Civil Aviation Authority

Drone Safety Risk: An assessment

CAP 1627

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1. Executive summary

1.1 The Civil Aviation Authority (CAA) supports the safe development of drones in the UK. Drones can bring economic and workplace safety benefits, but to achieve those we need everyone flying a drone to do so safely.

1.2 The use of small unmanned aircraft, more commonly known as drones, is rising in the UK, for both leisure and commercial purposes. With that increase in usage comes more questions about the unintentional risks of drones colliding with, or disrupting, manned aircraft.

1.3 At the time of writing there have been seven confirmed cases of direct in flight contact between drones and civil or military manned aircraft worldwide[1]. There have been no known collisions between small drones and manned aircraft in the UK. However, the number of occasions where pilots have reported suspected drones in proximity to their aircraft in the UK is increasing; there were 59 such occasions between April 2016 and March 2017. Two of these involved large passenger aircraft near Heathrow, leading to concerns being voiced in Parliament, in the media and by a range of aviation bodies about the possible impact of a collision between a passenger aircraft and a drone. A further incident in July 2017, where an object believed to be a drone was seen near Gatwick, led to the runway being closed briefly and flights being diverted.

1.4 The CAA has undertaken an assessment of available information about the likelihood of an unintentional drone collision and the severity of any possible impact between an aircraft and a smaller unmanned vehicle (defined as under 2kg in this report). The findings are:

- The drones most likely to end up in proximity to manned aircraft are smaller drones, typically of 2kg or less, flown by operators who either do not know the aviation safety regulations or have chosen to ignore them.
- It is considered unlikely that a small drone would cause significant damage to a modern turbo-fan jet engine; even if it did, a multi-engine aircraft would still be likely to be able to land safely.

[1] Aviation Safety Network drone database, 14th Dec. 2017 - 7 confirmed and 6 suspected collision events worldwide. (https://aviation-safety.net/database/issue/drones.php))

- The likelihood of a small drone being in *proximity* of a passenger aircraft when it is travelling fast enough to potentially damage a windscreen is currently observed to be about 2 per million flights, where proximity means within visual line of sight of the aircraft.
- The likelihood of a small drone actually hitting a passenger aircraft windscreen at sufficient speed to rupture it is very much smaller than the probability of it being in the proximity of an aircraft.
- The windscreens of small helicopters and light aircraft are more susceptible to rupture if struck by a small drone, even when flying below normal cruising speed.
- Helicopters face more particular risks because of the additional susceptibility of helicopter rotors to damage from a collision with a drone, and their operating patterns which typically involve lower-level flying and take-off and landing from a range of sites.

1.5 The standards of design and production of large passenger aircraft may provide some reassurance about the risk to life associated with a small drone collision. However, they raise concerns about the risks to other manned aviation. The CAA has produced a bowtie safety assessment model examining potential mitigations to these risks. At present, all such mitigations – which range from drone operator education to pilot action to enforcement to technical limitations on drones – remain essential to ensure the separation of small drones and all manned aircraft. Achieving this separation with high levels of confidence and consistency is the only way of securing high levels of aviation safety. It is critically important that those who operate drones **always** do so within the regulations and guidelines set by the CAA or Government Departments.

1.6 The risk of collision is a complex issue that depends on the interaction of many factors. For example, an increase in drone ownership may not automatically increase the probability of a collision if those drones are flown rarely or if they are flown in accordance within the safety rules and therefore away from aircraft. Comprehensive data about the frequency and nature of drone use is very limited, and therefore a reliable predictive model that would enable an assessment of changes to key risk factors is not possible at the current time. The assessment contained in this report is based on observed numbers of reported drone proximity events.

1.7 The prime responsibility for establishing research programmes into collision consequences rests with the aircraft certification authorities; in the UK, as in the rest of Europe, this is the European Aviation Safety Agency (EASA). In the US, the Federal Aviation Administration (FAA) has commissioned an extensive programme of research which is already under way and published[2] some initial results on 28th November 2017 on the modelling completed to date, which suggests:

- Small drones can introduce severe damage to some aircraft structures, with greater damage at higher speeds (and therefore typically higher altitudes);
- Non-severe structural damage can create significant economic burden to aircraft operators; and
- Drone collisions cause greater structural damage than bird strikes for equivalent impact energy levels.

1.8 The conclusions of the FAA's work, which are based on extensive modelling, are broadly consistent with the findings in this assessment. The FAA is planning further work over the next two years. The CAA will continue to monitor the outcomes of such programmes as new evidence becomes available.

1.9 In conclusion, CAA's review of existing risk evidence indicates that drones do pose a potential safety risk to other airspace users, though commercial aircraft are designed and manufactured to high standards. Light aircraft and helicopters are designed and built to different requirements and therefore the consequences of a small drone colliding with these forms of aircraft may be different from larger commercial aircraft. Further research is required by aircraft certification authorities and aircraft manufacturers to better understand the damage implications of a collision, and as data about usage becomes available, the probability of collision.

1.10 In any event, the best way to reduce safety risk is to prevent any two aircraft coming into proximity in the first place. The conclusions of this review therefore support the CAA's current drone priorities, which are to:

- Continue with the high-profile education and communications campaign to inform drone operators about how to fly responsibly;
- Define and publish geo-fenced areas to set electronic no fly zones;
- Strengthen the education and accountability of operators through mandatory training and registration of drone operators; and
- Link drone registration to the electronic conspicuity of drone flights and all other flights to help operators maintain safe separation from other airspace users and aid authorities in taking enforcement action against irresponsible drone operators.

[2] http://www.assureuas.org/projects/deliverables/sUASAirborneCollisionReport.php

2. The risk picture

2.1 For both recreational and commercial purposes, the use of small unmanned aircraft, commonly referred to as drones, has increased significantly over recent years. With lower costs and a wider range of available products, drones are now more affordable and attractive to a wider range of people. However, as their use increases, so does the unintentional risk of drones disrupting or even colliding with other air traffic.

2.2 At the time of writing this report, there have been seven confirmed collisions between drones and other civil and military aircraft across the world[3]; none of which occurred in the UK. However, there have been a number of reported instances of a drone being in the proximity of a commercial aircraft in UK airspace. These have led to growing public questions about the potential risk of collision and the damage that could result.

2.3 The Civil Aviation Authority (CAA) has considered available information about the safety risks linked to drones, i.e. the likelihood of a collision, or of a loss of control of the aircraft occurring as a result of proximity to a drone, and the possible impacts of such an incident. The focus, in the latter case, has been on the potential for harm to those on board an aircraft or those on the ground.

2.4 The CAA has not looked at the disruption that could be caused to air traffic by the presence of a drone in the flight path, nor at the potential economic costs to aircraft owners (and drone owners) of any damage to their aircraft.

How risk has been assessed

2.5 Risk is assessed as a combination of the likelihood of an event occurring and the severity of the outcome if it did occur. On this basis, an event that is deemed relatively likely to occur and would result in a fairly severe outcome may be considered a higher risk than either an extremely severe event that is very unlikely to occur or a minor event that may occur more often.[4]

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[3] Aviation Safety Network drone database, 14th Dec. 2017. (https://aviation-safety.net/database/issue/drones.php)

[4] The combination is often expressed in a risk matrix, with likelihood on one axis and severity on the other. See e.g. CAP795 Safety Management Systems (SMS) guidance for organisations https://publicapps.caa.co.uk/docs/33/CAP795_SMS_guidance_to_organisations.pdf p 14-16

2.6 In the case of this report, the “event” being considered is injury or death to those on board the aircraft, or to third parties on the ground, either as a result of a mid-air collision (MAC) between a drone and another aircraft or as a result of loss of control of the aircraft resulting from an abrupt manoeuvre whilst trying to avoid the drone.

2.7 In these terms, the most severe incident would be a collision between a drone and a large passenger aircraft that resulted in the loss of the aircraft. This is because of the greater number of passengers involved and the greater risk of third parties on the ground being injured by wreckage.

2.8 However, there are other possible outcomes of a collision or near miss which would result in fewer injuries or none at all; most obviously, despite a collision, it is likely that the aircraft would land safely.

2.9 The likelihood of a safe landing following a collision would depend on, among other things, what part of the aircraft was hit, how large the drone was and at what speed the collision occurred. It could also potentially be influenced by the type of aircraft. A large passenger aircraft with several engines would not necessarily be incapacitated by a drone colliding with one of its engines. By contrast, the consequences could be more severe for a single engine aircraft.

2.10 Similarly, if a drone struck the windscreen of an aircraft, this could result in the flight crew being unable to see clearly, suffer injury from debris, or potentially for the drone to penetrate the screen, which could in turn cause a loss of control.

2.11 The report does not only consider the risk of a collision. Even if a collision were avoided, the outcome could still be very serious if the aircraft pilot, in seeking to avoid the drone, lost control of the aircraft.

2.12 The picture is further complicated by the fact that a near identical collision (same size drone, same type of aircraft, same point of impact) could result in very different outcomes, depending on other factors. For example, if such a collision resulted in damage to flight controls, one factor affecting the outcome could be weather conditions: on a day when there was little wind and visibility was good, a successful landing of the aircraft would be more likely. In this context, it is also worth noting that drones are less likely to be flown in poor weather conditions.

2.13 Figure 1 summarises some of the potential events that could follow a collision between a drone and an aircraft. However, this report focuses on the ‘immediate’ risk associated with the collision, i.e. the likelihood of the event and the severity of the damage caused, rather than trying to determine the specific risk of each of the many potential consequences that could result from a collision.

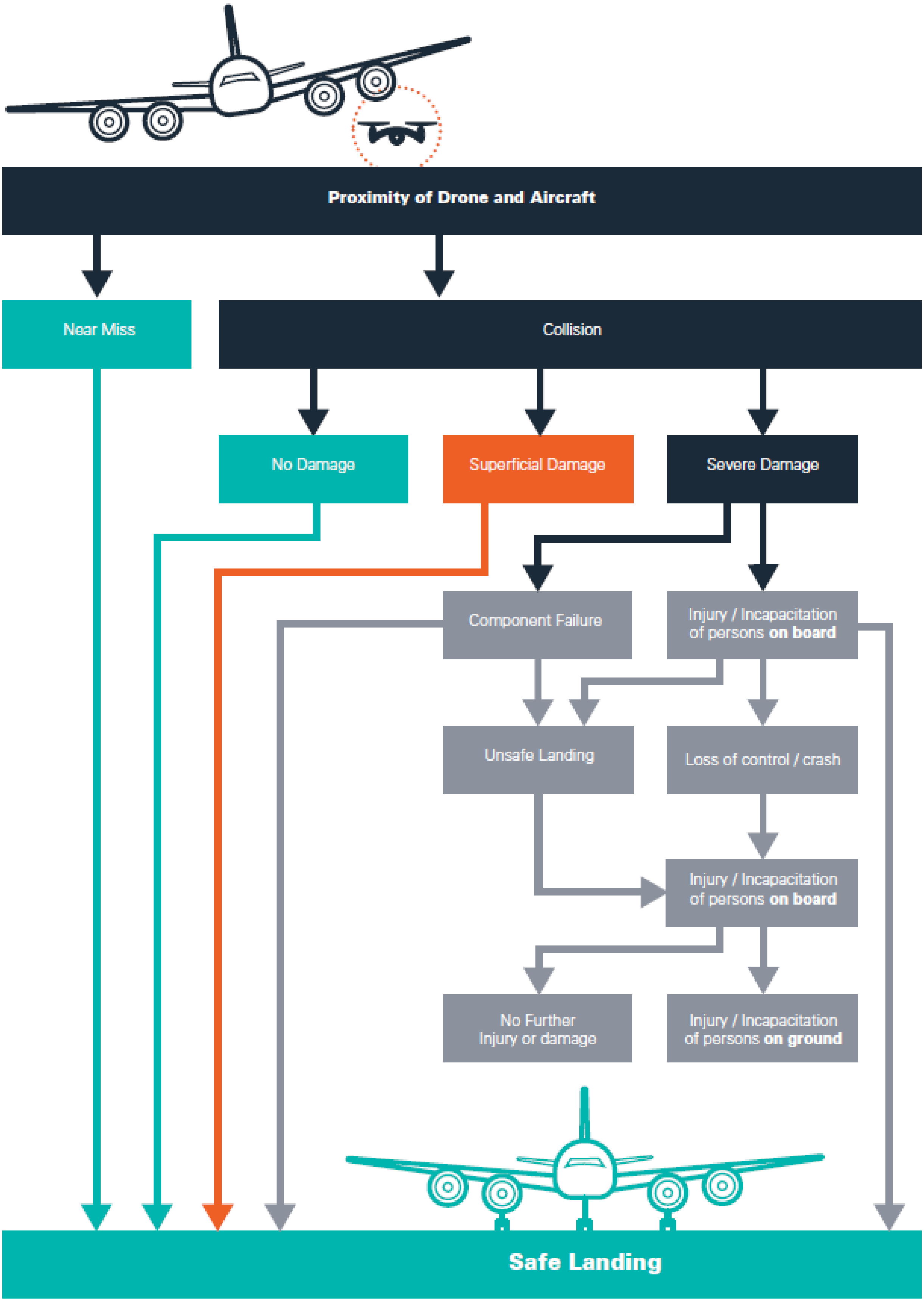


Figure 1 – Example of potential events following a collision

The CAA's approach

2.14 To assess both the likelihood and severity of a collision, the CAA has conducted a review of publicly available data and studies.

2.15 In terms of likelihood, the CAA has considered observed data that is available about drone ownership and usage, and about incidents where objects described as drones have been reported in close proximity to aircraft. This includes data from the Mandatory Occurrence Reporting (MOR) Scheme[5], Airprox reports[6], radar data, CAA data on aircraft movements and Office of National Statistics (ONS) data. We have looked at where these incidents have occurred, both in terms of the geographical location and the altitude to reach an assessment about observed level of current risk. The absence of comprehensive data about the levels of drone ownership and the frequency and nature of its use means that a reliable predictive model is not achievable at present. Moreover, the relationship between levels of drone ownership and risk to other aircraft is not likely to be straightforward. For example, while drone ownership is widely reported to be increasing, this will not automatically lead to a material change to the probability of drone collision risk. The risk of collision will depend on a range of factors including:

- How often drones are actually flown;
- How well drone operators educate themselves about the rules and regulations that are designed to keep other aircraft safe, and use technology such as recognised pre-flight information apps to give them information to enable them to fly safely;
- How well these operators adhere to the rules; and
- How well other aircraft are able to take avoiding action.

2.16 To help assess the severity of a collision, the CAA has looked at the effects of birdstrikes on aircraft – on the basis that these are potentially similar in size and weight to drones. We have also reviewed current aircraft certification standards, some of which include specific requirements for the aircraft to be able to withstand birdstrikes and other events.

[5] The MOR scheme is a means of recording data about all incidents which endanger or which, if not corrected, would endanger an aircraft, its occupants or any other person. The purpose of occurrence reporting is to improve aviation safety by ensuring that relevant safety information relating to civil aviation is reported, collected, stored, protected, exchanged, disseminated and analysed. See www.caa.co.uk/mor

[6] An Airprox is a situation in which, in the opinion of a pilot or air traffic services personnel, the distance between aircraft as well as their relative positions and speed have been such that the safety of the aircraft involved may have been compromised. Such incidents should be reported to the UK Airprox Board, which collects and analyses this data to support aviation safety. www.airproxboard.org.uk

2.17 The CAA has not conducted any primary research of its own, but it has been able to draw on the published outcomes of a recent study into the impact of drones colliding with commercial aircraft windscreens.[7] In addition, CAA technical opinion has been used to assert a case for likely damage severity.

2.18 On 28th November 2017, ASSURE, the research centre of US aviation regulator the FAA, published its own preliminary modelling research into the potential severity of drone collisions[8]. Based on detailed modelling, the conclusions of this work are that:

- Small drones can introduce severe damage to aircraft structures but whether it does so depends on the location of the impact on the airframe, the velocity of the aircraft and design and construction of the drone. Non-severe structural damage can cause significant economic burden for aircraft operators;
- Damage severity to the aircraft increases with the mass and velocity of collision;
- Velocities above landing speeds are critical for masses above 1.2 kg;
- Most damage is produced by the stiffer components of a drone (e.g. battery, motor); and
- Drone collisions cause greater structural damage than bird strikes for equivalent impact energy levels (mass and impact velocity).

2.19 The results of the FAA's work, which are based on extensive and detailed modelling, broadly align with the findings of this assessment. The FAA has further research work planned over the coming years. The CAA will monitor the outcome of this research and other published work on collision consequences.

2.20 This assessment has been reviewed by members of the Safety and Accident Investigation Centre at Cranfield University and reflects their input.

Bowtie model

2.21 Drawing this different data and input together, the CAA has developed a bowtie safety assessment model that examines the potential outcomes of proximity between a drone and a manned aircraft and how these outcomes could be mitigated.

2.22 Bowtie models are regularly used by the CAA to provide an effective, visual depiction of risk. They consist of different elements that build up the risk picture. The risk picture revolves around the hazard (something in, around or part of an organisation

[7] Department for Transport (DfT), Military Aviation Authority (MAA) and British Airline Pilots' Association (BALPA) - *Small remotely piloted aircraft systems (drones): mid-air collision study* www.gov.uk/government/publications/drones-and-manned-aircraft-collisions-test-results.

[8] FAA ASSURE UAS Airborne Collision Hazard Severity Evaluation Final Report: www.assureuas.org/projects/deliverables/sUASAirborneCollisionReport.php

or activity which has the potential to cause damage or harm) and the top event (the release or loss of control over a hazard known as the undesired system state).

2.23 Consideration then moves to the threats (a possible direct cause for the top event), consequences (results of the top event directly ending in loss or damage) and the controls (any measure taken which acts against some undesirable force or intention).[9]

2.24 The bowtie model is published alongside this report. However, all key findings are included within the report itself.

Drone usage: an overview

2.25 While there is no validated source of data about drone ownership and usage, it is widely recognised that drone usage in the UK is growing. Drones are flown by individuals and organisations, for both leisure and commercial reasons. They can be bought in a range of different sizes and with different capabilities, typically flown within Visual Line of Sight (VLOS) rules, but including the ability, in more advanced drones, to fly beyond the visual line of sight (BVLOS) of the user.

2.26 All commercial operators must obtain permission to fly their drone(s) from the CAA and, in the process, demonstrate required standards of training, knowledge and safe operation. Further, any drone with mass of over 20kg is, unless exempted or varied by CAA, subject to the full range of regulatory requirements set out in the Air Navigation Order (ANO) 2016[10]. These include registration, airworthiness certification and flight crew licensing. These requirements for drones of over 20kg mass mean the operator has to demonstrate, among other things, greater understanding of the pertinent regulations and behaviours that manage and mitigate collision risk.

2.27 As a broad rule of thumb, these heavier drones are also larger and more technically advanced. They are also far more expensive. As Figure 2 shows, purchase costs rise with greater mass.

[9] See www.caa.co.uk/Safety-Initiatives-and-Resources/Working-with-industry/Bowtie/ for more details

[10] See www.caa.co.uk/CAP393

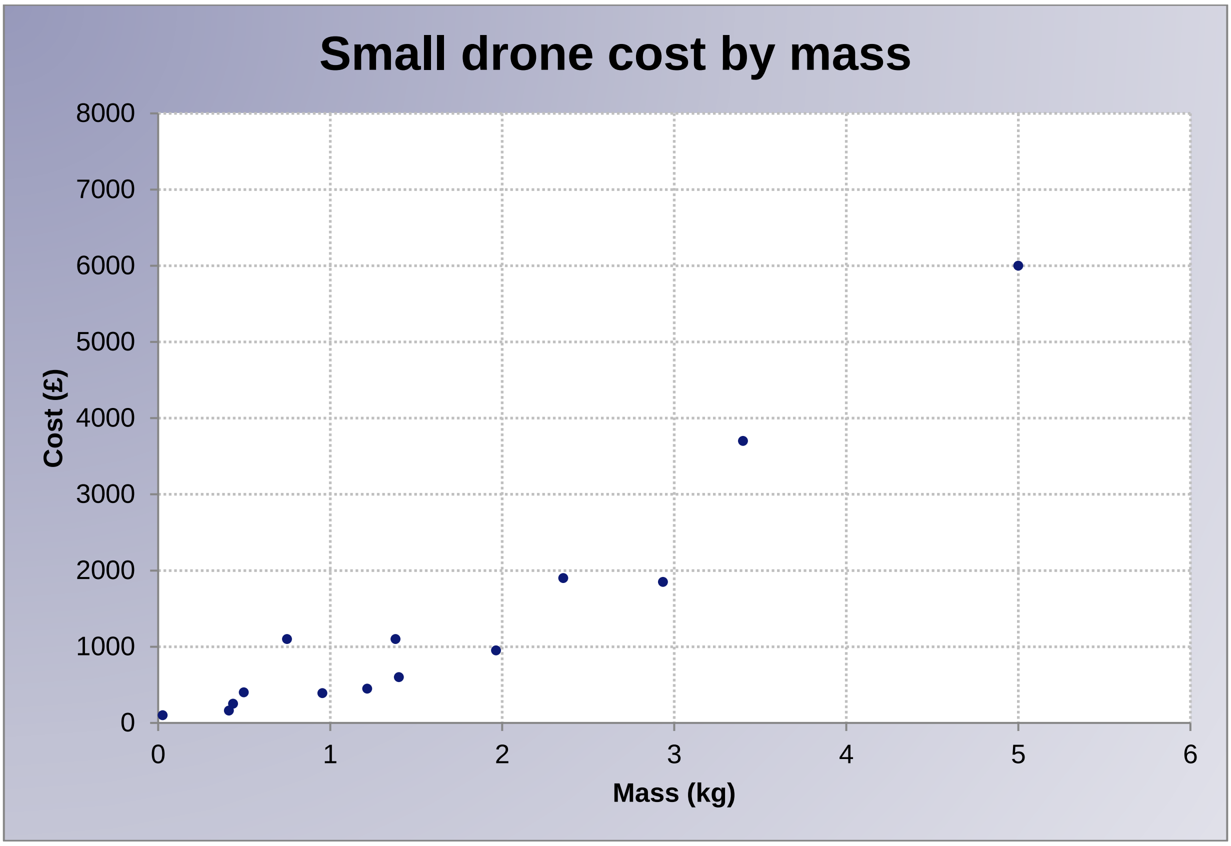


Figure 2 – Small drone cost by mass

2.28 A drone costing around £500 will typically weigh around 1kg, a drone of around £1000 is of the order of 2kg, and as indicated in Figure 2, above this the costs increase significantly. The main reason identified for the escalating cost is the complexity of the sensor package (typically a camera). The same drone chassis could be used to hold a simple low-resolution camera and associated gimbal mounting that costs about £300, or a studio-quality gimbal, camera and lens costing more than £100,000 and weighing far more.

2.29 The increased severity inherent in collisions involving heavier drones is therefore offset by the fact that such drones will be fewer in number due to the higher cost and are likely to be used by more informed operators, often for commercial purposes.

2.30 The greater risk of collision involves smaller drones operated by recreational users. While many such users are aware that aviation is a regulated activity and endeavour to adhere to the rules and use their drone(s) responsibly, there is currently no mandated requirement for users to seek permission to fly drones and to demonstrate awareness of applicable aviation regulations or to practice prior to use.

2.31 The CAA Drone Code[11] provides recreational users with a simple overview of the regulation. It sets out six basic rules to support safe drone operation. These are based on a subset of the ANO regulations covering small unmanned aircraft (SUA)[12], which applies to all drones under 20kg. One of the rules is that users must always operate their drone within visual line of sight (VLOS). Another is that users must keep their drone away from aircraft, airports and airfields.

2.32 The Drone Code has been widely publicised and many vendors and manufacturers provide a copy of it at the point of sale. However, there is currently no mechanism in place to test whether drone operators understand these rules before they operate a drone, though this is something the UK Government is considering addressing. It is also possible that some users who are fully aware of the regulations will chose to ignore them. Such activity cannot be controlled by regulation alone and represents a risk which cannot be analysed or quantified from existing safety data.

2.33 Together, these factors lead the CAA to consider that the likelihood of drone collision with other aircraft is highest in relation to small drones operated by recreational users. Given the cost and mass relationship in Figure 2, it is further considered likely that the majority of recreational small drones will be of less than 2kg mass. This is the category of drone covered by this assessment.

[11] See http://dronesafe.uk/drone-code/

[12] The ANO defines "Small unmanned aircraft" as any unmanned aircraft, other than a balloon or a kite, having a mass of not more than 20kg without its fuel but including any articles or equipment installed in or attached to the aircraft at the commencement of its flight. The applicable regulations for small unmanned aircraft are defined through Article 23 of the ANO (giving them exemption from the full scope of the ANO) and in particular Articles 94 and 95.

3. What is at risk?

3.1 The overall risk under consideration is of harm to the occupants of manned aircraft and to third parties on the ground. Of course, manned aircraft come in a variety of sizes and types, with large variation in the number of people on board.

3.2 This is already acknowledged within regulations and aircraft design requirements, which vary according to factors such as occupancy and use. Airworthiness certification requirements for aircraft include aspects to assure safe operation even if problems should occur – and large passenger aircraft are required to meet higher safety standards than light aircraft. For example, large passenger aircraft which have more than one engine are required to have the capability to continue to take off and land using only one engine, if the other fails. Further, as part of their training, pilots must demonstrate competence in managing these potential failure scenarios.

3.3 In the context of drone collisions, these different design requirements could affect the type and level of damage sustained and hence the severity of the event.

3.4 For aircraft designed in Europe including the UK, the standards are set out in Certification Specifications (CS) published by the EASA. For aircraft designed in the US, the certification body is the Federal Aviation Administration. Current EASA CS define nine categories of manned aircraft.

Certification Specification	**Description**	**Max. people on board**
CS-22	Sailplanes and Powered Sailplanes	1 or 2
CS-23	Normal, Utility, Aerobatic and Commuter Aeroplanes	~21 (commuter)
CS-25	Large Aeroplanes	~855 (A380)
CS-27	Small Rotorcraft	~11
CS-29	Large Rotorcraft	~90 (Mi-26)
CS-31GB/HB/TGB	Gas/Hot Air/Tethered Gas Balloons	~32
CS-LSA	Light Sport Aeroplanes	~2
CS-VLA	Very Light Aircraft	~6
CS-VLR	Very Light Rotorcraft	~4

Table 1 – EASA Certification Specifications

Note: ***The Maximum People on Board represents the maximum demonstrated capacity for the category of aircraft. The maximum number of persons on board varies for each aircraft type and is typically less than the maximum demonstrated.***

3.5 As stated earlier, this report considers the collision harm risk associated with large passenger aircraft (CS-25) from drones of 2kg or less. This is a risk that has been widely identified to be of prime concern, not only because of the number of passengers involved, but also because these aircraft often fly over densely populated urban areas. Furthermore, a large proportion of the reported occurrences of proximity between drones and manned aircraft have involved large passenger aircraft.

3.6 However, the paper also considers the collision harm risk to smaller General Aviation (GA) aircraft and to helicopters and other rotorcraft. These two categories of aircraft typically operate at lower altitudes – as drones do. GA aircraft have proportionately less demanding design and certification requirements than large passenger airliners which may increase their vulnerability in the event of a collision. For helicopters, there is the additional issue of the potential damage a drone collision could cause to rotors operating at speed.

What damage could a drone collision cause to an aircraft?

3.7 To assess the risk of immediate or subsequent harm to persons, the CAA has considered the potential consequences of small drone collision with six functional areas of an aircraft. These have been identified as the parts of the aircraft where a drone impact is most likely:

- Windscreen/canopy
- Engine(s)
- Wing/tailplane leading edges
- Undercarriage/flaps/spoilers (when extended)
- Flying control surfaces
- Rotors

Windscreen/canopy

3.8 The most obvious risk here is rupture of the windscreen, which could immediately cause injury to flight crew should debris or the drone itself enter the cockpit. Windscreen rupture or damage could also result in reduced visibility. Both scenarios could lead to subsequent loss of control.

3.9 Helicopter windscreens typically extend across more of the front of the aircraft than fixed-wing aircraft windscreens. This presents an additional vulnerability from small drone debris entering the cockpit and potentially interfering with instrumentation and control systems, such as the yaw pedals, which perform a similar function to the rudder pedals on a fixed wing aircraft.

3.10 There are two crucial factors in understanding: the potential severity of a drone strike on a windscreen:

- the material properties of the windscreen/canopy; and
- the energy of the collision.

3.11 A potential parallel here is to consider the risk of birds striking the windscreen. As this is a recognised risk for aircraft, some EASA certification specifications include a requirement for the aircraft to withstand a birdstrike in their 'normal' operating mode. For instance:

- CS-25 aircraft (including passenger airliners) are required to demonstrate that the windscreen can withstand impacts from a 4lb (1.8kg) bird at the cruising speed of the aircraft[13], typically of the order of 340kt for a passenger airliner.
- CS-29 aircraft (large helicopters) are required to have a windscreen that can withstand a 1kg bird impact at speeds of the order of 170kt[14].
- CS-23 commuter aircraft[15] windscreens must be able to withstand a 2lb (0.91kg) bird at speeds of the order of 140kt[16].

3.12 As identified earlier, the majority of recreational drones are likely to be of similar mass, i.e. 2kg, so the ability to withstand these birdstrike impacts would indicate *some* ability to withstand the impact of a collision with a small drone. However, the CAA recognises, and the recent FAA modelling work suggests, that the design and materials used in drone construction are likely to mean that drones cause more damage than birds for equivalent impact levels.

3.13 Other categories of aircraft, such as small helicopters and GA aircraft have no such birdstrike requirement and so are potentially more susceptible to windscreen damage.

3.14 To provide more specific insight, the Department for Transport, the Military Aviation Authority and the British Airline Pilots' Association jointly commissioned a study into the effects of a collision between small drones and a range of manned aircraft. It

[13] CS 25.631 Bird strike damage.

[14] CS 29.631 Birdstrike.

[15] Defined as propeller driven twin-engine aeroplanes with fewer than 20 passenger seats and a maximum weight of 8618kg.

[16] CS 23.2320 Occupant physical environment.

conducted tests using drones within classes of 0.4kg, 1.2kg and 4kg. The results were published in July 2017[1] and identified that:

- Overall, although the birdstrike certified windscreens tested had greater resistance than non-birdstrike certified, they could still be critically damaged by drone collision at normal cruise speeds.
- Airliner windscreens are much more resistant than any other category. However, there was a risk of critical windscreen damage when impacted by a 4kg drone at high, but realistic, impact speeds.
- Non-birdstrike certified helicopter windscreens have very limited resilience to the impact of a drone, well below normal cruise speeds.
- The non-birdstrike certified helicopter windscreen results can also be applied to GA aircraft which also do not have a birdstrike certification requirement.
- The construction of the drone plays a significant role in the impact of a collision. Notably, the 0.4kg class drones used in the testing, which included exposed metal motors, caused critical failure of the helicopter windscreens at lower speeds than the 1.2 kg class drones, which had plastic covering over their motors. This is believed to have absorbed some of the shock of the collision, reducing the impact.
- The testing and modelling showed that drones could cause significantly more damage than birds of equivalent masses, at impact speeds lower than required to meet birdstrike certification standards.

Engine(s)

3.15 The central question is whether a collision with a small drone could cause a loss of thrust to a manned aircraft. This can be divided into two distinct categories:

- jet engine powered aircraft, where the risk would relate to the drone being ingested into the engine compressor or turbine, and
- aircraft where the thrust is provided by propeller. These have a lower risk of engine failure due to the inherent properties of the propeller/engine design and engine installation. However, the propeller itself is a key risk area, because any damage may cause partial or complete loss of thrust and, more significantly, out of balance forces may cause further damage to the whole engine installation.

3.16 In terms of the risk to a large aircraft, the fact that a jet engine has been damaged may not cause an immediate risk to crew or passengers, even if the engine has failed. This is because they typically have multiple engines and are certified for continued safe flight and landing in the event of loss of one engine’s thrust.[17]

[17] CS 25.143 (Controllability and manoeuvrability - General).

3.17 Further, the expert opinion of a leading jet turbine engine manufacturer is that the current suite of certification requirements for aero-engines provides a very significant degree of protection for any structural integrity issues that might be posed by potential drone ingestion. With the possible exception of any particularly dense items that the drone might be carrying, which as identified earlier can vary considerably, the manufacturer believes it is unlikely that small drone ingestion would significantly affect the ability of the engine to produce thrust. The manufacturer also views it as extremely unlikely that drone ingestion would compromise the ability of the engine to be shut down safely.

3.18 Some subject experts have suggested that there may be a secondary risk to engines: the risk of fire caused by the combustion of lithium polymer (LiPo) batteries, used in most smaller drones. This concern cannot be quantified: the CAA has found no open-source testing that helps ascertain the likelihood of this scenario. More information on this outcome would need to come from research commissioned from the major aircraft and engine certification authorities.

Wing/tailplane leading edges

3.19 The leading edges of aircraft wings and tailplanes are load-bearing structures. If their shape or form is damaged, this can result in reduced structural integrity as well as asymmetric aerodynamic loads, making the aircraft harder to control. This is particularly the case for small and very light aircraft, where leading edge impact could result in disruption of critical load paths further back in the structure. Obviously, the significance of this depends on the energy of impact, but in the worst case the result could contribute to a catastrophic failure of the wing or tailplane element and subsequent loss of control.

3.20 While the size and construction of larger and more complex aircraft makes this less of a concern, their leading edges often contain important systems such as hydraulic pipework, de-icing systems or electrical trunking. Existing design standards typically require such systems to be designed in such a way that there is a built-in back-up. So if one wing is damaged, there may be a separate system in the other wing. This requirement for independent and redundant systems provides a degree of overall protection in the event of disruption to any one system. It is very unlikely that systems on both wings would be disrupted by a single collision with a small drone.

3.21 There is an unknown probability that a small drone LiPo battery could become embedded in an aircraft structure, and then be sufficiently disrupted that it could create a fire hazard. This risk is identified as part of the FAA modelling work.

Undercarriage/flaps/spoilers

3.22 Aircraft undercarriages, when lowered, and flaps and spoilers, when lowered or extended, present potential impact areas for a small drone collision.

3.23 The main undercarriage is, by the nature of its function, very robust – particularly in a large passenger aircraft – and a small drone collision should not cause significant damage. However, some components could be affected and damage could be caused to undercarriage doors or fairings, to tyres and brake packs or to ancillary systems such as electrical or hydraulic control or indication circuits.

3.24 Although it is possible that such items breaking off could then strike other parts of the aircraft, the risk of immediate harm to the aircraft occupants from any such damage is considered negligible due to the undercarriage location and surrounding structure. However, if this resulted in a reduced braking or steering capacity on landing, there could be a risk of subsequent harm.

3.25 Any damage to a flap or spoiler will likely be confined to the wing which was the point of impact. Again, the risk of immediate harm is considered negligible due to the location of the flap/spoiler. However, if damage causes a reduction in lateral controllability or forces the use of a higher approach speed than normal, then take-off or landing manoeuvres will be affected.

3.26 The scenarios outlined here are similar to those already considered when assessing aircraft safety systems for certification and in establishing pilot training requirements. There are therefore mitigations in place for such damage and aircraft regularly land safely despite damage to flaps, spoilers or landing gear.

3.27 The collision severity may be greater for a small aircraft, due to the larger relative size of the drone and potential damage area. This conclusion is supported by the recently published FAA modelling, which indicated greater levels of potential damage to a business jet compared with a narrow-bodied jet.

3.28 There is a further potential risk related to the possibility that drone impact could result in harm to third parties from debris, either from the aircraft or more likely from the small drone. As undercarriage and lift augmentation systems are deployed only on approach to, and until shortly after departure from, an airfield, the areas at risk from this would be approach and departure tracks over urban areas near to the airfield.

Flying control surfaces

3.29 Flying control surfaces would potentially be vulnerable to drone impact damage and associated risk of loss of control. However, because these control surfaces are normally positioned on the trailing edge of the wings and tailplane, they are afforded a degree of protection by the structure ahead.

Rotors

3.30 The CAA has considered the consequences of a drone collision with helicopter rotor blades. There are two potential risks here. Firstly, either the main or tail rotor blades and associated rotating components could be damaged by a collision. The angular velocity of their operation would 'add' energy to the collision, over and above the aircraft's closing velocity.

3.31 Secondly, rotating assemblies are dynamically balanced to prevent vibration and undue control load. This means that relatively minor levels of damage from the impact of the drone itself – insufficient to cause failure of a rotor blade in itself – could nevertheless result in major disruption of this dynamic balance. If this caused loading that exceeded the ultimate limits of the blades or supporting structure, it could result in failure and possible loss of control of the helicopter.

3.32 The DfT, MAA and BALPA study also identified that helicopter tail rotors are particularly vulnerable to the impact of a drone. Impacts with even the smallest drones would be likely to result in blade failures. Research, including modelling and testing, would be required to better understand this risk.

Evaluating the risks

3.33 This report provides an initial assessment of the risks posed by drones to manned aircraft in the UK. The CAA has drawn on available evidence to support this assessment and in particular focused on the very specific case of risk from collision between a small drone of 2kg or less (see 2.34) and a large commercial airliner within the vicinity of an airport.

3.34 Different considerations would apply for other categories of aircraft – notably helicopters and GA aircraft. These aircraft operate mainly at lower altitudes, predominantly below 10,000ft and typically below 5,000ft, so the likelihood of drone proximity would increase. Additionally, the critical speed for windscreen rupture for these aircraft is considered to be lower than for large passenger aircraft; they are not required to be certified to withstand a strike at higher speeds. Further, helicopters are subject to the additional dangers inherent in the operation of rotors.

3.35 Set against these concerns, these aircraft typically operate at lower speeds than larger aircraft and have greater manoeuvrability, potentially giving them some opportunity to detect a small drone in proximity and avoid it. Unfortunately, there is only limited research in this area with these classes of aircraft, i.e. the recent DfT, MAA and BALPA study[4]. Therefore, estimation of helicopter and GA risk remains qualitative and the CAA has not sought to quantify it.

3.36 The previous section provided an overview of the parts of aircraft that could be vulnerable to a collision with a small drone. This section provides an evaluation of the risk, considering severity and likelihood.

3.37 To underpin this evaluation, the CAA developed a safety assessment bowtie model, considering the potential outcomes of any event where a drone is in close proximity with a manned aircraft such that their safety is or may be compromised.

3.38 Five potential negative outcomes were identified:

- The manned aircraft undertakes an abrupt avoidance manoeuvre, resulting in harm to flight crew or passengers.
- Aircraft components are damaged, resulting in loss of control.
- Rotorcraft components are damaged, resulting in loss of control.
- The flight crew are incapacitated in some way, resulting in loss of control.
- The aircraft suffers undetected damage which compromises its future airworthiness.

3.39 Near misses with no safety concerns were not considered as an outcome in the study, nor were factors such as disruption to air traffic or repair costs to the aircraft.

3.40 The CAA identified that there are six potential means of controlling these outcomes:

1. Drone operators comply with the ANO and use the advice in applicable CAA guidance publication (CAP[18]) and the Drone Code.
2. Drone operators see and avoid aircraft.
3. Aircraft pilots see and avoid drones.
4. Air Traffic Control detects the drone and warns the aircraft pilot (if applicable).
5. Some form of technical limitation to the drone – e.g. a limit to its altitude or position – prevents a collision.
6. Drone operators comply with the rules due to effective enforcement of the rules.

3.41 The full bowtie model is available at: www.caa.co.uk/CAP1627BT

[18] CAP722, CAP658

Severity

3.42 The CAA reviewed open source research into drone collisions from around the world.[19] The team identified that these collision studies were based on a number of assumptions, and that there was a lack of comprehensive quantitative testing into the precise effects and vulnerabilities of a drone collision.

3.43 For example, the majority of investigations into the severity of drone impact on windscreens focuses on modelling of the failure response of brittle materials and is based largely on research conducted into birdstrike effects. The recent DfT, MAA and BALPA funded study apart, there is lack of open-source theory and testing on drone impact with aircraft windscreens that could support a robust evidence-based view.

3.44 However, the available information does indicate that due to their more rigid structure, a collision with a drone is likely to result in a higher peak impact than a collision with a bird.

3.45 Following this assumption, it would appear that the densest components of the drone – the motors, battery pack and payload – would contribute most significantly to the severity outcome. Further work is required to quantify those effects.

3.46 Additionally, the severity of a small drone collision with a windscreen would be greater in aircraft that are not required to have windscreens certified to withstand birdstrikes. The higher the birdstrike certification – with large aircraft certified under CS-25 having the highest level – the more likely the windscreen would be to withstand a drone collision, though it should be noted that the design and production materials of a drone mean a collision is more likely to damage an aircraft than an equivalent energy level impact with a bird.

3.47 In general, therefore, the severity of a drone collision will depend on the specific context: the size and or mass of the drone, the speed of the collision, the point of collision and the type of aircraft involved.

Likelihood

3.48 Although tens of thousands of small drones have reportedly been sold in the UK, there are no confirmed ownership and usage statistics and there have been no known collisions between small drones and any type of manned aircraft in the UK. There have at the time of writing been seven such confirmed collisions worldwide.

[19] As noted earlier, on 28 November 2017, ASSURE – the research centre of US aviation regulator the Federal Aviation Authority - published its own research into the potential severity of drone collisions. (See www.assureuas.org/projects/deliverables/sUASAirborneCollisionReport.php) ASSURE's study was released too late to affect the findings set out in this paper but the CAA is now reviewing it to assess whether it should affect our risk assessment.

This indicates that collisions between small drones and manned aircraft are at present statistically unlikely but certainly possible.

3.49 However, the number of MOR and Airprox reports related to drones has increased in recent years – suggesting the risk of collision may be increasing. It is important to underline that these reports refer to the sighting of an object identified as a drone in close proximity to another aircraft. In some cases, it has subsequently been confirmed that the object in question was not a drone. Furthermore, these reports do not necessarily provide accurate information on the object size or mass. Therefore, their value as a means of assessing likelihood is limited.

3.50 Likelihoods of other aviation specific events can be used as a useful comparator to put a small drone collision risk into perspective. For example, based on current levels of reporting, a pilot is currently around twice as likely to have a birdstrike resulting in damage to the aircraft as they are to report seeing a drone in proximity[20]. Whilst bird numbers may be relatively stable and there are mechanisms in place to control them at airports, the volumes of drones sold is likely to increase. As outlined in paragraph 2.15 above, however, an increase in the number of drones sold does not necessarily increase the probability of a drone being in proximity of an aircraft.

3.51 While this serves as important context, it is nonetheless recognised that useful insights can be drawn from MOR and Airprox data about drone sightings – in particular, the altitude and the geographical locations at which they have occurred. We have used this information to help assess both the likelihood of a collision occurring between a drone and a large airliner at a speed which would result in damage to the aircraft's windscreen, for example.

Altitude

3.52 When submitting a report under the MOR scheme, reporters are required to include an assessment of the altitude at which the occurrence took place. By examining the relevant reports, the CAA has assessed the probability of a drone proximity incident by altitude based on observed historic data.

3.53 Figure 3 below includes all MORs received in 2016 which related to drones, showing the altitude at which they took place.[21] The majority of sightings took place below 2,000ft. 95% of sightings took place below 10,000ft.

[20] Derived from 2015/16 birdstrike MOR data.

[21] Drone MOR were reported mostly as altitudes, with a few reported at a Flight Level. Given the inaccuracy inherent in reporting the UA's altitude and the variation of sea-level pressure, all reported values have been equated to altitudes.

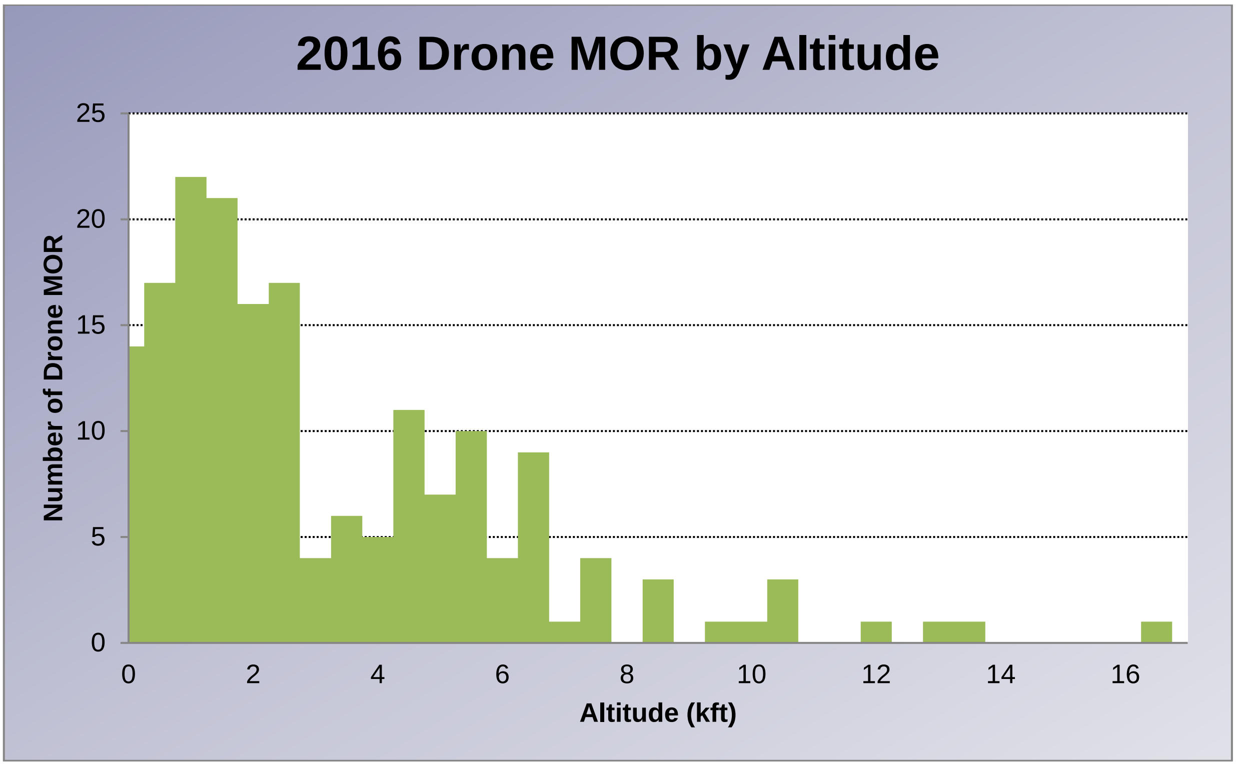


Figure 3 – 2016 MOR Data drone reports by altitude

3.54 Drone MOR data is subject to a number of uncertainties. It involves assessment of altitude, rather than a precise measure. It relies on voluntary reporting from non-commercial users. There are also factors which can skew the data. For example, for any given distribution of drone activity, proximity reporting will be proportional to the amount of time spent at any given altitude. However, aircraft do not climb or descend at a constant rate and are often held at intermediate altitudes before reaching cruise altitude or before landing. This could result in 'over' reporting of drones at particular altitudes.

3.55 Notwithstanding these issues, the MOR information provides a reasonable basis for a quantitative assessment of likelihood that, with conscientious reporting, will over time provide a more consistent data set.

3.56 Appendix C provides the dataset for 2017 thus far. This indicates a similar trend but with an increased number of MOR reports.

3.57 We have therefore used it to derive an assessment of the likelihood of a pilot sighting, or coming into conflict with, a drone at or below a given altitude, while flying above a given velocity within the airspace around a major airport.

Location

3.58 The location we have focused on is the London Terminal Manoeuvring Area (TMA).[22] This area covers flight paths in and out of the main London airports so is one of the busiest areas of airspace in the UK. It also accounted for a large proportion of the drone MORs recorded in 2016: 121 events occurred in the London TMA out of a total of 248. Using movement data covering the same period as the drone MOR data, the CAA has calculated that there were approximately 10,000 aircraft movements per drone MOR.

Aircraft Speed

3.59 As discussed previously, aircraft design requirements to withstand birdstrike may offer a degree of resilience to damage from a small drone collision. For large passenger aircraft, these requirements are based on an impact speed of 340kts, which itself is based on cruising speeds of such aircraft.

3.60 To support a drone collision risk assessment, the CAA has looked at what sort of speeds aircraft typically operate when at the altitude where drone MORs are most likely.

3.61 By plotting radar data in the London TMA, it is possible to derive passenger airliner altitude and True Airspeed (TAS)[23]. This is shown in Figure 4 below.

[22] See www.nats.aero/nsf/TMAPopup.htm for a map of the London TMA.

[23] True Airspeed is the speed of the aircraft relative to the airmass in which it is flying. It is considered a more useful measure for assessing impact velocity than Indicated Airspeed (IAS), which is the speed shown on flight deck instruments.

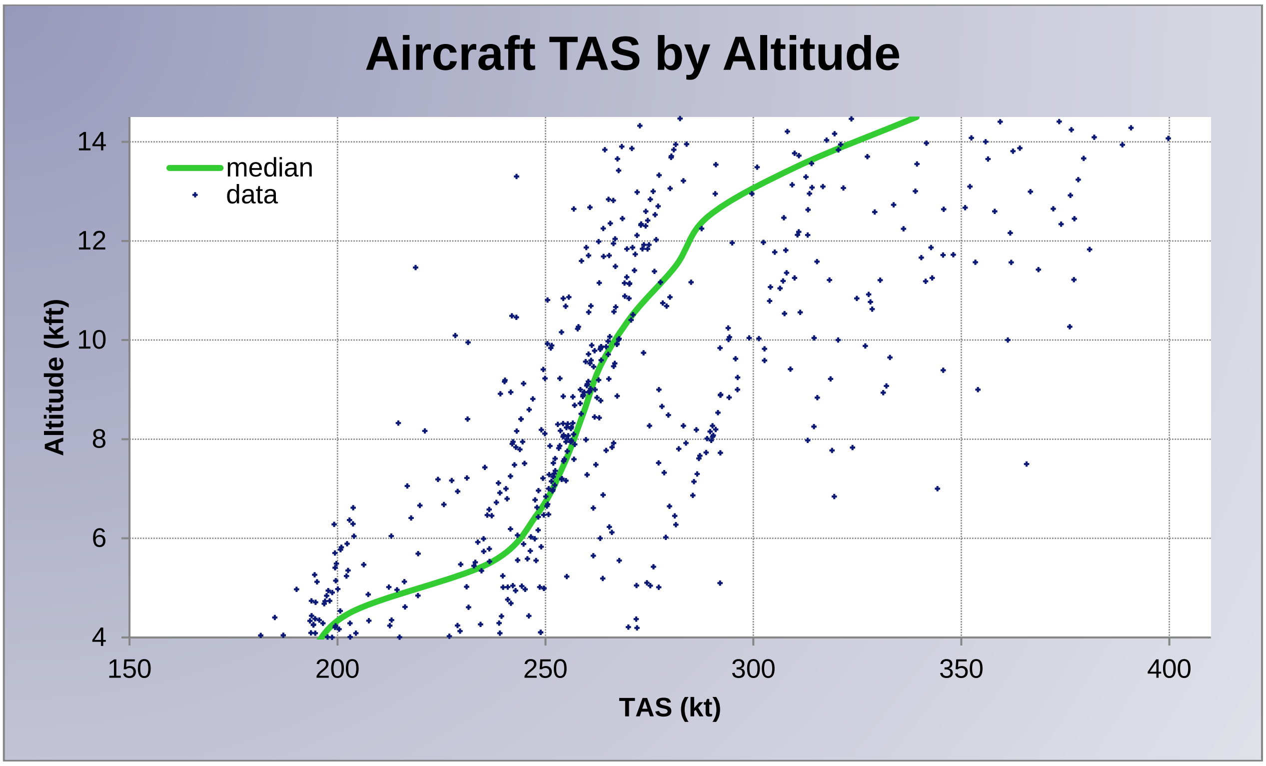


Figure 4 – 2016 Radar Data – aircraft TAS by altitude (London TMA)[24]

3.62 This shows two important points:

- At 10,000ft, aircraft were operating at a TAS between 225 and 375kt. The average TAS was around 270kt.
- Just 0.7% of flights had TAS over 340kt (the velocity used for birdstrike certification) at an altitude of 10,000ft or below.

3.63 As stated previously, 95% of drone MOR occurrences took place below an altitude of 10,000ft.

3.64 Combining this observed data – drone MOR occurrence by altitude, the ratio of aircraft above a given velocity by altitude and the drone MOR rate for the London TMA – the CAA has derived the probability of a pilot of a passenger airliner sighting a drone in proximity, whilst at or below a given altitude and above a given velocity. This is shown in Figure 5 below.

[24] NATS provided data

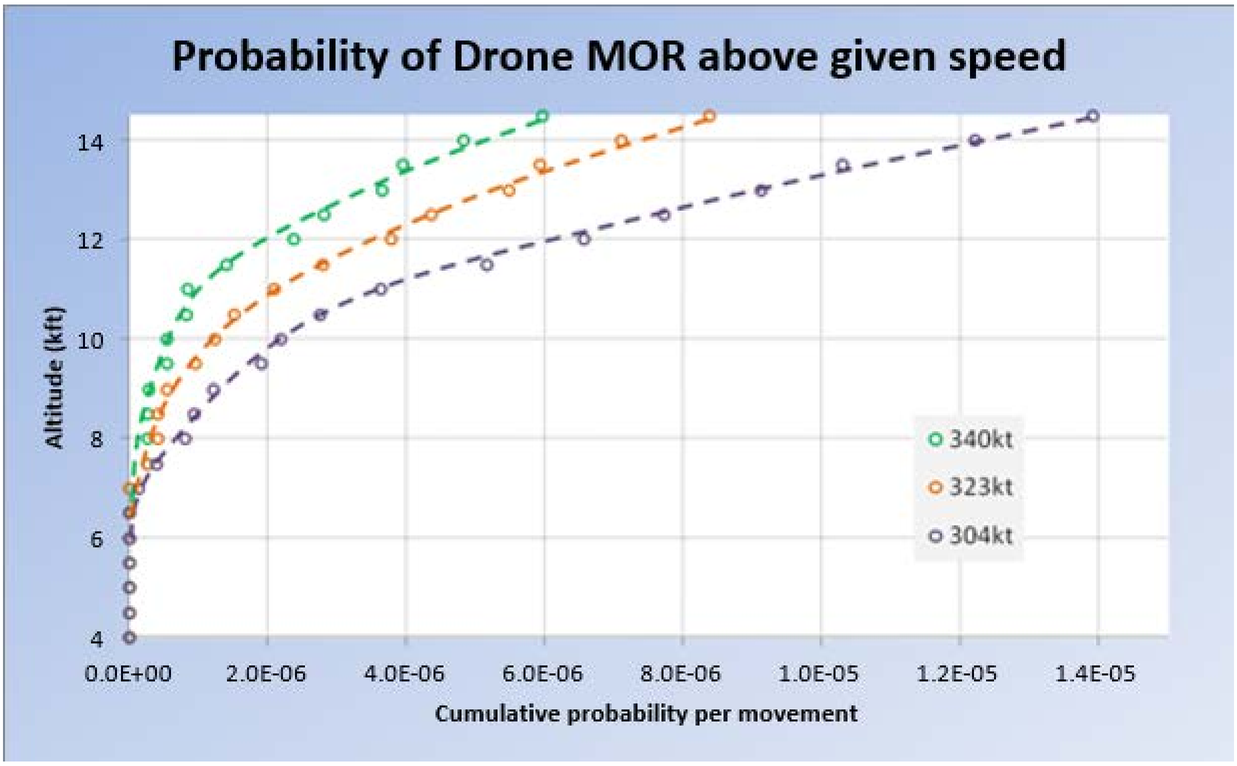


Figure 5 – Probability of airliner pilot sighting/conflict with a drone whilst at or below a given altitude and above a given velocity

3.65 This graph shows the probability of a sighting at 340kt – the velocity used to determine birdstrike requirements in CS-25 – as well as for speeds which represent 10% less (323kt) and 20% less (304kt) kinetic energy for any given drone mass.

3.66 It indicates that, in 2016, the probability of a passenger airliner experiencing a drone in *proximity* whilst above 340kt and at or below 12,000ft[25] in the London TMA was about $2x10^{-6}$ per flight. This equates to a probability of two drone *proximity* incidents above the velocity to which airliner windscreens are certified per million aircraft flights.

3.67 A proximity incident is far more likely than a collision. Furthermore, proximity reports relate to all areas of the aircraft and not just the windscreen[26]. It therefore follows that the estimated probability of a drone collision damaging an airliner windscreen, and causing immediate harm to the crew (resulting in subsequent harm to passengers or third parties) is, at present and based on this data, very much lower than the probability of a drone being in proximity of an aircraft. The CAA does not have the

[25] Although the probability is given with respect to altitude, aircraft use a standard datum pressure, the Standard Pressure Setting, when at higher levels and their altitude is referred to as a flight level. The variation of surface pressure is sufficiently small that a given altitude will typically be within a few hundred feet of the equivalent flight level on any given day.

[26] Likelihood of windscreen impact may be calculated as the ratio of windscreen area to overall frontal area, assuming an even distribution of likely impact points.

data to be able to assess the difference in the probability of a drone being in proximity of an aircraft and the probability of an actual collision and this data is not anticipated to be available in the near future.

3.68 For the purposes of a severity assessment of any drone strike, we have assumed that the aircraft's windscreen would meet the standards mandated by birdstrike CS requirements. We have also assumed in the above calculation that there is no difference between the impact of a small drone weighing 1.8kg (the mass defined in CS-25) at 340kt and the impact of a bird of the same mass at the same speed. As noted earlier, the greater rigidity of small drone components would potentially create a higher impact force than a bird would, meaning the critical speed for windscreen rupture by drone may be lower than that for rupture by a bird.

4. Next steps

4.1 This report has provided an initial assessment of the risks posed by drones to manned aircraft in the UK. The CAA has drawn on available evidence to support this assessment and in particular focused on the very specific case of risk from collision between a small drone of 2kg or less and a large commercial airliner within the vicinity of an airport at speeds that may be considered close to birdstrike design considerations. The CAA's analysis indicates two incidents of *proximity* per million flight movements and for this specific risk the likelihood of an actual collision would be considerably less than this.

4.2 While this offers some reassurance, it is important to reiterate that this is just one collision scenario and one category of aircraft. As the report has made clear, the risk of collision is a complex subject that depends on the interaction of many factors. There is currently a lack of data around other collision scenarios, and data around likelihood in particular will continue to be difficult to obtain. As such we cannot, at this stage, predict a full risk profile. Therefore, focus in the near future may be best placed on improving the understanding of the potential severity of impact between a small drone and different categories of aircraft – in particular GA aircraft and small helicopters which have been identified as having specific vulnerabilities to drone collision – through further research and testing. The findings of such research could then be used by aircraft certificating authorities in determining whether there is a need to review certification specifications to protect against drone collision.

4.3 Another focus area is the development of mitigation techniques that would help minimise the chances of drones coming into proximity with manned aircraft. These include a variety of technical solutions built into the drones by the manufacturers, such as height or distance limiters, or as services and data provided by other organisations that inform drone users of the locations of restricted areas, or through strengthening further the education and accountability of all drone operators.

4.4 Whilst this assessment may consider the current risk to the specific scenario to be unlikely, a wide range of factors could easily change this – in particular, wider ownership and more frequent use of drones without complying with the drone safety rules, and advancing technology which would allow drones to fly further and reductions in the cost of drones, which could lead to a substantial increase in the number of leisure users. Such an increase in the use of drones does not mean an increase in risk. Provided all parties comply with the rules and the barriers remain effective, the overall risk profile should be similar. The CAA will continue to monitor available research from across the world, including the ongoing research conducted by the Federal Aviation Authority in the US and the recently published ASSURE report, as well as usage data from the UK.

4.5 Educating drone users so that they understand how to operate their drone in line with current legislation is also a key activity. The CAA is committed to continuing its work in this area working with a range of partners and promoting the Drone Code.

4.6 The CAA will continue to work with the UK Government, EASA, ICAO and other overseas aviation authorities to better understand the risk of drones and to take steps to proportionately mitigate the risk to aviation safety arising from drone use.

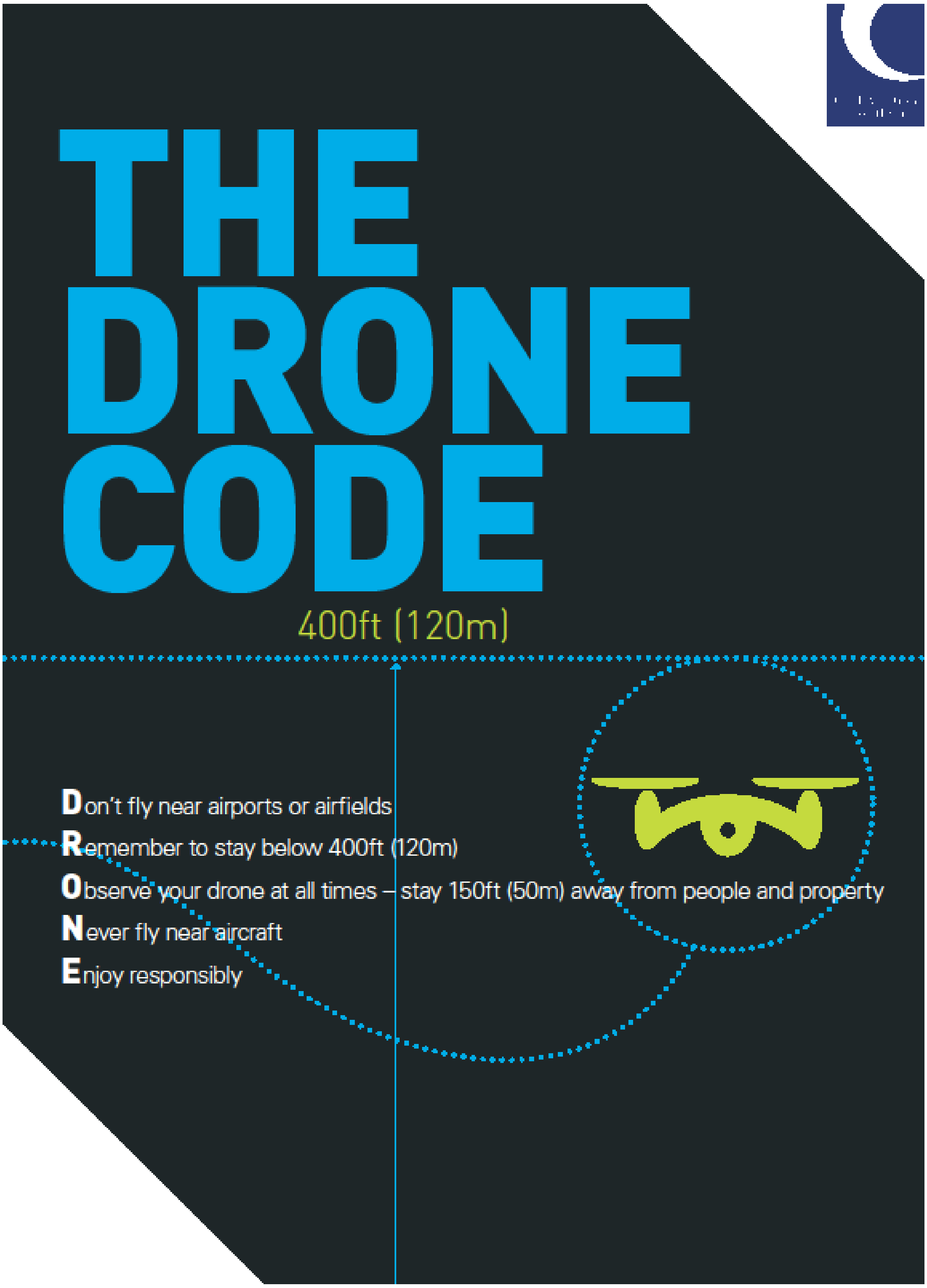
APPENDIX A

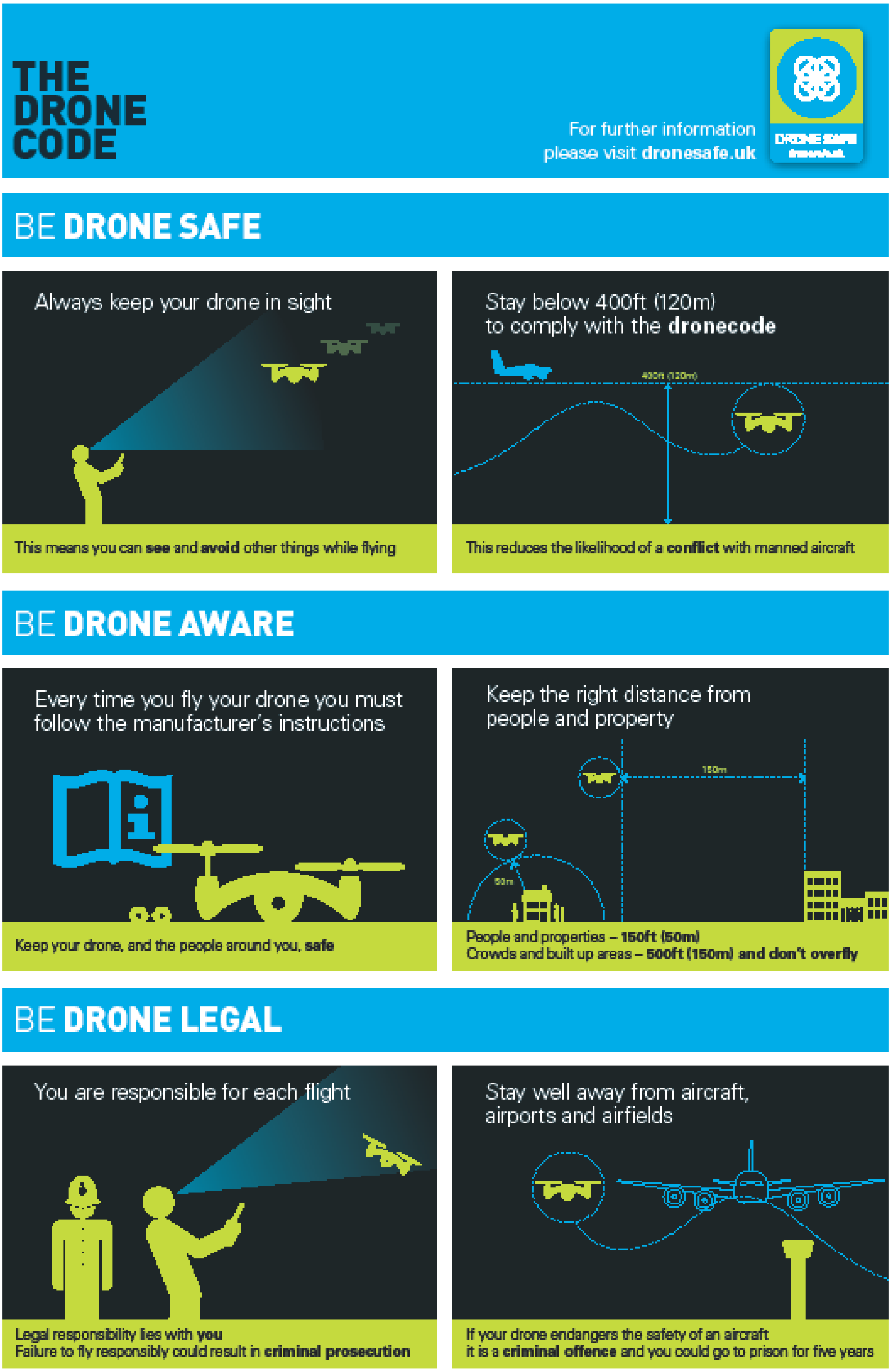
Abbreviations

Abbreviations	
ANO	Air Navigation Order 2016
BALPA	British Airline Pilots' Association
BVLOS	Beyond Visual Line of Sight
CAA	Civil Aviation Authority
CAP	Civil Aviation Publication
CS	Certification Specification
DfT	Department for Transport
Drone	Generic term for unmanned aircraft system (UAS)
EASA	European Aviation Safety Agency
FAA	Federal Aviation Administration
HB	Hot Air Balloon
GA	General Aviation
GB	Gas Balloon
LiPo	Lithium Polymer
LOC	Loss-of-control
LSA	Light Sport Aeroplanes
MAA	Military Aviation Authority
MOR	Mandatory Occurrence Reports
TGB	Tethered Gas Balloons
TMA	Terminal Manoeuvring Area
UA	Unmanned Aircraft
UAS	Unmanned Aircraft System (comprising the UA, the control station and system of “command and control” between the two)
SUA	Small Unmanned Aircraft
TAS	True Airspeed
VLA	Very Light Aircraft
VLOS	Visual Line of Sight
VLR	Very Light Rotorcraft

APPENDIX B

The Drone Code





The UK Dronecode is published by the Civil Aviation Authority to assist drone users in flying safely.

APPENDIX C

2017 Drone MOR Data