multirotors feature the best performance for short-range missions because they have better hover performances. Multirotors cannot accomplish long-range missions because their range is limited. The vectored thrust jet is more efficient on the cruise and has a higher range. The lift and cruise are a compromise.

Subsequently, eVTOL can be used as a personal motorbike and for entertaining (Jetson One [26] or Hover Scorpion [27]). Additional flight modes can be identified as avoidance—

the aircraft manoeuvres to deconflict with a detected collision hazard [40] that has to be considered.

4. Occupant Safety in a Personal Drone

Occupant safety must be an integral part of the technical processes associated with designing, developing, and operating aeroplanes—personal drones. Structural design for aeroplane safety combines airworthiness and crashworthiness design objectives pertaining to the ability of the airframe to withstand design loads or to maintain aeroplane flight safety relative to the operational environment [41].

As was noticed by Airbus, about 60% of aircraft accidents occur during the take-off or landing phases [42]. However, the study was done for commercial aircraft, which are quite different from personal drones. Nonetheless, according to these statistics, it can still be concluded that take-off and landing can be dangerous for any aircraft, particularly personal drones. Therefore, these flight cases must be considered more accurate when assessing occupants' safety. On the other hand, NASA's report on Functional Hazard Assessment for the eVTOL Aircraft Supporting UAM Applications [40] notices that during each change in flight mode, the risk profile changes at these transitions. Based on the above, we can conclude that each stage of the flight has its own level of accident risk, and each flight mode should be evaluated.

For an aircraft to be allowed to operate, it goes through a rigorous certification process that determines that the aircraft is airworthy with a satisfactory level of safety.

Certification of aviation vehicles is part of the system for ensuring flight safety in civil aviation and is aimed at ensuring the admission to the operation of civil aviation vehicle that meets state requirements for airworthiness and environmental protection. Closest to the purpose of personal drones can be attributed to helicopters that have the same capability for vertical take-off and landing. For example, helicopters have to be certified according to Part 27—Normal Category Rotorcraft [43] and CS 27—Small Rotorcraft [44] of FAA (Federation Aviation Administration) and EASA, respectively. Each regulation document has requirements, and each new aviation vehicle must meet these requirements. Current FAA and EASA certification standards consider vertical landing impacts by incorporating criteria such as crashworthiness testing, dynamic seat testing, and energy-absorbing structures. However, given the unique nature of eVTOL operations, ongoing efforts aim to refine impact testing methodologies, including drop tests that simulate vertical descents and crash pulse variations specific to UAM vehicles. The regulations consist of rules from flight and operation limitations to design and safety.

Vieira noted in his work [45] that this type of aircraft, such as the eVTOL, brings a mix of helicopters and aeroplanes, yet with a number of other aspects that none of these regulations cover, the existence of an electric-based propulsion system, the in-flight transition phases required by some of the proposed designs, and the battery issues ignited fires in post-crash conditions.

As mentioned, there are more and more personal drone startups every year. There is a question of certification of this type of air transport. Consequently, government aviation administrations, such as the FAA [6] and EASA [5], investigated a new type of aircraft to describe the envisioned operational environment that supports the expected growth of flight operations in and around urban areas.

This study helped create a new certification document for this type of aircraft. In particular, EASA released a Special Condition for this type of aircraft that prescribes airworthiness standards for the issuance of the type certificate and changes to this type of certificate for a person carrying VTOL aircraft in the small category, with lift/thrust units used to generate powered lift and control [46]. This certification document has a paragraph dedicated to structural occupant protection. Unfortunately, this paragraph does not contain specific information about safety in this type of aircraft (like load factors, speeds, and accelerations that can be used for designing structures). This is mainly due to the lack of knowledge of the problem in this area, which needs in-depth research.

4.1. Passenger Injury Criteria

Ensuring occupant safety is one of the most critical considerations in the design of personal drones. This study examines existing methodologies for assessing aircraft safety, with a particular focus on occupant protection. Traumatic injuries in aviation incidents can generally be classified as either contact injuries or acceleration-induced injuries [47]. Contact injuries, which result from the relative motion between the occupant and a contacting surface, tend to be more severe than those caused by acceleration forces alone. Consequently, designers prioritize the mitigation of contact-related injuries through structural and restraint system optimizations, whereas inertial forces inherent to crash events, can only be minimized rather than entirely eliminated.

The assessment of occupant injuries necessitates specialized evaluation techniques. A review of the relevant literature on injury assessment methodologies indicates that dynamic acceleration responses obtained from crash test dummies serve as the primary metric for injury risk evaluation assessment [48–56]. These responses are analyzed to quantify the likelihood and severity of injuries, providing essential data for refining safety measures in personal drone design.

Several methods are typically used to evaluate human injury potential, including the dynamic response index (DRI) [57–59], the Brinkley index [59,60], lumbar load limits [58], Eiband whole body acceleration tolerance limits [61,62], head injury criteria [58,63], and neck injury [64].

For aircraft, the vertical component of the load is decisive (especially for aircraft that have the ability to hover in the air and do not have a horizontal speed to dampen the force of impact during an emergency landing) and can constitute a determination for the survival of the pilot or passenger. The brain and spinal cord are the most vulnerable parts of the human body, injury to which can be fatal. The major functions of the vertebral column are protection of the spinal cord and stiffening for the body, as well as attachment for the pectoral and pelvic girdles and many muscles. Eiband's curves were used to assess traumatism spinal column acceleration and reference the time duration (Figure 4).

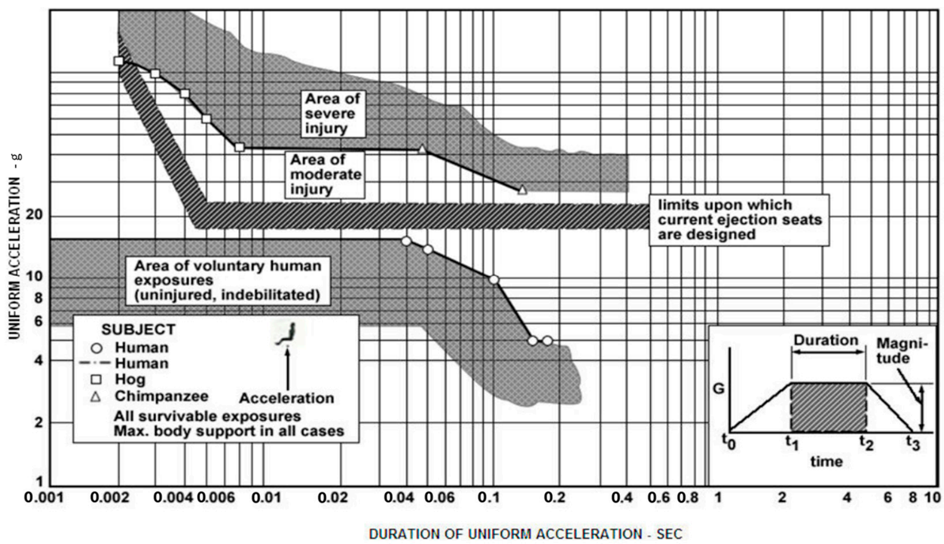


Figure 4. Duration and magnitude of headward acceleration endured by various subjects. Adapted from [65].

The Eiband approach describes the assessment of injury based on the acceleration of the whole body rather than separating the injury to individual parts of the body. With these considerations in mind, a new approach to injury has been developed—the dynamic response index (DRI) [66].

A physical model of spinal cord loading can be represented as a single lumped-mass, damped-spring system—shown in Figure 5.

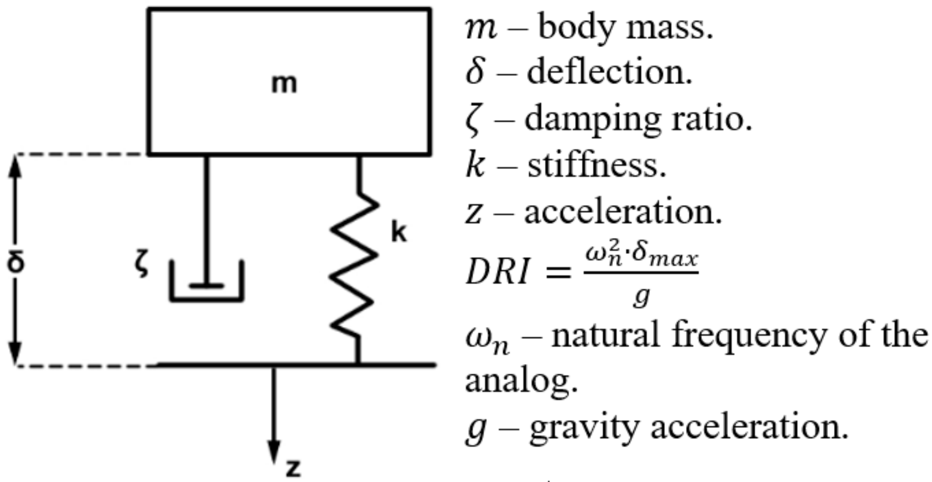


Figure 5. Physical model of the spinal cord. Reprinted from [58,61].

The following chart determines the degree of correlation between the spinal injury (DRI) model and injuries experienced in operation (see Figure 6).

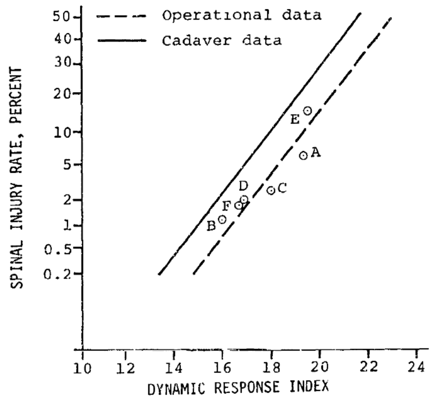
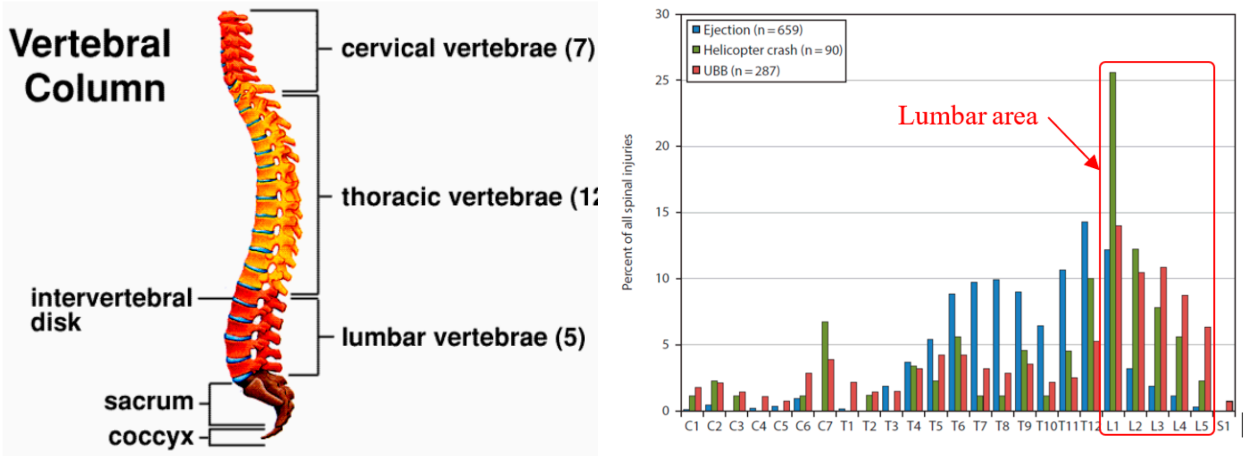


Figure 6. The probability of spinal injury estimated from laboratory data compared to operational experience. Reprinted from [58].

The DRI (dynamic response index) criterion was mainly developed for military seats that have a relatively rigid structure. This method is not sensitive to the design, such as seat cushions, restraint systems, and seat stiffness [66,67]. Since the load in the lumbar region is a determining factor causing injuries to the spinal cord (see Figure 7), a criterion for assessing the load directly in the lumbar zone had to be developed. Therefore, the FAA decided to develop a lumbar load tolerance value [66,68]. To find the load threshold, the FAA conducted a series of dynamic impact tests using aviation-specific pulses. Accomplished several tests, the FAA determined the criteria load for a lumbar area of the spinal cord—1500 lbs (~680 kg), which is correlated to a DRI of 19, or approximately a 9% risk of a detectable spinal injury).



(**a**) (**b**)

Figure 7. Lumbar zone injuries: (**a**) Anatomy of the human spinal cord. Reprinted from [68], (**b**) Spinal injuries for military causalities. Reprinted from [45].

For the brain, there is another injury criterion: Head injury criteria (HIC) does not exceed 1000 in value.

$$HIC = \left[(t_2 - t_1) \cdot \left[\frac{1}{t_2 - t_1} \cdot \int_{t_1}^{t_2} a(t)dt \right]^{2.5} \right]_{max} \quad (1)$$

where: t_2 and t_2—the initial and final times during which HCI attains a maximum value; $a(t)$—the resultant acceleration (G) measured at the head center of gravity.

The HIC (head injury criterion) may not be well defined or repeatable for several head impacts [58]. Although correlations of the HIC with actual injuries might not be as successful as desired, it is still one of the most widely used criteria for testing in relation to head injury protection, and an HIC of 1000 is still used as the criterion for head injury tolerance in general mechanics [48,69] and aviation [70,71].

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 [72]. To account for the different sizes and types of aircraft, the FAA has created subdivisions on the certification documentation, separating fixed-wing aircraft from rotorcraft and civil transport from small private aircraft. Each type of certification has its own set of rules that address the size, flight conditions, and construction differences to obtain similar levels of safety across the categories [45]. Some brief information about the requirements for dynamic tests according to 14CFR *.562 is shown in Figure 8.

Additional injury criteria can be added for the neck. This criterion combines the bending moment and the axial force acting on the neck. As noticed in the work authored by [73], this is not the main criterion for aviation, and the limit for this criterion can be used from automotive tests and must not exceed 1. The proposed neck injury criteria can thus be written as the sum of the normalized loads and moments [74].

$$Nij = \frac{F_Z}{F_{int}} + \frac{M_Y}{M_{int}} \quad (2)$$

where: F_Z—is the axial load; F_{int}—is the critical intercept value of load used for normalization (1530 lbs [73]); M_Y—is the flexion/extension bending moment; M_{int}—is the critical intercept value for the moment used for normalization (1530 in-lb [73]).

Dynamic test requirement: sled-test with Hybrid-II or FAA Hybrid-III dummy	**Part 23**	**Part 25**	**Part 27**	**Part 29**	**Set-up**
Test 1					
Velocity [m/s]	9.45	10.67	9.14	9.14	
Peak Acceleration [m/s^2] (pilot/occupant)	186 / 147	137	294	294	
Time to Peak [s]	0.05 / 0.06	0.08	0.031	0.031	
Seat Pitch [deg]	60	0	0	0	
Seat Yaw [deg]	0	0	0	0	
Test 2					
Velocity [m/s]	12.8	12.8	12.8	12.8	
Peak Acceleration [m/s^2] (pilot/occupant)	255 / 206	157	180	180	
Time to Peak [s]	0.05 / 0.06	0.09	0.071	0.071	
Seat Pitch [deg]	0	0	0	0	
Seat Yaw [deg]	10	10	10	10	
Compliance Criteria					
Lumbar Load [N]	6672	6672	6672	6672	
HIC [-]	1000	1000	1000	1000	
Femur Load [N]	-	10,005	-	-	
Belt Load-One strap/Two Strap [N]	7785/8896	7785/8896	7785/8896	7785/8896	

Figure 8. 14CFR *.562 Dynamic test requirements—adjusted to SI units. Adapted from [65].

Based on a review of the injury criteria, it can be concluded that the level of damage depends on the acceleration of a particular part of the body in the crash situation. It can also be assumed that a decreased level of acceleration in an accident reduces the risks of getting serious injuries to the body. To achieve a high level of passenger safety, the designer must design an aircraft that will have the properties to reduce acceleration during an emergency landing.

The physical testing of aircraft seating systems is increasingly being replaced by numerical simulation models, thus providing a faster and less expensive way to evaluate design concepts. In lieu of physical tests, an accurate numerical model could potentially be used to evaluate the seating system, saving both development time and cost. G. Olivares, in his work [75], provides the baseline test data required to define specifications for numerical occupant models of the Hybrid II and FAA Hybrid III anthropomorphic test dummies (ATD) suitable for aviation impact test simulations.

Notably, the safety evaluation approach employing the FAA Hybrid III dummy and numerical simulation models extends beyond the aviation industry. For instance, Dzialak et al. [48] conducted numerical simulations to investigate floor uplift—one of the phenomena observed in mine galleries following a rock burst. To assess the injuries sustained by the machine operator, they utilized the FAA 50th percentile Hybrid III dummy within the MADYMO 7.5 software framework. MADYMO is widely recognized for its multibody dummy models, which incorporate rigid bodies, ellipsoids, flexible bodies, and facets [76]. This study successfully identified limitations in the operator's safety systems and proposed potential enhancements. While these findings on general occupant safety are likely to advance research in this field, our primary interest lies in studies specifically targeting the aviation industry.

4.2. Integrated Safety Approach

A visually integrated safety approach can be represented as a system receiving the impact energy at the time of the accident (see Figure 9).

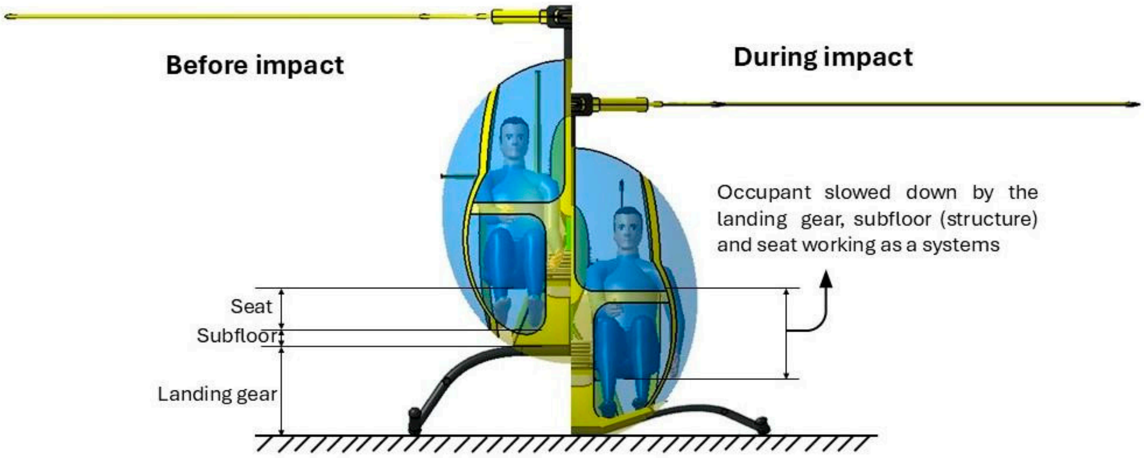


Figure 9. Crashworthiness systems-level approach.

A reduction in crash fatalities can be achieved by a cabin safety concept based on some safety features: airbags, seats, belt restraint systems, energy-absorbing material, the advanced shock-absorbing structure of vehicles (stiffness of the landing system, etc). Airbags and deployable energy absorbers may play a critical role in mitigating crash forces in eVTOLs, particularly in vertical impact scenarios where traditional horizontal crash dynamics do not apply. While preliminary studies suggest that modular airbag systems integrated into seats or structural components could improve passenger survivability, more research is required to optimize their deployment timing and positioning in UAM applications. Moreover, the increased mass of the vehicle is also a contradicting component.

In 2001, aviation companies thought about integrated passenger safety that could reduce the weight of vehicles while maintaining a high level of occupant safety. An example of such type of research was HeliSafe [77]. This project was directed at studying the safety of occupants during helicopter crashes.

The main objectives of HeliSafe are:

- to improve the survivability in the cockpit and cabin;
- to minimize the risk of injuries;
- to analyze crash data in order to define typical crash scenarios, usable for simulations;
- the definition of injury criteria, the development of a simulation tool;
- the integration of safety concepts developed in the automotive industry;
- the definition of an advanced safety system concept by analyzing interacting safety features for new projects and for retrofit;
- recommendations for airworthiness standards.

It is worth noting that the objectives outlined above can be applied to emerging aircraft, such as personal drones, provided the unique characteristics of this aircraft type are taken into account. Achieving the assigned tasks requires the development of crash scenarios (see Figure 10), which should be informed by existing crash data and airworthiness standards. However, for aircraft such as personal drones, deriving crash scenarios from airworthiness standards is challenging due to limited historical data and experience. Collaboration with companies and institutions involved in personal drone operations is thus essential to obtain real flight data, enabling the creation of crash scenarios tailored to this aircraft category. The novelty of personal drones has so far precluded the accumulation of sufficient crash scenario data. Consequently, at this stage of eVTOL design development, establishing partnerships with companies and institutions working on personal drones is critical to generating the necessary crash scenario data.

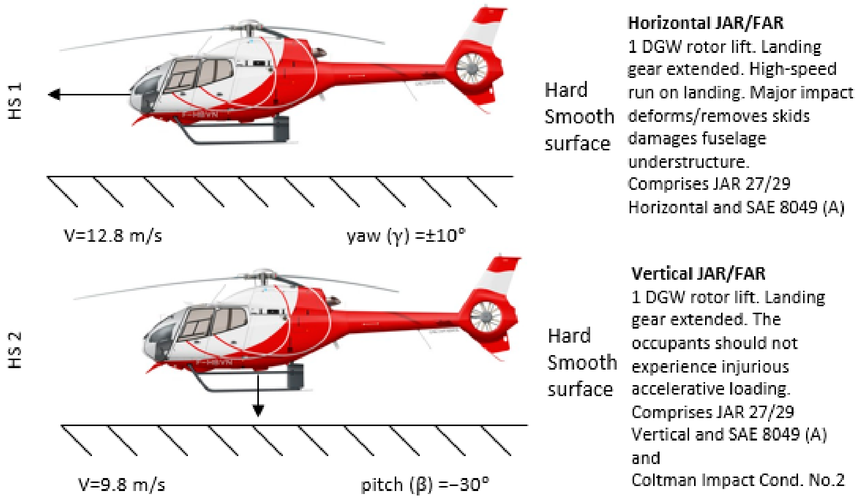


Figure 10. The HeliSafe selected crash scenarios. Adapted from [77].

A continuation of this study is the work by Blundell et al. [78], where t they used simulation methodologies during the work, which were multibody dynamics, finite element method, and experimental testing. As a result, the capability to include a model of the seat, dummy, restraint system, and airbag in a full MADYMO helicopter model has been demonstrated. This investigation helped to select the best restraint designs for side and front seated occupants (see Figure 11 for front seated). The body-centred harness, 3/4 point harness, 3-point harness, X-harness, 4-point harness, and triangle harness concepts of seat belts were reviewed. In the form case, the 4-point harness was given the best injury results for the HS1 case [78]. In addition, the airbag's optimal positioning and firing time were determined (see Figure 11) and used in the final drop test.

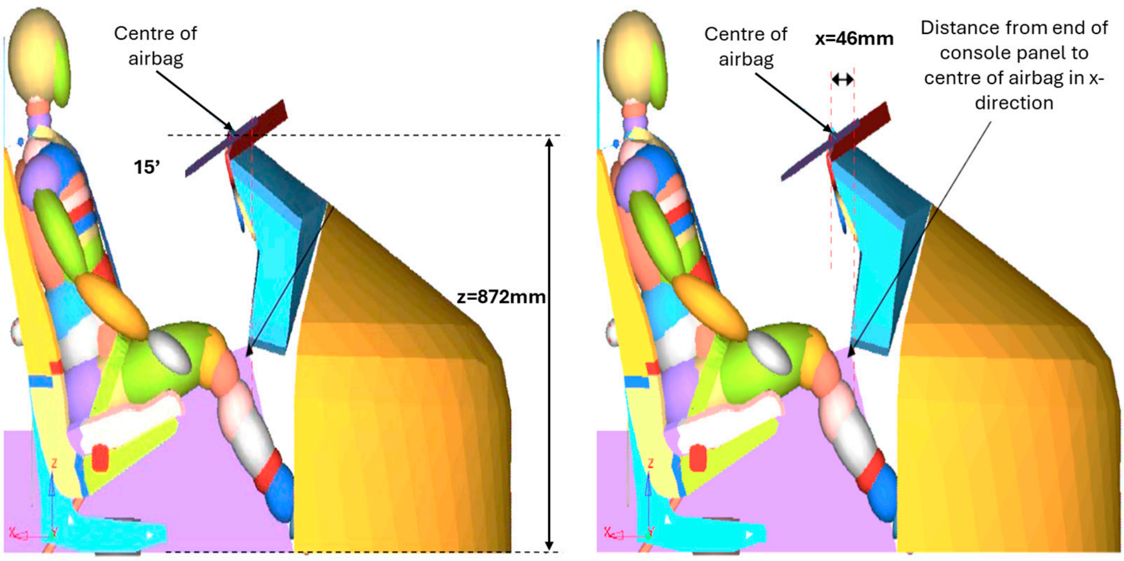


Figure 11. Investigation of airbag position. Adapted from [78].

In the work by Caputo et al. [79], the authors investigated the energy absorption capabilities of a full-scale composite fuselage section of a regional aircraft, along with the associated biomechanical injuries affecting passengers. The numerical model of the tested fuselage was developed using the LS-DYNA and MADYMO environments [80]. All major structural components of the aircraft were modeled, including frames, skin, stringers, beams, cargo floor, stanchion supports, and other structural features. For validation of the numerical results, relevant displacements were assessed using the ground-to-target distance as a measure of vertical displacement.

Composite materials, predominantly carbon-based (widely used for aircraft structural elements due to their excellent strength-to-weight ratio), were explicitly modeled to account for their destruction. Several studies have demonstrated that the failure of carbon-based elements under crush loads involves pulverization, splaying, or peeling [81–84]. However, such fracture mechanisms have a limited effect on load absorption during impact.

The extensive use of composite materials has enabled the development of elements oriented in the warp direction. In work authored by [85], NASA conducted tests on tubular specimens with a 3-inch diameter and 6-inch length fabricated from various material systems, including traditional carbon and hybrid woven fiber layers. Both static and dynamic tests were performed. Figure 12 illustrates the crush responses of different tube types.

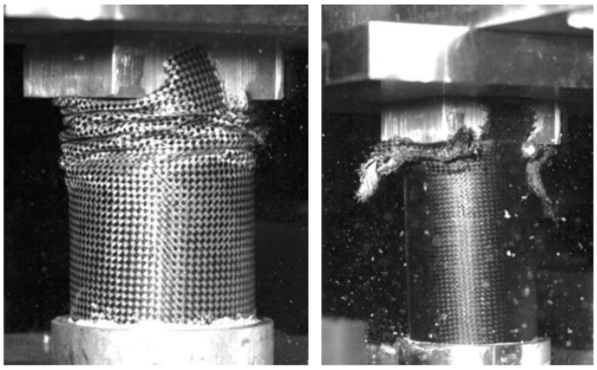


Figure 12. Full foam core left: hybrid material; right: traditional carbon plain weave crush responses. Reprinted from [85].

Such structural elements were introduced into the design model of the eVTOL NASA concept vehicle, and numerical analysis was performed to assess its effectiveness [64]. The analysis was evaluated under pure vertical loading. The hybrid composite tube, as a stroking mechanism between the seat and floor, reduced the lumbar load by more than half during impact in the aluminum airframe (see Figure 13).

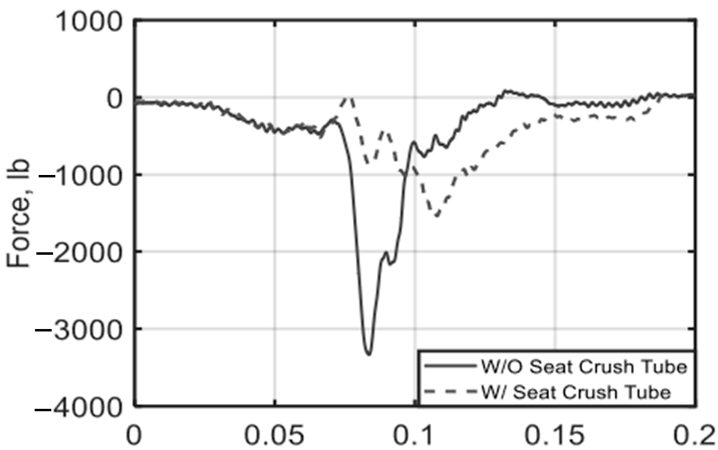


Figure 13. Lumbar load change due to the implementation of composite crush tube within seat design in the aluminium vehicle. Reprinted from [64].

One of the trends in absorbing the crush energy of aviation vehicles is the use of external protection systems such as airbags [86]. This system can be called an active Crash Protection System (ACPS) [87]. As indicated in work authored by [88], this system has a complex system, including the gas generation system and burst discs, which require significant tests to confirm operability. An additional drawback of such a system includes the fact that the airbag and gas generation system are on board the aircraft all the time of operation, which is not a payload on board and affects MTOW (maximum take-off weight). This fact is especially critical for light vehicles such as personal drones.

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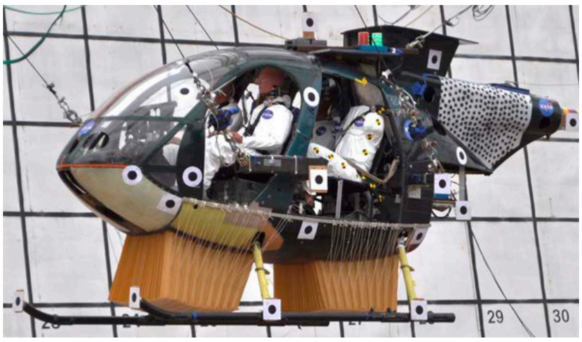
As noted by Littell J. in [88], one more potential injury protective system and alternative to an airbag system is a crushable concept called the deployable energy absorber (DEA). DEA is based on a unique and patented flexible hinge at each junction of its cell walls. This feature enables almost any size and strength energy absorber to be fabricated and readily deployed [59]. This system was utilized on a full-scale crash test of an MD-500 helicopter. The DEA was made from Kevlar-129 fabric and consists of multiple hexagonal cells. The full-scale crash test was performed with the following conditions of 25.6-ft/s vertical and 38.8-ft/s horizontal with −5.7° pitch, 7.0° roll, and 9.3° yaw attitude at impact with DEA and without DEA [89], see Figure 14. The DEA system reduced the lumbar load almost three times [88].



(a)

(b)

Figure 14. Deployable energy absorber system on MD-500 helicopter: (**a**) before test. Reprinted from Ref. [89], (**b**) after test. Reprinted from [88].

Alternatively, such a system can serve as a stiffening element within the main structure of an aircraft, particularly as an energy-absorbing component in seat elements or subfloors. Specifically, lightweight energy-absorbing subfloor concepts have been developed for potential use in electric vertical take-off and landing (eVTOL) vehicle designs utilizing Kevlar-129 fabric [88,89].

It is also evident that more cost-effective alternatives, such as cork, could be employed instead of expensive composite materials typically used for absorbent elements. Cork is already recognized as an impact energy-absorbing material, notably as a component in motorcycle helmets [90,91]. This versatile material is finding new applications in aviation, reflecting the interest of research initiatives such as the Educational Development for

Sustainable and Eco-friendly Cork Composites in Aerospace Applications project [92]. In other words, composite materials offer significant mass reduction benefits, improving range and efficiency. However, their crash response differs from traditional metals, as composites tend to fail through delamination rather than plastic deformation. The trade-off lies in balancing structural stiffness with energy absorption. Hybrid material solutions, including fiber–metal laminates and advanced polymer matrices, including cork-material in aerospace, are now being explored to optimize both mass efficiency and crash safety [93,94].

To enhance occupant protection during a crash, additional design features can be incorporated into seat structures to reduce or absorb impact energy. In particular, in work [52], Xiang Zhang conducted a helicopter seat crash test using LS-DYNA. The numerical model included a seat structure, a 50th percentile Hybrid III dummy, and a rigid floor. The results of this study were used to explore potential optimizations of the inversion tube and seat pan, aiming to improve crashworthiness performance.

Research has demonstrated that a well-designed seat, combined with an appropriate restraint system, can significantly enhance occupant protection during a crash [93]. In the work authored by [94], Putnam and Littell performed numerical simulations to evaluate crashworthiness design mechanisms, including a crushable subfloor, a crush tube design implemented between the seat and floor, and a deployable energy absorber (DEA) made of Kevlar-129 honeycomb. These mechanisms were assessed within a six-passenger lift-and-cruise eVTOL concept vehicle under multi-axis dynamic loading conditions. The numerical model was evaluated under combined $60^\circ/30^\circ$ vertical/horizontal impact loading with a 10° yaw component, uniaxial vertical impact conditions, and a 35 ft/s vertical impact condition.

The following conclusions were made based on the results of the study: using energy-attenuating mechanisms' efficiency depends on the impact condition's directional complexity. It was also found that the reduction in effectiveness of this mechanism within the more complex loading environment indicates the need for full system evaluation of occupant protective mechanisms across the range of dynamic impact conditions to which they may be subjected. This finding is particularly important for UAM vehicles, where omnidirectional impact conditions are more likely than those of traditional aircraft due to their design and flight environment.

Numerous studies have focused on the energy-absorbing properties of aircraft structures during crashes [49,50,80,81], reflecting the aviation industry's growing interest in this energy-absorption method. This approach enables high occupant protection performance while simultaneously achieving mass efficiency.

It is worth noting that this method presents a viable option for vehicles in this class—primarily relying on hover rather than lift generated by aerodynamic forces on wings. In scenarios where a propulsion module fails, the system can autonomously initiate an emergency procedure to mitigate the risk of high-impact collisions with the ground or other obstacles. The vertical take-off and landing (VTOL) capabilities of personal drones eliminate the need for a high-demand airstrip, making emergency landings feasible even in densely populated urban areas, where suitable landing spots are more readily available. Ultimately, during an emergency, the active safety system prioritizes slowing the vehicle as much as possible to avoid high-impact collisions. For flying vehicles, such collisions are particularly severe due to the necessity of optimizing performance through mass reduction, which increases the risks associated with kinetic and gravitational potential energy.

Public perception of UAM safety remains a key challenge for widespread adoption. Concerns regarding crash risks, noise pollution, and air traffic management can slow regulatory approvals and market acceptance. While strategies such as transparent safety demonstrations and early use cases in controlled environments (e.g., medical transport, logistics) may help build confidence, further studies on public attitudes and risk communication strategies are needed.

5. Conclusions

In recent years we have witnessed growing interest in personal drones, as evidenced by the extensive efforts of aviation regulatory bodies such as the Federal Aviation Administration (FAA) and the European Union Aviation Safety Agency (EASA). The organizations are actively investigating the potential of a novel class of aircraft featuring vertical take-off and landing (VTOL) capabilities for urban air mobility (UAM). The current review highlights a substantial number of prospective designs and existing prototypes currently undergoing certification. Additionally, a comprehensive assessment of the state-of-the-art occupant safety measures for personal drones, alongside established protection methods for similar aircraft, has been conducted. Similar to conventional aviation (e.g., airplanes and helicopters), personal drones necessitate a high level of occupant protection during crash scenarios. An integrated safety approach has recently emerged as a primary strategy for enhancing occupant safety, as these aircraft are highly sensitive to structural weight constraints, necessitating the exploration of new impact resistance techniques. Notably, one of the key technical contradictions in eVTOL safety design is the trade-off between lightweight construction and impact resistance. While reducing structural weight is essential for flight efficiency and extended range, it poses challenges in ensuring adequate crash protection. The holistic methodology integrates multiple safety features to mitigate risks effectively. The evaluation of occupant injuries in aviation traditionally relies on a range of established criteria, which, based on extensive research, can be effectively adapted for application to electric VTOL (eVTOL) vehicles. A novel approach to steering and propulsion control in personal drones offers innovative opportunities for enhancing passenger safety by dissipating energy prior to a crash. The presented research emphasizes the integration of eVTOL vehicles into UAM systems, with a particular focus on passenger safety through the implementation of an integrated safety system. Similarly, NASA (National Aeronautics and Space Administration), a pioneering institution in aviation research, prioritizes the advancement of passenger safety features for eVTOL vehicles. As highlighted in relevant studies, it is imperative to evaluate vehicle designs across a spectrum of potential dynamic impact conditions to characterize their impact resistance. Nonetheless, the diverse designs and operational profiles of eVTOL vehicles present challenges in standardizing flight profiles and, consequently, crash scenarios. The analysis presented in this article reveals the existence of various eVTOL configurations. The existing literature on eVTOL occupant safety predominantly addresses vehicles designed for UAM. Nonetheless, it is critical to recognize other eVTOL variants, such as the Jetson One and Hover Scorpion, which prioritize practicality (e.g., rapid boarding), point-to-point travel, or recreational use. Future research should prioritize refining the safety strategies while maintaining the structural efficiency necessary for sustainable eVTOL operations.

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Abbreviations

CAD	Computer-Aided Design
CAE	Computer-Aided Engineering
EASA	European Union Aviation Safety Agency
EC	European Commission
eVTOL	Electric Vertical Take-off and Landing Aircraft
FAA	Federal Aviation Administration
FEA	Finite Element Analysis
FEM	Finite Element Method
FHA	Functional Hazard Assessment
HIC	Head Injury Criterion
MTOW	Maximum Take-off Weight
MB	Multibody
NASA	National Aeronautics and Space Administration
UAM	Urban Air Mobility
THUMS	Total Human Model for Safety

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