Decision Support for Risk Assessment of Mid-air Collisions via Population-based Measures

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Abstract

Specifying proximity warning functions for aircraft in managed airspace has received considerable attention. However, similar functions for aircraft operating in unmanaged airspace have received comparatively little analysis despite the fact that these functions are stressed to a greater physical degree, and perhaps more frequently, than in managed airspace. The mid-air collision hazard and its associated risk are re-examined from both an historical and a systematic engineering modelling viewpoint. Historic measures of this transport risk in managed airspace have been based on fatalities normalized by flight hours or flight movements. However some of these data may not be available in unmanaged airspace. Another approach to measurement directs attention to populations at risk where several measures are now well known: collective risk, individual risk and the frequency of occurrence of the hazards that give rise to such risk. A decision support methodology is presented that relates both transport and population based approaches. A cohesive and consistent set of aspired goals for various stakeholder groups can be set taking into account the different stakeholder needs. A case study is drawn from historic mid-air collision data to illustrate the process. A consistent basis for national-level policy decisions harmonised with proactive engineering design requirements is achieved. The strengths, limitations and implications of this approach for engineering design purposes are discussed.

Keywords: airspace design, aircraft proximity, collective risk, design space, individual risk, mid-air collision.

1. Introduction

The risk of mid-air collisions has been studied over many decades, principally through a measure called Target Level of Safety (TLS) – *number of flights (hours) per fatal accident*. The method of measurement of TLS presupposes that the number of flights over the period of measurement and the number of fatalities due to mid-air collisions are recorded. Both of these presuppositions are appropriate in the case of managed air space. However, in the case of unmanaged airspace, the situation is different because the number of flights undertaken over a given period of measurement may not necessarily be recorded. Thus, whilst TLS may be taken as an appropriate risk assessment measure in managed air space, the same cannot be said about its suitability in unmanaged airspace and, therefore, there is need to investigate alternative measures.

One alternative is to use a population-based measure and it is known that various decision making policies follow such an approach. These population-based measures are categorised as: collective risk, individual risk, and survival functions (that are closely related to societal risk paradigms). In observing actual practice of this approach, we have recognised two major problems. First, measures have been treated as essentially disparate by policy makers when in fact they are related mathematically. Second, no explicit account is taken of the fact that different stakeholder groups act independently accepting different levels of risk yet their activities in airspace may be associated by very close proximity that raises the instantaneous risk of each participant's activity.

In this paper, we put forward three propositions in addressing these problems. The propositions are:

1. Population models can be used to augment TLS for situations where flight hours and/or movements are not systematically or completely recorded.

2. The relationship between Collective Risk (CR), *the number of fatalities per annum,* and Individual Risk (IR), *the fraction of a population to die due to a specified accidental cause per annum*, may be used to form an effective harmonious decision aiding tool for assessing risk associated with mid-air collisions and thus provide a guide to both policy making and engineering design.
3. The relationship between Collective Risk and Individual Risk provides further insight for guiding the engineering design and implementation of airspace rules and procedures, inclusive of communication requirements.

In putting forward these propositions, we introduce a visualisation tool that permits presentation of the historic risk of airspace use for different major stakeholder groups yet also unifies the visualisation of the aggregate performance of those groups in a policy making environment. We also present mathematical models that that further underpin the use of the visualisation tool and also provide the predictive basis for operational requirements analysis, the precursor to detailed engineering design of future systems.

In Section 2 a review of the context of international and national level regulations specifying the categorisation of both flight operations and of airspace itself is provided. The multi-dimensional nature of this categorisation is critical to understanding the management of aircraft proximity and therefore the prevention of mid-air collisions.

The concept of a feasible design space of a complex system from engineering design (or a rational decision space from Operations Research) is introduced in Section 3. The development of this visualisation aid provides a tool suitable for use in engineering specification, in management and in policy decision making.

An example of the use of the approach is provided by presenting a case study of historical data for mid-air collisions in Australia in Section 4. On this basis a risk assessment is conducted for each of the three major categories of activity: Air Transport Operations (Regular Public Transport), General Aviation (GA) and sports aviation as represented by gliding activity.

Acceptable historical estimates do not necessarily guarantee future performance and therefore in Section 5 a number of mathematical models are presented to guide new design. These include: a general approach for linking population based models with transport based models (e.g., TLS) and a method for aggregating individual risk measures over an hierarchical population base. Limitations of the approach and implications for design are also discussed. The characteristic elements of these generic mathematical models provide insight during operational requirement capture and engineering design. They reveal the nature and important design characteristics of requirements to be placed on all airspace design. The interpretation of these characteristics and concluding remarks are presented in Section 6.

2. Context of investigation

At an international level, Air Traffic Management (ATM) systems have been subject to significant change over the past two decades. First, there has been an increasing use of airspace by both new and established groups: the number of recreational sports aircraft have increased significantly; the Unmanned Aerial Vehicle (UAV) industry is reported as the fastest growing segment within the aerospace sector; the personal jet and regional jet markets are also growing strongly (Mozdzanowska, Delahaye, Hansman, Hinston, 2003), and concurrently, well established commercial and regular public transport services are increasing aircraft numbers as demands for air travel continue to rise (Babikian, Lukachko, Waitz, 2002). Second, in various parts of the world ground-based ATM equipment and communication infrastructure (e.g., data links) have been updated. Such change imparts new and collective engineering demands with ATM systems now being stressed in ways that can either cause latent failure modes to manifest or, as change to infrastructure occurs, new failure modes to emerge. A graphic example of this is on record (Australian Transport Safety Bureau occurrence number 199900420) where a Dash-8 aircraft passed laterally within 30-60 meters of a glider 28km SE Mildura aerodrome. For both pilots this distance translated to operation within a loss-of-control regime with inadequate response time available for both pilots. Further, in a study for Broome International Airport (BIA) in 2004 over one million simulated collision situations were tested for adequate communication response times with 55,000 failures recorded. These observations, together with other studies conducted by BIA, confirmed a decision to retain ground based traffic advisory services at the airport when, in a broader national context, such services were being generally reduced or removed. The questions arising are: "How will the risk of mid-air collision be adequately managed, and the safety of flight maintained, taking into account the diverse nature of the operations involved?"

The research presented here was conducted in context of nearly two decades of national debate related to the meaning of Equivalent Level of Safety (ELOS) when applied to airspace changes. This debate has recently achieved an ever sharper focus as operators of UAVs seek to conduct flights in common airspace and over populated areas (Clothier, Walker, 2006; Clothier et al. 2007). Traditional measures such as TLS are known to have technical limitations with respect to the midair collision event particularly for regions of airspace for which there is limited or no official recording of the individual flight activity and consequently no recording of the emergent patterns of interacting flight-paths. Other measures are clearly needed to augment TLS. Guidance came from both the international commercial space launch industry and from studies arising from several decades of development of risk management in civil engineering. Both approaches have investigated the role of IR. However, as ATSB (2002a) notes, there has not been agreement between government air traffic service providers and civil aviation regulators as to the most suitable population-based approach: individual risk is put in mutually exclusive contrast with societal risk (SR) when in fact both are mathematically related and IR can be derived from SR data (see also Section 2.2.2).

The study of the mid-air collision event is of significant interest to airspace designers since this event can be viewed as a system constraint both from an operational and also an engineering perspective. An ATM system must provide for the safe transport of aircraft through airspace without invoking a collision. Second, if a mid-air collision occurs, the occurrence of the event can be viewed as a functional failure of the airspace sub-system. To prevent such events, rules and procedures are imposed such that aircraft/pilot must comply with these when in proximity. An integral part of the design of the rules and procedures is the development of communication procedures required to exchange information on aircraft proximity and flight-path intent.

2.1 Flight regimes and flight operations

The rules of the air and related procedures are specified within an hierarchical, multidimensional, regulatory framework that includes both the international regulations from the International Civil Aviation Organisation (ICAO) as well as regulations imposed by ICAO States (e.g., Australia, Canada, the U.K., etc.). In ICAO Annex 2, flights are categorised according to whether flight in cloud is permitted, Instrument Flight Rules (IFR), and mutually exclusively, whether there is an operational need to remain in visual flight conditions, Visual Flight Rules (VFR). Second, in ICAO Annex 11, flights are also categorised by the Class(es) of Airspace in which the flight will be conducted. This class is essentially an indicator of the level of services to be provided by ground-based facilities to a flight operating under either the IFR or VFR flight category. Annex 11 refers to Controlled and Uncontrolled airspace but modern usage is to refer to the corresponding terms Managed airspace (MAS) and Un-managed airspace (UMAS). These categorisations give rise to four flight regimes as shown in Table 1.

Table 1

2.1.1 The ICAO State and flight operations

At the ICAO State level further categorisation of airspace operations occurs but now the focus moves more towards whether an operation is concerned with Air Transport Operations (ATO – also known as Regular Public Transport (RPT)) a category representing scheduled public services, or general aviation (inclusive of: commercial aviation operations; charter; private scheduled services; pilot training; private flying and business aviation); or sports aviation such as gliding and other recreational in-flight sports; or finally, military aviation. Categorisation schemes at this level are not uniform from one State to another. Such difficulties are similar to the problems of categorisation reported by Motevalli & Salmon (2004). For example, in the U.S.A. categorisation is via the FAR Parts (e.g., FAR part 121, FAR Part 135 and FAR Part 91 etc.) whereas in Australia historical categorisation in the official accident reports has been according to: High Capacity RPT, Low Capacity RPT, General Aviation, Sports Aviation or Military operations (ATSB, 2003).

Whilst it may be more common for ATO aircraft to only operate as IFR flight category in MAS, in general, there is no restriction that they always have to do so. In fact it is the nature of flight, and part of its utility, that there may be many transitions between MAS and UMAS in the one flight for either flight category. Airspace rules and procedures are required to function dependably in all situations and in all transitions.

Throughout much of continental Australia the low level airspace below Flight Level 185 (circa 18,500 feet above mean sea level) is UMAS (Class G). Here, in this airspace, ATO, GA and Sport aviation can all become proximate as aircraft approach and depart from regional airports. An example of such operations is that at Broome International Airport where ATO aircraft such as the B737 and small GA aircraft (e.g., Cessna 172 and Piper 140) share common Class G airspace on a regular basis. This use of airspace, together with the particular communication infrastructure available, may contrast markedly with both the use of other low level airspace in Europe or North America for example, or with high level enroute airspace over most continents as another example, where operations may be primarily IFR in MAS.

On occasion, but perhaps not routinely, ATO is permitted legally to operate in UMAS under both the IFR and VFR flight categories. For example an RPT flight may cancel IFR operations to then proceed by VFR flight procedure to a destination or alternate. Alternatively an RPT flight may conduct a short transit (e.g., 70-100 NM) for scheduled flights under the IFR flight category. Some companies may specifically preclude this flight regime via a prohibition in their operations manual, while others may permit it. Regardless of the flight regime or flight operation airspace rules and procedures must provide an adequate line of defence for any combination of aircraft that form a proximity pair. In this paper the model developed essentially considers the risk associated with three different representative classes of operational category (RPT, GA and Sport) that exist in Australia. This particular classification is chosen to match historical data the most closely but the methodology employed is not limited to this classification. However, the categorisation chosen should serve the purpose that it should indicate in some degree the broad differences in the acceptance of risk that the air transport sector imposes on different users and stakeholders. Passengers of GA and ATO aircraft generally wish to safely transit airspace without undue risk of collision with other aircraft. Pilots of GA and ATO aircraft, not participating in sports activities, generally do not wish unsolicited (un-alerted) proximity to other aircraft. Pilots of sports aircraft, of which gliding activities are the most representative, often choose to actively compete in close proximity and appear to voluntarily accept higher levels of risk for this reason.

2.2 Equivalent Levels of Safety (ELOS)

During the past two decades there has been an emphasis in Australia (Clothier, Walker, 2006; Clothier et al., 2007) and internationally (Weibel, Hansman, 2005) on providing measures of Equivalent Levels of Safety (ELOS) for airspace change. Clear understanding has emerged that historical measures are not applicable in all situations. A need to develop alternative (but augmenting) measures of risk has increased as new aircraft operations, such as UAVs, are introduced. The focus of the historical measures of risk was on technological risk (e.g., aircraft system failure), first party risk (crew fatalities) and second party risk (passenger fatalities). Traditionally, TLS has been used but industry focus is now equally directed to third party risk (to the general public located in proximity of and under the flight path). The risk to crew, passenger and the public may well be better modelled by population-based measures. For many decades, official accident records have captured CR data. However, more recently engineering disciplines have also investigated a measure of risk for constructed artefacts such as dams, buildings, bridges etc. (Ingles, 1983, 1985). This measure is that of individual risk IR. Both CR and IR are better suited to the UMAS classes of airspace since not all individual flights are recorded in this airspace and because, should an accident occur, any fatalities are required to be reported by law. The only other data required are those which identify the sizes of the different populations of the at-risk stakeholder groups. Then it is straightforward to assess the levels of risk arising in these populations due to the various activities. This is the methodology to be implemented in this paper.

2.2.1 Historical measures of risk – the Target Level of Safety

International approaches to the measurement of air transport risk have been diverse, but the most consolidated approach has been that of TLS. A thirty year history of this measurement is discussed in detail in Machol (1995). However, the practicality of such an approach to risk measurement assumes that flight hours (or movements) are recorded. Much of the research focus in the past has been on the MAS/IFR regime (e.g., the Trans-Atlantic route) of Table 1 with much less attention based on the UMAS/VFR regime (e.g., regional airports in the Australian outback). The TLS measure is an appropriate measure for the MAS/IFR regime where flight hours are recorded and the traffic patterns known but it is not appropriate for regimes where flight hours (or aircraft movements) are not recorded and traffic patterns are unknown.

Another reason for pursuing a population based measure for mid-air collisions is due to an inherent weakness in the TLS approach when measuring system performance due to accidents involving more than one aircraft. This weakness is one of consistency of comparison and interpretation. Suppose a goal for TLS is set (e.g., 1×10^{-8} fatal accidents per flight hour). Now suppose there are two different airspaces with different Class designations, different IFR/VFR mixes and different dynamic densities (flow rates). The question arises as to "How does one compare the safety performance of one airspace against that of the other?" For the same measured performance (value of TLS) does it mean that the two airspaces are equally safe? The answer is that in general such a comparison cannot be made. The reason lies in the fact that TLS does not capture the exposure to collision through measures of the complexity of flight-path interaction. An extreme example will help illustrate the issue. Suppose there are N flights per day in each airspace. Further, suppose that in one airspace all the flight-paths come into proximity in a combinatorial maximal way but in the other airspace flight-paths never interact at all except for one isolated collision. With this information we can say that the first airspace is truly performing to the specified TLS but for the second airspace no such claim can be made. Yet both share an equal value for measured TLS. For this second airspace the communications protocols and rules provided to manage proximity situations have never been fully exercised. A confident conclusion cannot be drawn as to the safety of operation within the second airspace in these circumstances. For this reason it is important in design to assess the role of information exchange, particularly between the pilots of both aircraft during the proximity event. In this paper we show the necessity of this because the mathematics that underpins the development of population-based risk measures also points to the critical role that the dependability of communication plays in the management of aircraft proximity. This is discussed further in Section 6.

There is a clear need to develop other measures of risk to provide a suite of methods to cover all flight regimes and their flight-path interactions.

2.2.2 Societal Risk – a passing association

Another approach to population-based risk is Societal Risk (SR) in which consequence (e.g., number of fatalities) in each and every accident is important. Societal risk is broader in concept than IR, as it specifies how the number of fatalities may accumulate. The distinction is an important issue and its full scope requires that it be addressed in a separate publication. However, there is considerable similarity between SR and the approach presented in this paper. The raw data (i.e., date of accident, aircraft types involved, fatalities and injuries, location etc.) for SR and CR are already collected by accident investigation bureaus. One aspect of SR beyond the scope of this paper, that requires policy input, is the setting of criterion lines to demarcate acceptable and unacceptable performance of the transport mode under scrutiny. Here we ignore the criterion lines of SR and concentrate on the mathematical relations between all three measures of SR, CR and IR: CR can be derived from SR data by aggregating all fatalities over a given time period and then averaging the fatality rate; IR can be related to CR by noting the population to which both apply and finding the individual fatality rate per annum.

2.2.3 Individual risk measures

As already stated, IR so defined, has been investigated intensively for a number of decades and represents the identification of broad levels of risk which represent different responses of a population to risk laden activities. We note here that the set of IR levels is not a fully developed physical scale but rather is a categorical ordering of fairly well defined risk levels. In this manner, and on this basis, the acceptability of risk can be measured and the perception of risk accommodated. In our approach both the acceptance of risk by a passenger in an ATO operation and that of a pilot performing in a sporting activity are naturally separated and can be assessed objectively and independently. Perceptual aspects of risk assessment are naturally included through the research supporting the determination of the IR levels.

3. Rational Decision Space

A rational decision space (feasible design space) is developed in this section to illuminate the relationship between collective risk (F_A) and individual risk (IR_A). The purpose of a graphical presentation is to illustrate fundamental properties of the relationship being investigated, to enable visualisation of the constraints on the variables and parameters and to present the local context of measured decision points. The decision space is a two dimensional space where a decision (operational) point (OP) is defined through the coordinates (IR_A, F_A). The fundamental relationship is: if, in the population at risk, F_A is the number of fatalities per year and if I is the size of the population at risk, then a simple function relates F_A and the Individual risk (IR_A) defined as the fraction of individuals within a population that die per year due to the specified accidental cause (Royal Society 1992). Thus

$$F_A = I \cdot IR_A \tag{1}$$

In this section this equation is treated as a closed form deterministic equation. There is no measurement error considered or associated with any of the variables in this equation which permits a template for the rational decision space (template) to be constructed. The concept is analogous to the construction and use of a flight envelope in aerospace design. In later sections concerned with either the measurement of historic data or prediction of future values the equation will be recast in terms of random variables and their associated uncertainties.

3.1 Constructing a rational decision space for midair collision risk

The decision space being considered is shown in Fig.1 being a log-log plot of Eqn. 1. The dimensions of the abscissa are the exponents of the reference levels of *IR,* - we note that this definition of individual risk is not same as in Ale (2005). A correct dimensional analysis should keep the two apart.

Fig. 1:

Each individual has a unique portfolio of risk bearing activities that may lead to accidental death. The expected accidental risk of death to an individual as a member of the national population is called the actual (de facto) individual risk-level, $E(IR_A)$, and is defined from a knowledge of the expected number of fatalities per annum, occurring in the population (I_A) of at-risk people (Kletz, 1982; The Royal Society 1983, Ingles, 1983; Wilson, 1984, Ingles, 1985; The Royal Society, 1992). A set of reference levels for this measure has been well investigated, and this helps to further develop a categorisation of risk for different activities (Table 2). The Federal Aviation Administration (FAA, 2000) and the U.S.A. Commercial Space Launch program requirements (IRIG, 2000) have both referenced IR levels as in Table 2 as providing broad guidelines as to the acceptability of any given risk.

The aspired F_A (ordinate) is derived from IR_A and the respective population size, *I*. Horizontal lines are iso-F_A lines, and the vertical lines are iso-IR_A lines. In Fig. 2 population sizes are represented as parallel iso-population lines. Being deterministic, the graph representing the design space is not subject to uncertainty of measurement of its lines and may be used as a template and planning tool. An operational envelope is formed by considering the rational constraints on the CR and IR variables. An upper bound on CR is set by the national CR in aviation from all accidents. For Australia this is circa 45 fatalities per annum. The lower bound is zero.

Table 2

The upper bound for IR is proposed at $IR_A = 1 \times 10^{-3}$, being that level generally accepted as an upper limit of acceptance for workers (HSE, 2001). The de facto accident risk, IR_{Aest}, is approximately 2.45×10^{-4}, providing a benchmark reference level for all accidents (not just air transport) that lies within the envelope. A lower bound in IR_A is formed at a value of 1×10^{-8}. In the Australian RPT category to 2004, there has been only a single non-fatal air-ground collision in 33 years (ECCAIRS sub-category, 2050102). Assuming a population of people who fly at least once a year of 2.2 million, and assuming one hypothetical death, then RPT has achieved an IR_{Aest} at approximately 1×10^{-8}. This performance is significantly better than IR_{Aest} of 8.3×10^{-8} for the national population (Table 2) as is the case for the analogous goal of the commercial space launch industry (IRIG, 2000; Robinson and Fulton, 2002). Further, this level is of order the level of risk of death due to dam failure in Australia and is well accepted in other engineering disciplines.

3.2 Selecting representative populations

Here the term population is used in a statistical sampling sense to denote the aggregate from which a statistical sample is to be chosen, and not simply the population of the country. As Cochran (1977) notes:

> *The population to be sampled (the sampled population) should coincide with the population about which the information is wanted (the target population).*

Further, two types of population are of particular interest. First is the group at risk. Second are the population groups with which the primary group of interest might interact. This distinction is particularly relevant for midair collision risk, where the event can only occur from an interaction!

The population at risk has a number of attributes categorized in various ways, including the:

1. activity that may lead to the event of interest;
2. circumstances under which the activity is conducted; and
3. level of exposure.

Unless the population is carefully and precisely defined in an application, potential errors and misjudgements can occur all too easily. For this reason, we now look at various ways of defining populations at risk, and illustrate them using Australian air transport and aviation data.

This selection has a natural justification that links with the notion of acceptable risk. To some degree, it reflects the variability in the willingness with which participants take on the risk of the activities. For example, a sports aviator will accept a higher risk of death than a passenger on an ATO aircraft. This in turn reflects the degree of volition of the participant in the activity. As The Royal Society (1992) says:

> *"One of the dilemmas for engineers in risk assessment is in defining what is acceptable risk. ... there is a problem with this concept. For example, it appears that individuals involved in rock climbing or hang gliding or motor cycling accept a very high risk, whereas they would probably expect a much lower risk when travelling on public transport and yet an even lower risk for a nuclear power plant. Though engineers involved in the assessment of risk are sensitive to the public perception of risk, it is necessary for them to quantify what is an acceptable risk in particular circumstances to have a target for their risk assessment exercise."*

One circumstance of particular relevance to this paper is when there is interaction between activities from different categories. If so, which level of acceptable risk is used? The level of risk imposed on an individual needs to be consistent with the observation that an individual exposed to involuntary risk demands a level of risk as much as 1000 times less than the level of risk that would be acceptable on a voluntary basis (Starr, Rudman, Whipple, 1976). If another design choice is considered in a particular instance, a clear and compelling case for that choice must be made. This logically relates to the work of Brun (1992) who investigated the question of who manages a risk: an individual, or society? In this context the following four considerations arose:

1. The national population provides a basis for comparing assessments of the relative risk of mid-air collision with other hazards in the national portfolio of risks.

2. Passengers of GA and RPT aircraft generally wish to safely transit airspace without undue risk of collision with other aircraft.

3. Pilots of GA and ATO aircraft, not participating in sports activities, generally do not wish unsolicited (unalerted) proximity to other aircraft.

4. Pilots of sports aircraft, of which gliding activities are the most representative, may often choose to actively compete in close proximity and will thus voluntarily accept higher levels of risk for this reason.

A population size for sport aviation activities such as ballooning could not be determined because this activity solicits many itinerant passengers such as tourists. We further note that the population sets discussed above are not necessarily disjoint, nor is there necessarily a strict subset ordering. In this paper a population, I_A, may mean one of four different populations to be considered. These are the:

1. Australian national population (2003) - 19 872 600 (ABS Australian Demographic Statistics (3101.0)),

2. population of people who fly by Air Transport Operations (RPT) one or more times per annum (2003 estimate) - set to a nominal value of 11% of the national population - 2 200 000

3. population of licensed pilots (2003) - 32 344 (Civil Aviation Safety Authority Flight Crew Licensing), and

4. population of registered glider pilots (2003 estimate) - 3 200 (Gliding Federation of Australia reports a membership of 3,774 in 1974 peaking at 5 100 by 1977).

In like manner templates can be generated for other populations, other transport sectors and other countries, by adjusting the bounds on the risk scales and selecting iso-population lines that are relevant to the situation at hand.

3.3 Operational point and trends

Aspired performance for different populations can be set as system goals as shown in Fig. 1 and the actual risk affecting the different population groups can be monitored over time. The impact of any major changes to airspace designs on the achievement of those goals can also be conceptualised. A first order assessment of trends can be derived by considering a local co-ordinate system with its origin located at the actual operational point (OP) for the specified population. The iso-population line through the OP together with the local F_A and IR_A axes form six sub-partitions of the plane categorised by considering the triple (ΔI, ΔF_A, ΔIR_A) of incremental movements in the values of the components. The sub-partitions comprise two sets of three according to population growth and population decline respectively:

1. Region 0: Best performance (+, -, -)
2. Region I: Monitor (+, +, -)
3. Region II: Remedial (+, +, +)
4. Region III: Acceptable (-, -, -)
5. Region IV: Remedial (-, -, +)
6. Region V: Worst performance (-, +, +)

For example, the region (+, -, -) indicates an increase in population, but a decrease in both F_A and IR_A and therefore represents the best system condition, whereas the region (-, +, +), indicates a decrease in population, with increased in both F_A and IR_A, and therefore represents the worst outcome. The four other regions require actions ranging from continue (acceptable) operations to remedial action is required. The conditions (+, -, +) and (-, +, -) are impossible due to equation (1).

It is important to realise that the manner in which populations are selected is critical to enabling any divergence from stated policy outcomes to be tracked. A precedent for this principle has been set by a similar approach developed by the US space launch industry which seeks to regulate the probability of a failed launch, and hence the risk of consequential debris striking third party aircraft or ships. In this approach non-participants are included in the assessment of consequences of catastrophic accidents (IRIG, 2000).

4. Case Study: Australian Historical Data

4.1 General comments on data characteristics

The study of accident risk is deeply concerned with the frequencies of accidents with multiple fatalities (The Royal Society, 1983, 1992; Hirst, 1998; Evans, A.W., 2003; Ale, 2005). These data are typically presented as an ***f*.*N*** probability density graph: a graph showing the function *f* that is the frequency of accidents with precisely *N* fatalities. The related survival function *F* is the frequency of accidents with *N* or more fatalities (Hirst, 1998). The Expected Number of Fatalities per Year (*ENFY*) given by:

$$ENFY \equiv E\left(F_A\right) = \sum f\left(N\right) \cdot N \qquad (2)$$

There have been a number of approaches for partitioning the ***f*.*N*** and *F.N* spaces into regions: for example, a Negligible risk (low frequency for accidents with high fatalities) region; an "as low as reasonably practicable" (ALARP) region; and an Intolerable region (high frequency for accidents with high fatalities). It is not within the scope of this paper to develop this concept further, however, an enlightening discussion as to the process involved may be found in Jongejan, Ale and Vrijling (2006).

The UK.'s Health and Safety Executive (HSE, 2001) para. 130 uses these terms with reference to the IR reference levels (see Section 3.1 and Table 2) whereas similar terms are used with *F.N*-criteria (see for example, Evans and Verlander (1997)). There is nothing inappropriate in either definition, providing the frequency scale of the *F.N*-criteria is clearly understood to be a frequency of events with *N* or more fatalities not individual risk since the two are not the same. This we believe to be the explanation to the source of concern as discerned in Appendix D of ATSB (2004b) which states:

> *… acceptable risk criteria are presented in Figure D.1. This figure shows the acceptable risk line, scrutiny line and intolerable line for each level of severity. … The vertical axis represents the cumulative annual frequency that an event involving N or more fatalities occurs. … descriptions of its acceptable risk criteria stated that the acceptable risk line was equivalent to 0.0001 fatalities per year… However, these figures* **[values]** *were incorrect as they did not correspond to the risk lines shown in Figure D.1…*

There is also occasional confusion between the notions of IR and frequency of one death per annum; $f(1)$ in the notation of equation (2). For example, CASA (2000) refers to a value of 10^{-4} on the vertical axis of an F.N graph as being “one chance in 10,000 of one death per year", but later refers to a value of 10^{-3} *on the same axis* as being "the risk per individual is 1 chance in 1000 per year of death". We stress that they are not the same thing. In an Appendix, we give two models that have the same values of IR and *ENFY* but very different values of $f(1)$ and $F(1)$.

The *ENFY*, assessed over a specified population, is an aggregate, over all specified types of accidental risks, during a given time period. Fatalities are well identified and in countries with which this paper is concerned must be formally reported. The error in this quantity is mainly to do with the completeness and repeatability of the processes by which data can be retrieved from the accident databases covering the period (44 years in this case) in question.

Accidental causes at a national level include car accidents, work place accidents and domestic (home) accidents and are not just limited to aircraft collisions. All contribute to the nation's portfolio of accidental deaths. The *ENFY* has a temporal component. The importance of this is seen from Wilde's homeostasis theory which makes a crucial distinction between spatial, temporal and per capita measures of risk (Wilde, 1983; The Royal Society, 1992). The theory proposes that a level of preferred risk (e.g., IR) act as a controlling variable such that (Wilde, 1982):

> *"fluctuations in the accident rate are followed by adjustment actions that tend to stabilize the average accident rate over time"*

As stated the *ENFY* is the expected number of fatalities per year in the population at risk. If the size of the population at risk is *I*, then a simple function relates the concepts of *ENFY* and *IR* as discussed in this paper.

$$E\left(F_A\right) = I \cdot E\left(IR_A\right) \tag{3}$$

These are theoretical notions. The values assigned to them in an application may be based on theory, chosen for discussion purposes or derived as estimates from data. In the latter cases, it is important to appreciate that the values are subject to error. This issue is discussed later in the paper. The definitions of *ENFY* and $E(IR_A)$ have a number of components, some of which are implicit. We believe it is important to list them explicitly. They are the:

1. hazardous event whose occurrence would cause the risk;
2. consequence (harm) associated with the event that constitutes risk;
3. population at risk;
4. risk per unit of exposure; and
5. level of exposure, the degree to which members of the at-risk population participate in the hazardous events.

Changing any of these components will change the risk. It is easy to overlook one or more components in a given application. One consequence of this can be that supposedly comparable risks are not in fact comparable. Realising this quickly can reduce incorrect conclusions and pointless arguments.

In this paper, the event of most interest is a mid-air collision, and the risk consequence is death.

4.2 Estimation of ENFY

4.2.1 Estimation of ENFY: National level – all causes.

The Australian Bureau of Statistics national data for 2003 (ABS, 2005) show that there were 1811 deaths due to "Transport Accidents" and a total of 4 865 deaths due to "External causes of morbidity and mortality" (inclusive of Transport Accidents), that is, external causes inclusive of codes V01 - X59, using the tenth revision of the International Classification of Diseases and Related Health Problems (ICD-10).

4.2.2 Estimation of ENFY: Air Transport Sector

In the air transport sector the historical average, $\overline{F}_A$, is typically reported as covering all risks, not only those of mid-air collision. Data from the Australian Transport Safety Bureau (ATSB, 2003) for the Australian air transport sector show that in the ten-year period (1993 - 2002) for all causes of accident:

1. High Capacity Air Transport category resulted in zero fatalities;
2. Low Capacity Air Transport category resulted in seventeen fatalities; and
3. GA category resulted in 384 fatalities from all causes (minimum 24, maximum 51 per annum) over the period yielding an average rate of 38.4 fatalities per annum.

The indicative $\overline{F}_A$ for the air transport sector in recent years is therefore approximately 40 fatalities per annum. These fatalities arose from accidents due to all causes - engine failure, adverse weather conditions, loss of control, mid-air collision, etc. Thus, within this context, the mid-air collision fatality rate is a sub-category of the "all causes" fatality rate and is shown for the period 1961-2004 in Table 3.

Table 3

4.2.3 Estimation of ENFY: mid-air collisions

A mid-air collision is defined as a collision between at least two aircraft that are airborne. It is sub-category 2020101 in the Australian Transport Safety Bureau accident database, in accordance with the European Co-ordination Centre for Aviation Incident Reporting System's ECCAIRS 4 Data Definition Standard.

Historical data for Australian mid-air collisions for all flight categories have been collected for the period, 1 January 1961 - 31 December 2004 from the ATSB (2002b, 2004a) - and its predecessor the Bureau of Air Safety Investigation (BASI, 1998). The case where a pilot chooses to conduct an unnecessarily hazardous operation in non-compliance with the rules of the air (BASI, 1998) causing a collision, is specifically excluded from any assessment. A similar approach has been taken, for example, by ATSB (2004a).

Our bound on $\overline{F}_A$ for mid-air collisions within Regular Public Transport (RPT) operations was formed by assuming one hypothetical death since no death has occurred due to a mid-air collision in 44 years, which seemed a reasonable approach for countries with sparse data. They are presented in Table 4.

Table 4

These data may also be presented in the form of an $f.N$ probability density plot (see Hirst (1998)) as shown in Fig. 2.

Fig. 2

We note the following features of these data.

1. There have been 55 accidents and 68 fatalities in 44 years due to midair collisions, or 1.55 fatalities per annum.
2. The data are dominated by accidents with $N = 0$ and $N = 1$ and for $N \leq 5$ (apart from $N = 3$) accidents have occurred multiple times. There is only one instance of an accident with $N > 5$ being $N = 13$.

3. The number of mid-air collisions with zero fatalities (28) is almost exactly the same as the number with at least one fatality (27). This result may be compared with the work of Barnett et al. (1979, 1989) who show that, for the aircraft categories of their studies, there was a high probability that either very few, or all, people on board died in a midair collision. Some fortunate examples are now given of collisions involving high capacity Air Transport Operation (ATO) aircraft in which one of the aircraft proceeded to a controlled landing with no fatalities. The aircraft that landed safely is listed first: a Boeing-707 at Carmel U.S.A., 4 December 1965 (with a Constellation L1049C); a Boeing-707 at Newark, U.S.A., 9 January 1971(with a Cessna 150); a Convair 990A at Nantes, France, 5 March 1973 (with a Douglas DC-9-32), and most recently, on 1 October 2006, an Embraer Legacy 600 corporate jet carrying nine people collided with a Boeing 737-800. Amazingly, the crew of the Legacy 600 jet, despite losing a portion of one wing, landed safely.

4. The above results based on historical measurement are mathematically correct but are derived from sparse data. The results therefore need careful interpretation for planning purposes so as not to be mis-applied. Methods to address this are discussed further in Section 4.4.

5. The sparsity is a welcome reflection of the historically low probability of mid-air collision. However, for Australian traffic flows, the average interval between mid-air collisions involving two high-capacity RPT aircraft needs to be of the order of several hundred years if required design goals are to be met. The utility of historical information in these circumstances is low since these data cannot pre-empt future performance under system changes or increasing traffic flows.

4.2.4 Summary on ENFY

Mid-air collisions contribute approximately 4% of the total air transport *ENFY*. Again, the data are sparse and at the Australian traffic levels and risk levels, the 44 years of available data is simply too short to estimate trends or to draw reliable conclusions. Even if trends could be estimated, if two high capacity RPT aircraft were to collide tomorrow, the estimates of trends and therefore conclusions would dramatically change. This is a difficulty facing most countries when assessing the ability to achieve aspired risk levels by using their historic data.

4.3 Estimation of Individual risk

The estimate, $IR_{A\mathrm{est}}$, can be found directly by plotting the $\overline{\mathrm{F}}_{\mathrm{A}}$ on its respective population line. Uncertainty in $IR_{A\mathrm{est}}$ depends mainly on the uncertainty in the size of the population. Pragmatic interpretations of this uncertainty by graphical, numerical or statistical means will provide an estimate of the variation in $IR_{A\mathrm{est}}$.

If the individual groups achieve their respective IR goals then their risk signatures, ($IR_{A\mathrm{est}}$, $\overline{\mathrm{F}}_{\mathrm{A}}$), should not be prominent in the public's perception based on a comparison with the levels identified in Table 2.

Typically, the cumulative $\overline{\mathrm{F}}_{\mathrm{A}}$ must not exceed some specified value. This constraint in turn places a constraint on any incremental $\overline{\mathrm{F}}_{\mathrm{A}}$ associated with a specific accident type and each different person within the population. Given these constraints, either a small population participating in a high risk activity or, a large population participating in a low risk activity may both incur consequences that aggregate to exceed the cumulative constraint. It is the trade-off between partitioning of sub-populations and identification of high and low risk activities that is important in the management of this hazard. Of course, in practice, a different risk of collision will exist for each and every flight and these risks will aggregate within each person's *IR* profile. The complexity of the real situation will only reduce to the simplicity of this analogy after a statistical operator is applied to the raw data (e.g., mean, 99^{th} percentile, etc.). Never-the-less this analogy has proven useful for discussion of the relationships involved. Further discussion on this point is given in Section 6.

We note that measured values of actual performance using data from Table 4 need to be transposed into data assessed on a "per annum" basis to be applied to the rational decision space template Here, the value of F_A is an historical average over the period of data collection, $\overline{F}_A$, and therefore the corresponding value of *IR* will be an historical estimate, IR_{Aest}. As such, these measurements should be periodically subjected to the standard statistical methods of estimation of measurement error and/or application of confidence intervals to address any uncertainty in the data. We note that both the measured values F_A and $\overline{F}_A$ need to be plotted with reference to a common scale when plotted on the template. The same is true for IR_A and IR_{Aest}.

4.3.1 Estimation of IR: National (all-cause) de facto risk level.

The expected risk of death, IR_{Aest}, was approximately 2.45 x 10^{-4} when using the 2003 (ABS, 2005) data for accidental deaths from all external causes occurring in Australia's national population in 2003. A similar level, (approximately 2.2 x 10^{-4}), was reported by Wilson (1984) for the U.S.A.

4.3.2 Estimation of IR: Air Transport Sector.

Estimates of *IR* for various activities within the Australian air transport industry have been derived in Table 5, using the appropriate candidate populations.

Table 5

There were zero fatalities in RPT operations with no mid-air collisions during this period (and only one non-fatal RPT air-ground collision), which is a reflection of the data sparseness. A single notional fatality was defined for RPT in order to keep this category within the analysis for comparative purposes.

The task now is to interpret the results of Table 5, and their acceptability, with reference to the research that establishes the meaning of the various reference levels of *IR* (Table 2). Acceptability of risks encountered by an individual due to private activity, industrial activity or activities of other individuals may be assessed by their relativity to the *IR* reference levels of Table 2.

4.4 Risk assessment

4.4.1 RPT sector performance

In the Australian RPT category to 2004, there has been only one single non-fatal air-ground collision in 33 years (ECCAIRS sub-category, 2050102). Assuming an average population of people who fly at least once a year of 2.2 million, and assuming one hypothetical death, then RPT has achieved an IR_{Aest} at approximately 1 x 10^{-8}. This risk level is significantly below the IR_{Aest} level of risk (of 7.8 x 10^{-8} in Table 5) for the national population with respect to mid-air collision. This level should also be compared with the analogous goal of the commercial space launch industry (IRIG, 2000). However, while this result is respectable it is not to be read with complacency as the Boeing (2004) statistical summary shows.

In the decade 1994-2003 there were 420 fatalities due to mid-air collisions in the world wide commercial jet fleet which comprised 14 621 aircraft in 1998. These fatalities arose from: the New Delhi, India accident on 12 November 1996 between a Saudi B 747-100 and a Kazakhstan Air Lines IIyushin 76 cargo aircraft with 349 fatalities; the Ueberlingen, Germany accident on 1 July 2002 involving a DHL B 757 and a Bashkirian Tu 154 aircraft with 71 fatalities; and the Brazilian Para accident on 1 October 2006 when an Embraer Legacy 600 corporate jet carrying a crew of two and seven passengers collided with a Boeing 737-800 operated by Brazilian Gol Airlines resulting in 155 fatalities from the B 737. Surrogate rates based on this data could be proposed for Australia thus increasing the predicted $E(IR_A)$ over the estimated IR level. However, use of surrogate measures raises many issues about the relevance of the measure when comparisons cannot be made between the traffic flow patterns of one airspace environment with another. Such difficulties may make such an approach non-practical.

The most simple underlying Poisson model has an unknown accident rate per unit time, λ. For a time period of length, T, the estimate of the expected number of accidents is λT. The rate, λ, may be estimated by equating λT to the number of accidents observed. For Australia, this estimate is 0 for mid-air collisions involving RPT in the period 1961 - 2004. This is not very useful for either planning or discussion purposes! However, estimates should also have a measure of their accuracy where possible. One such measure is a confidence interval or bound. For the Poisson model, the upper 95% confidence bound on λT is $\log_e 20 = 3.0$ (see Cox and Hinkley (1974), Example 7.4 for the derivation and meaning; Brooker (2004) for an application). So the upper 95% confidence bound on λ for RPT mid-air collisions in Australia is 3.0/44 = 0.068. This could be used as a very cautious choice for planning or discussion. An alternative is to choose a value somewhere in the range [0, 0.068] on other grounds.

The model may be developed further to include fatality rates. The fatality rate may be considered as being the Poisson accident process with another random variable attached to each accident, this being the number of fatalities. The expected number of fatalities over T is $\lambda T \kappa$ where κ is the mean number of fatalities per accident. In the light of Barnett et al. (1979, 1989), κ is likely to be close to the average combined load of the aircraft involved. Note, in passing, that $\lambda \kappa / I$ is an estimator for $E(IR_A)$.

4.4.2 General aviation performance

For all licensed pilots who potentially fly in GA activities $IR_{A\mathrm{est}}$ is 2.7 x 10^{-5} close to the level at which the community as a whole becomes aware of the emergent rise of risk. It is also less than the de facto level (benchmark) for IR being 1 x 10^{-4}, indicating a level of risk acceptable to the public who have a risk imposed upon them (HSE, 2001). The population of persons travelling in GA is greater than that of the pilots alone because there are often passengers in GA aircraft. However, no data were available to the authors as to the number of persons transported in GA, and the level used above is acknowledged to be conservative.

4.4.3 Sport aviation performance

For gliding, inclusive of towing and GA accidents, $IR_{A\mathrm{est}}$ is 1.1 x 10^{-4}. This is significantly higher than the $IR_{A\mathrm{est}}$ for GA, though it is marginally less than the de facto IR level, and significantly less than the level, 1 x 10^{-3}, generally accepted as an upper limit for workers (HSE, 2001). This demonstrates the acceptability of a higher level of risk within the gliding fraternity. One possible reason is that this fraternity is willing to accept situations in which proximity is sought (e.g., gliders sharing the same thermal to gain competitive advantage).

4.4.4 Limitations of population-based approaches

Analyses based on sparse historical data cannot assure reasonable confidence in system performance. Where accidents are rare, it may take decades to hundreds of years to collect enough data to gain statistical significance (e.g. the RGCSP criteria of ICAO (1973)), and the historic fatality rate may not have been derived from a sufficiently long time series to reflect the potential for future disaster. In these situations, a lower fatality rate may be taken to imply a higher confidence in airspace design than is warranted. Conversely, if two accidents were to occur within a short time of each other, this does not necessarily mean that the airspace design is performing poorly, in a statistical sense. Neither extreme event can be ignored.

Exposure to a proximity event is a key concept within airspace design. There are many dynamic factors that influence its assessment. For example, it is clear that traffic flows and operational procedures may change over time, changing the rate at which proximity is generated. The measure $\overline{F}_A$ is not necessarily dependent in any strong sense on the number of movements per annum. As a consequence, using $\overline{F}_A$ may produce misleading indications of the robustness of airspace design for different traffic flows. Clearly, we can say something when traffic flight-paths (movements) are stationary over time and consistent patterns of interaction and communications between aircraft are exercised, but very little is demonstrated when individual flight-paths do not interact or where interactions change dynamically.

4.4.5 Summary on historical performance

The results presented in this section are based on historical performance of the airspace system. They show that each operational category investigated has demonstrated a measured level of risk commensurate with an appropriate, acceptable, level of risk as found in Table 2.

However, the measured levels are reflexive and apply only to the specified aircraft operational category and its associated population. The interaction within and between operational categories has not been explicitly addressed. Official accident reports such as the Mildura incident cited in Section 2 and the data of Table 3 show that interaction within and between operational categories cannot be ignored.

Further, historic measurements cannot be used for prediction of future performance since this would assume that there would be no change in engineering infrastructure or in the patterns of use by the aircraft themselves, or in the numbers of aircraft using airspace, or in the performance (e.g., speed) of the aircraft.

While this section has demonstrated that acceptable levels of risk have been achieved in the past the assessment provides little design insight as to how to ensure that such levels are achieved in the future. To address this concern, in Section 5, a number of statistical models are developed that explore the essential mathematical nature of the problem at hand.

5. Mathematical models for population-based approaches

As has already been discussed, historical data for mid-air risk have provided some utility for policy and planning decisions. Such data have also been used as a reference for equivalent levels of safety (ELOS) when changes to airspace have been proposed but available data are often skewed. For most countries, the period of the recorded historical time series, traffic levels and risk levels are such that the available data are simply too sparse to permit the estimate of trends or the drawing of reliable conclusions. Conversely, proactive engineering design of the airspace system requires observable performance measures based on much shorter operational time scales. In control theory it is necessary to determine whether or not the system state can be determined, in practice, by measurements made on the output of the system. This is the concept of observability. It is infeasible for airspace design to be assessed on the basis of the occurrence of a mid-air collision (a rare event). Rather one would want to observe the more tractable short-term measure being the dependability of the communication links used to prevent the mid-air collision from occurring in the first place. Therefore a change in focus from long-period historical measures to that of measures based on time scales of the aircraft proximity encounter itself is required.

We set a foundation for this shift of focus by investigating a number of theoretical models. It will be argued that a common design theme applies regardless of the approach taken in determining *ENFY* or $E(IR_A)$: there is a need to succinctly define exposure to the collision event and the probability of a collision per unit of exposure. Having defined these concepts a final step relating fatalities and collisions may be taken thus arriving at the probability of fatality per unit of exposure. Both exposure and probability of collision per unit of exposure have engineering implications, as we shall indicate in Section 6.

5.1 Aggregation of Individual Risk over a number of populations

The estimate, $IR_{A\text{est}}$, can be found directly by plotting the $\overline{F}_A$ on its respective population line. Uncertainty in $IR_{A\text{est}}$ depends mainly on the uncertainty in the size of the population.

Pragmatic interpretations of this uncertainty by either graphical, numerical or statistical means will provide an estimate of the variation in $IR_{A\text{est}}$.

If the individual groups achieve their respective IR goals then their risk signatures, ($IR_{A\text{est}}, \overline{\mathrm{F}}_{\mathrm{A}}$), should not be prominent in the public's perception based on historical interpretation of the levels identified in Table 2.

When aggregating risk across a number of groups, say, m = 1 ... M, then the aggregate risk is given by:

$$IR_{aggregate} = \frac{F_A(1) + \ldots + F_A(M)}{I_A(1) + \ldots + I_A(M)} = \alpha_1 \cdot IR(1) + \ldots + \alpha_M \cdot IR(M) \tag{4}$$

where

$$\alpha_m = \frac{\lambda_m}{\lambda_0} \quad \text{and} \quad \lambda_0 = \sum_{m=1}^{M} \lambda_m \quad \text{with} \quad \lambda_m = \frac{I_A(m)}{I_A(1)} \qquad \therefore (\lambda_1 = 1) \tag{5}$$

with
$$\sum_{m=1}^{M} \alpha_m = 1 \quad \text{and} \quad 0 < \alpha_m < 1 \tag{6}$$

The particular normalisation presented above was chosen to exploit the use of raw data with the least uncertainty. Fatalities are required to be reported under law and uncertainties in population sizes can be reasonably estimated or bounded through legal pilot licensing requirements, club membership records and numbers of participants in frequent flyer programs. Other more simple normalisations can be achieved but these require the summation of derived terms with higher uncertainties, such as the IR estimates themselves.

The constraints imposed on the overall $\overline{\mathrm{F}}_{\mathrm{A}}$ have already been discussed in Section 4.3.

5.2 A conservation equation relating population-based measures to transport-based measures

Historically, analysis of aircraft collision risk has principally used transport-oriented models (ICAO, 1973). This paper has shown that a population-based analysis is also possible. These two approaches are related through a simple three-dimensional conservation equation. Two dimensions form the array of Fig.3; the population of people who fly during some unit time interval (such as a year) and the number of flights in that period. An entry in the array, $S_{i,j}$ say, is assigned to 1 if person i travels on flight j, and 0 otherwise. Counting the non-zero entries in the ith row gives the number of flights taken by person i in the period, X_i say. Counting the non-zero entries in the jth column gives the number of filled seats on flight j, which is the flight load L_j. The third dimension is time, which we do not consider further here.

Fig. 3.

In the further development of this paper we shall consider the time period to be a year.

Formally, suppose that in a year a population of *I* people travel on a total of *T* flights. Summing over all the entries in the array gives the number of filled seats S_A in the year. This can also be regarded as either the sum of the flights X_i made by the *I* travellers or the sum of the loads L_j on the *T* flights. Equating these leads to the simple conservation equation

$$\sum_{i=1}^{I} X_i = S = \sum_{i=1}^{I}\sum_{j=1}^{T} S_{i,j} = \sum_{j=1}^{T} L_j \qquad (7)$$

or,

$$I \cdot \overline{X} = S = T \cdot \overline{L} \qquad (8)$$

where $\bar{X}$ is the average number of flights per person and $\bar{L}$ is the average load per flight during the year. The left side of Eqn. (8) refers to the population at risk, the right side to the transport load.

In a theoretical analysis, the array entries $S_{i,j}$ are random variables. If *E(X)* represents the expected number of trips by an arbitrary member of the population and *E(L)* represents the expected load on an arbitrary flight, taking expectations in Eqn. (8) gives

$$I \cdot E(X) = T \cdot E(L) \tag{9}$$

If relevant data are available, the expectations can be estimated by calculating the numerical values of the averages in Eqn. (8).

5.3 A model for Collective and Individual risk

The model has the following assumptions.

1. When a mid-air collision occurs, everybody on the aircraft involved is killed.
2. The probability of a flight being involved in a mid-air collision is a constant, *p*.
3. For an individual person, the avoidance of a mid-air collision by a flight they are on is an independent event for each flight.

Assumption 1 is conservative for design purposes. Assumption 2 can be relaxed at the cost of added complexity of notation; see the next subsection. Assumption 3 seems very plausible and simplifies the model substantially.

Initially, assume also that the number of trips planned for person i, X_i, is fixed. This will be relaxed shortly. Under these assumptions, it is clear that the chance, P_i, of individual i avoiding death from a mid-air collision during a year is

$$P_i = (1-p)^{X_i} \tag{10}$$

The *IR* per annum for individual *i* is 1 - P_i. If the product is small, as would typically be the case for mid-air collision risk, we have the good approximation

$$IR_i = 1-(1-p)^{X_i} \approx X_i \cdot p \tag{11}$$

The *ENFY* for the population is clearly

$$E(F_A) = \sum_{i=1}^{I}(1-P_i) \approx p \cdot \sum_{i=1}^{I} X_i = I \cdot \overline{X} \cdot p \tag{12}$$

so the *IR* per annum for an arbitrary member of the population is, by definition, approximately $\overline{X}.p$. This is consistent with the *IR* for a particular individual in Eqn. (11). It is discussed further in the next subsection.

Note that the approximation in Eqn. (11) is the answer obtained by ignoring the fact that a person can only die once! For rare events such a mid-air collisions, this will generally be quite acceptable in practice. When X_i is a random variable, as is typically the case, these approximate expressions for *IR* and *ENFY*, Eqn. (11) and Eqn. (12) respectively, become

$$IR_i = E(X_i) \cdot p \tag{13}$$

$$E(F_A) \approx p \cdot \sum_{i=1}^{I} E(X_i) = I \cdot E(X) \cdot p \tag{14}$$

while the *IR* for the population is approximately *E(X).p*.

5.3.1 Generalization of the model

Equations (11) and (12) reinforce the point that, for population-based calculations to be relevant to each individual in the population, the population must be relatively homogeneous. In this case, `relatively homogeneous' means that the individual X_i do not differ greatly. This would not be the case if the population included both professional pilots and casual air travellers, whose individual X_i might differ by at least an order of magnitude.

The same would be true if an individual's flights during the year had very different probabilities of a mid-air collision, in violation of Assumption 2. The data in Section 3 show this is very possible with a mixture of RPT and sports aviation, for example.

To extend the model, we modify Assumption 2 as follows.

Assumption 2a. There are K types of flight, and the probability of a flight of type k being involved in a mid-air collision is a constant, p_k ($k = 1, \ldots K$).

If individual, i, makes $X_{i,k}$ flights of type k during a year, again assumed fixed for the moment, then Eqn. (10) generalizes to

$$P_i = \prod_{k=1}^{K} \left(1 - p_k\right)^{X_{i,k}} \tag{15}$$

the approximation in Eqn. (11) becomes (assuming each $X_{i,k}.\ p_k$ is small)

$$IR_i \approx \sum_{k=1}^{K} X_{i,k} \cdot p_k \tag{16}$$

and the *ENFY* in Eqn. (12) becomes

$$E\left(F_A\right) \approx \sum_{i=1}^{I} \sum_{k=1}^{K} X_{i,k} \cdot p_k = I \cdot \sum_{k=1}^{K} \overline{X}_k \cdot p_k \tag{17}$$

Here, X_k is the average number of flights of type k per person per annum. The approximations with random flight numbers follow readily from these in the manner of Eqn. (13) and Eqn. (14).

5.4 Summary on mathematical models

The models introduced above are fairly simple, but they serve to highlight the two components of any risk calculation;

1. the level of exposure (the $X_{i,k}$), and

2. the risk per unit of exposure (the p_k).

The term dynamic density is now being used to describe essential factors that govern the rate of generation of conflict in airspace. Generically, dynamic density refers to both a population density and to the degree of interaction between members of that population. In the case of airspace the population of aircraft and their interaction is considered. However, for the mid-air collision the focus of design measurement moves from a measure of static density (traffic density is the number of aircraft in a given volume of airspace) to that of a proximity pair (the number of interacting flight path segments in that volume of airspace) a relation formed between aircraft on the basis of the complexity of flow occurring in the airspace and on the physical separation standards to be applied. It is the proximity pair that must be managed, not so much individual flight movements. Proximity pairs arise from all possible combinations of aircraft pairs regardless of flight regime, operational category, or aircraft performance. Since this is an event comprised of physical entities all aircraft must be accounted for; no artificial exclusion based on categorical delineation such as aircraft flight regime or operational category is permitted. The number of proximity pairs and the risk associated with each pair is determined by such factors as: the geographical dispersion of the total flow patterns, the topological nature of the flow interaction, aircraft performance and the dependability (availability, reliability, integrity) and characteristics (e.g., transaction length) of communications available to pilots for managing and controlling proximity pairs.

The evaluation of the level of exposure, $X_{i,k}$, and the risk per unit of exposure, p_k, are both strongly dependent on the individual's exposure to the rate of generation of proximity pairs. Exposure can be interpreted as more a measure of the number of proximity pairs encountered by an individual than a count of all flights undertaken in a given time period.

Thus proactive design should seek to manage the proximity pair to acceptable physical standards (distance and time) rather than base assessment on static measures of traffic density as has been done historically.

6. Implications for design

The rational decision space permits the risk assessment process to be visualised. Both historical data and future impact analyses ("what-if" situations) for the various candidate populations can be presented.

For example, by informed reasoning we can deduce the implications and consequences of a collision. Suppose, for example, an ATO aircraft suffered a mid-air collision with a single crew glider. Suppose also that there were 183 fatalities for the ATO aircraft and that there was one fatality for the glider. The consequence for ATO is that the minimum IR_{Aest}. for the year of the accident would be 8.3 x 10^{-5} when assessed over the national at-risk population of 2.2 million people. According to Table 2, this is a level where the public become aware of the emergent rise of risk. Conversely, for the gliding fraternity one fatality in 3 200 at-risk glider persons represents an IR_{Aest} of 3.1 x 10^{-4} which, according to Table 2, is still below the level generally accepted by workers and certainly below that level where risk is willingly accepted for purposes such as sport. The direct consequence of this accident for the gliding fraternity is minimal. However, the broader industry consequence and response, according to Table 2, will be very different. Further, the aggregation of the fatalities over both populations can be considered. In this case, assuming mutually exclusive populations, the aggregated IR_{Aest} is 8.3 x 10^{-5} a level near to that for the ATO outcome but also near the upper limit of acceptance for the public who have a risk imposed upon them. The analysis shows that the national acceptance of this accident type may be in question.

The “what-if” analyses can be further developed to include more detailed operational considerations. Interactions of heterogeneous operational categories (e.g., ATO - GA, ATO - Gliding, GA-Gliding, etc.,) are of particular concern especially in regional airspace. For example, in Western Australia a diversity of aircraft types now operate in low level UMAS (regional) airspace (CAPA, 2002). Boeing B737-800 with 177 seats, through mid-size to small regional Dash-8 aircraft (with 19 to 36 passenger seats), to small GA aircraft of 1-4 seats all share common airspace. Should any two of these aircraft collide then the consequence could range from zero when all occupants survive, through 42 (passengers plus crew) to 366 fatalities if all involved were to die. The historical data do not explicitly reflect this potential level of risk. A mid-air collision with the maximum number of potential fatalities would increase the *ENFY* (from all air transport operations) from 1.55 (using Table 3 data) to ((366+366+68)/44) =18.18.

Aircraft categorised by disparate flight regimes, operational categories and performances intermingle in common airspace. The resultant activity increases the overall potential for proximity of operational concern. This is important when considering the design of a communication infrastructure for airspace.

6.1 Consequences for design of communication links

The dependability of communication links between proximate aircraft emerges as a critical design issue. Such dependability directly influences the assessment of the probability of a collision given the occurrence of a proximity event.

The term communication link is used here in its broadest scientific sense. It is a means of transferring information between aircraft and has characteristics of directness, mode and latency. Direct links can form between aircraft. Indirect links rely on provision of a ground-based air traffic service. While air-to-ground links are of strategic importance, air-to-air links are of tactical importance.

Communication modes include: “see-and-avoid”, direct voice communication (VHF, UHF, or even HF radio), ground-based radar and data links (such as ADS-B). The physical availability of each mode of communication is a dynamic concept and multiple modes may be in use simultaneously. In this situation each direct and indirect link is naturally modelled by a parallel redundant heterogeneous communication scheme. The overall airspace design requires that both the direct and indirect links are required since ground-based services may not exist, may fail, or may simply not be rapid enough to respond to an immediate proximity situation at hand

Progressively data link (such as ADS-B) is being introduced to augment, but not replace, historic modes of communication. Once implemented this mode should remove much of the variation in performance now experienced due to the failure modes of the existing heterogeneous links. Specifically, the dependability measures of reliability, availability, continuity-of-service, and integrity are required for all short-term, on-demand inter-aircraft communications used during sustained proximity. A point to note is that, in different parts of the world, the system performance of the proximity management function as implemented may in fact be very different simply because of the differences in the local communication link infrastructures underpinning that implementation. Regardless of changes in infrastructure the proximity warning function must continue to function dependably as a flight progresses from one locality to another. This has not always been the case in past systems but such differences should be minimised in future implementations.

In an historical context avionics and air traffic control technology have realised a useful life of ~20 to 30 years, but today such systems may be changed or replaced on a much more frequent basis. In these latter cases reliance can no longer be placed on historical data to assess the dependability of communications in managing proximity. The main focus of future design must turn from long-term historic measures of risk to include new approaches based on an understanding the nature of traffic flow interactions, the generation of proximity within those flows and the dependability of the lines of defence provided to manage that proximity. Ultimately, this translates to setting performance requirements and specifying permitted failure rates for communication links between proximate aircraft.

7. Conclusions

This paper has presented a unified approach to the management of mid-air collisions in airspace that points to the need for a more comprehensive interpretation of the design requirements. The approach is based on well-founded operations research and engineering methods that exploit the concept of a design space. The relationship between collective risk, F_A, and individual risk, IR_A, is used to create such a space. The movement of the level of risk in the system can then be monitored over time. Different management situations can be explored through examination of the hypothetical movement of risk levels in response to "what-if" situations. Also, in response to these situations changes in risk level can be visualised for both individual and aggregate populations. By associating each population group with an individual risk level an assessment as to the acceptability of that risk can also be formed.

Theoretical approaches for deriving relationships for *ENFY* and $E(IR_A)$ were also examined. It was shown that predictive modelling and historic measurement is useful in developing these approaches to setting national policy and for long term monitoring of accident and fatality rates. However, both approaches have limitations from a prospective engineering design perspective. It is argued that for this purpose the engineering design must address two further issues: management of an individual's (and therefore an aircraft's) exposure to a proximity event and minimisation of the probability that a collision occurs given the proximity event occurs. Both requirements must be explicitly addressed in the design of the communication links to ensure that the appropriate risk levels as identified in Table 2 can be achieved.

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Appendix

Two extreme versions of a simple model for midair collision fatalities in a population of size I are given. They give insight into the relationships between the standard risk measures and provide bounds for some of them.

Independence model

In the first version, every population member is subject to risk independent of any other member. The aviation equivalent is a population who fly in single-seat aircraft and are never in the air at the same time. Hence they risk collision only with members of other populations. If we define π as the probability of a population member dying in a midair collision during the year, assumed the same for all members, then clearly:

$$IR = \pi$$
$$ENFY = I.\pi$$
$$F(1) = 1 - (1-\pi)^I \approx I.\pi$$

Note that IR is defined directly here, though it still satisfies the basic defining equation (1).

Total collective model

In the second version, every population member is simultaneously subject to exactly the same risk. The aviation equivalent is a population who always fly together.

If now, π is the probability of a midair collision during the year, involving this population, then by our Assumption 1 the number of deaths during the year is either *0* or *I*. Hence:

$$IR = \pi$$
$$ENFY = I.\pi$$
$$F(1) = \pi$$

So although *IR* and *ENFY* have the same definition in the two models, the values of $F(1)$ (and $f(1)$) can differ considerably. Further, the models provide practical bounds on $F(1)$ for a given *IR* or *ENFY*.

We do not claim that these models are realistic. Rather, they provide useful insight. It is possible to construct a continuum of more realistic models spanning the extremes in which $F(1)$, for each model, lies between the bounds presented above. These models show how the degree of collectivity in the risk exposure of a population is reflected in various risk measures under different assumptions.

Terminology

In this paper there are three contexts in which a variable, say B, may be used. First, it may be used as a parameter in a deterministic equation representing a physical law or a relationship that satisfies a dimensional analysis, in which case it will be denoted B. Second, the variable may be treated as a random variable of a statistical model in which case the expectation for the random variable will be used, viz. E(*B*). Third, the measured data of a random variable may be required in which case it will have a mean, denoted $\overline{B}$ (and a variance).

Nomenclature

i	index for people flying per annum i = 1(1) I
j	index for number of movements (flights) j =1(1) T
k	index for different aircraft types k = 1(1) K
m	index for different population categories m = 1(1) M
α_m	linear multiplier for the mth population
λ_m	normalised population multiplier for the mth population
κ	[mean number of fatalities per accident]
ΔF_A	sign of incremental change in Collective Risk for a specified time
ΔIR_A	sign of incremental change in Individual Risk for a specified time
ΔI	sign of incremental change in Population at risk for a specified time
ENFY, $E(F_A)$	[Expected number of fatalities per year (annum) in a specified population]
$E(IR_A)$	expected [proportion of deaths in a specified population per annum].
E(L)	expected [number of individuals per movement]
E(X)	expected [number of movements (flights) made by an individual] within a population
f, f(N)	frequency of accidents with precisely N fatalities
F, F(N)	frequency of accidents with N or more fatalities
F_A	number of fatalities per annum

$\overline{F}_A$	average [number of fatalities per annum]
$F_A(m)$	number of fatalities per annum in m^{th} population
I	[Population at risk]
I_A	[total number of individuals who flew per annum]
I_A (m)	[total number of individuals who flew per annum in m^{th} population]
K	[total number of types of flight]
IR	Individual Risk [proportion of a specified population at risk that die per unit time]
IR_A	Individual Risk [proportion of a specified population at risk that die per annum]
$IR_{aggregate}$	Individual risk aggregated over M population groups
$IR_{Aest.}$	estimated [probability of death per person per annum].
IR_i	[individual risk per annum for individual, i]
$\overline{L}$	mean [number of individuals per movement] as measured
L_j	[number of individuals (load)] on the j^{th} flight
M	[total number of population categories]
N	number of fatalities in an accident
P_i	[chance of an individual, i, avoiding death per annum]
p	[probability of collision]
p_k	[probability of collision when a flight is flown in aircraft type-k]
P_i	[probability that the i^{th} individual will die in a mid-air collision]
S	the total number of occupied seats per annum
$S_{i,j}$	a binary variable: S(i, j) =1 if the i^{th} person is a passenger on the j^{th} flight, 0, otherwise.
X_i	the total number of seats occupied by the i^{th} individual per annum
$X_{i,k}$	the total number of flights of type k that individual, i, makes per annum
$\overline{X}$	mean [number of movements (flights) made by an individual] as measured
X_K	mean[number of flights of type k per person per annum]

T [total number of movements per annum] stated as a design bound

T [period of time in Poisson model]

T_M [total number of movements between mid-air collisions] stated as a design bound

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Fig. 1: Rational Decision Space: Australian mid-air collisions

The individual risk index is the exponent from the individual risk levels as documented in Table 2. (RPT - Regular Public Transport)

Fig. 2 *f. N*: Australian mid-air collisions (1961 - 2004)

The graph shows the ***f.****N* data for all aircraft activities (the Y axis has a logarithmic scale). The predominant contributors are GA activities and gliding with the exception of the occurrence of a single accident in ballooning with 13 fatalities (data in Table 4).

Fig. 3. People-flight incidences

Representation of total seat occupancy per annum (S_A), numbers of flights by members of the population at risk ($X_i(\bullet)$) and numbers of people aboard each flight ($L_j(\bullet)$) as summations of people-flight incidences.

Table 1
Categorisation of flight operations – the first two levels

	VFR	IFR
Managed Airspace (Classes A, B, C, D &E)	Mid Level enroute Terminal airspace	High Level enroute Mid Level enroute Terminal airspace
Unmanaged Airspace (Classes F & G)	Regional enroute and terminal airspace	Regional enroute and terminal airspace

Table 2
Reference levels for Individual Risk, IR_A

Risk level	Description
3.5×10^{-2}	The mean acceptable risk of injury (Ingles, 1985).
6.42×10^{-3}	The overall Australian mortality rate (ABS, 2005).
1×10^{-3}	If risk is perceived at this level then action will already have been taken to reduce it (Rasmussen, 1975; Ingles, 1985). Generally accepted as an upper limit for workers (voluntary) (HSE, 2001).
2.45×10^{-4}	Australian accidental death risk level - all external causes (ABS, 2005).
1×10^{-4}	Generally accepted as an upper limit for the public who have a risk imposed upon them (HSE, 2001). (Also called the de facto or benchmark level in this paper.)
1×10^{-5}	The community as a whole becomes aware of the emergent rise of risk (Kletz, 1982; Ingles, 1985; Villemeur, 1992).
2×10^{-6}	Estimate of maximum individual risk from air transport in Australia over the national population. (Robinson and Fulton, 2002).
1×10^{-6}	Natural events such as death due to lightning strike typically occur at less than this level (Ingles, 1985). The Dutch government assessed this level as requiring effort to reduce risk (Schipol accident, 1992) (Robinson and Fulton, 2002).
7.8×10^{-8}	The average individual risk in Australia for the national population due to mid-air collision (1961 - 2004).
3×10^{-8}	The death risk from dam failure in Australia per annum (Ingles, 1985).

Table 3

Collective risk (fatalities per annum) for mid-air collisions in Australia - (1961-2004)

Operational category	**Fatalities**	**Collective risk (fatalities per annum)**
En route GA and minor airports	8	0.18
At or near major airports	24	0.55
GA fatalities due to collisions with gliders	6	0.14
GA total	38	0.86
Gliding fatalities due to collisions with GA aircraft	1	0.02
Gliding	7	0.16
Glider - tow	7	0.16
Glider total	15	0.34
Ballooning	13	0.30
Other sport aviation	2	0.05
Sport aviation total	15	0.35
Air Transport sector - total	68	1.55

Source: ATSB (2004a), ATSB(2002), BASI (1998)

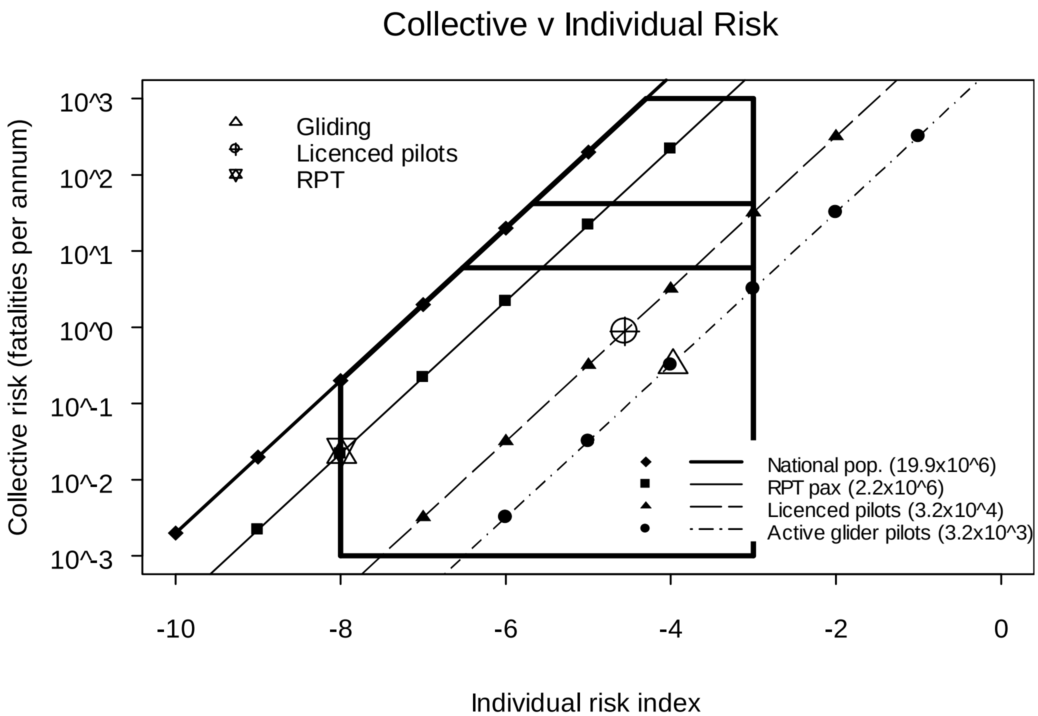
Table 4
Number of mid-air collisions and fatalities - Australia (1961 - 2004)

Number of fatalities per accident (N)	GA Enroute & GAAP[a]	GA/ Sport/ Gliding	Gliding	Glider tow	Sports	Total accidents	Total fatalities
0	14	1	11	0	2	28	0
1	4	0	4	5	2	15	15
2	1	1	0	1	0	3	6
3	0	0	1	0	0	1	3
4	4	0	0	0	0	4	16
5	2	1	0	0	0	3	15
13	0	0	0	0	1	1	13
Total accidents	25	3	16	6	5	55	
Total fatalities	32	7	7	7	15		68

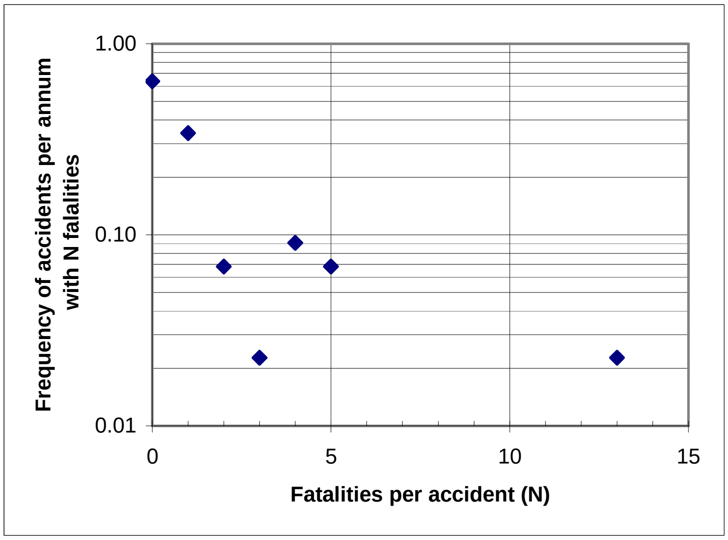
Source: ATSB (2004a), ATSB (2002), BASI (1998)
[a]General Aviation Airport Procedures (GAAP)

Table 5
Individual risk for mid-air collisions in Australia - (1961-2004)

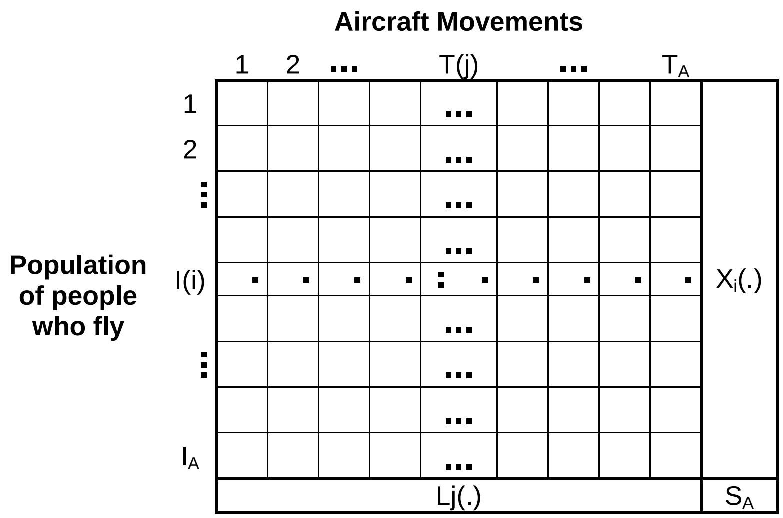
Operational category	Fatalities in period	Candidate population	Estimated Individual risk
Gliding including fatalities due to GA collisions	15	3.2×10^{3}	1.1×10^{-4}
General aviation including enroute, GAAP, interaction with gliders, and sports such as formation flying and aerobatics	39	3.2344×10^{4}	2.7×10^{-5}
Ballooning and other sports	14	not determined	-
RPT	1 (notional)	2.2×10^{6}	1.0×10^{-8} (notional)
National Individual Risk due to the air transport sector	68	19.9×10^{6}	7.8×10^{-8}



Collective v Individual Risk
Collective risk (fatalities per annum)
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
Gliding
Licenced pilots
RPT
National pop. (19.9x10^6)
RPT pax (2.2x10^6)
Licenced pilots (3.2x10^4)
Active glider pilots (3.2x10^3)
-10
-8
-6
-4
-2
0
Individual risk index



1.00
0.10
0.01
Frequency of accidents per annum with N falalities
0
5
10
15
Fatalities per accident (N)


Aircraft Movements
1
2
T(j)
TA
1
2
I(i)
IA
Population of people who fly
Xi(.)
Lj(.)
SA