Collison Risk Analysis in Air Traffic Control

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Abstract: A model is developed for collision risk estimation in air traffic control system, which resolves the problem of the collision risk assessment of the recent air traffic management system. It is a systemic model, in contrast to the old models, in which the defensive barrier and human factors are modeled and the focus is on systemic analysis. The collision event tree is used to calculate the collision risk. This model makes it straightforward to see what leads to collision, and easy to understand the roles of the main parameters. It is a good starting point for the incorporation of defensive barrier and the human factors.

Key Words: Air Traffic Control, Collision Risk, Separation Minima

1. INTRODUCTION

In recent air traffic environment there is an emphasis on traffic flow increasing, economic, cost-efficient operations and the need to maintain aviation safety and dramatically improve it. This is being accomplished by transitioning to data link communication, satellite-based navigation and radar surveillance, the equipage of ground facilities and aircraft cockpits with new technology, and the introduction of new airspace procedures and rules.

There are no mid-air collisions in many years in china, but the incidents data collected show that 14 air misses occurred in recent years (1996-2006), which means potential strong collision risk. Domestic air traffic flow is scaling up about 10 percent in recent years, which induce the increasing of collision risk inevitably. So it is crucial to study the mid-air collision risk.

Because of the limited size of airspace sectors and the need for fuel-efficient flight paths, separation minima are established. The safety of the separation minimum is verified by quantified collision risk. In 1966 Reich published three very influential papers in the Journal of Navigation on the analysis of long-range air traffic systems separation standards (Reich, 1966a; Reich 1966b; Reich 1966c). This Reich Model has been used extensively in safety analyses of Air Traffic Control (ATC) track structures, but it is not appropriate for the air
traffic service nowadays. In 2003 an event-based lateral model is presented by Brooker (2003), and then an event-based longitude model (Brooker, 2005a). Event-based model is a dynamic model and enables collision risk estimation to be made for a system using data link communication and satellite navigation.

Previous derivations were not systemic, in that they have not attempted to take properly into account all main factors that might lead to collision risk. This paper presents a systemic collision risk model. The CNS (communication, navigation, surveillance) system, the defensive barrier – STCA (Short Term Conflict Alert) and TCAS (Traffic alert and Collision Avoidance System) and the human factors are modeled. The main difference from the earlier work lies in that this is a systemic model rather than one focusing on deviations or events.

Systemic collision risk model is more advanced than the former collision risk models because the existing risk assessment are over-pessimism for defensive barrier is deemed not be part of the total system. The ATM (Air Traffic Management) operational concept defines three layers of conflict management: strategic conflict management, separation provision and collision avoidance. The existing collision risk model just cover the separation provision but exclude the collision avoidance. The third layer will be activated when the separation mode has been compromised, which decrease the risk of collision for the collision avoidance. Therefore, systemic collision risk model is more prominent than other models.

2. GENERAL CONCEPT ON COLLISION RISK

In order to present the collision risk, some concepts related must be made clear. It should be noted that the focus on the collision risk on the given separation minima meet the target level of safety. To introduce the avoiding system, the defensive barrier is presented here too.

2.1 Separation Minimum

Separation is the generic term used to describe action on the part of air traffic services (ATS) to keep aircraft operating in the same general area at such distances from each other that the risk of collision is maintained below an acceptable safe level (ICAO, 1998). Such separation can be applied horizontally and vertically. Separation in the horizontal plane can be achieved either longitudinally or laterally. Vertical separation is achieved by requiring aircraft using prescribed altimeter setting procedures to operate at different levels expressed in terms of flight levels or altitudes.

The determination of longitudinal separation minima, lateral separation minima and vertical separation minima should be based on the performance of the CNS system. Longitudinal separation minima are related to the quality of information available to ATC and the pilot. Lateral separation minima are determined mostly by the quality of the navigation. Vertical separation minima are based primarily on the accuracy of the altimeter.

2.2 Collision Risk

Four of the main interdependent parameters that affect the collision risk of a given traffic density are aircraft navigation performance, ground and airborne communication performance and surveillance performance and human factors.

Among the four main factors, collision risk analysis focused on very much on navigation rather than others. The navigational accuracy and altimetry system accuracy improved...
considerably because new technologies were fitted, so that the major cause of larger errors arose from human errors rather than navigation system, such as the use of incorrect waypoints, when the pilot entered the wrong track into the on-board computer.

2.3 TLS (the target level of safety)
The maximum tolerable risk is normally expressed in terms of a TLS which is a quantified risk level. Generally the TLS is expressed in terms of the number of fatal accidents per flight hour (where a collision between two aircraft represents two fatal accidents). The current ICAO-RGCSP-1995 figure of $1.5\times10^{-8}$ fatal aircraft accidents per flying hour is the rate corresponding to mid-air collisions, for any reason and in any spatial dimension, in en route flight in controlled airspace.

2.4 Defensive Barrier
Defensive barrier comprises two main components - STCA and TCAS which interact to reduce the collision risk of flight operation effectively.

STCA monitors aircraft locations from ground radar and provides advisory alerts to air traffic controllers if a pair of aircraft is likely to become dangerously close. The STCA system is designed to raise a warning to air traffic controllers if there is a developing conflict between aircraft, giving them time to redirect the aircraft.

TCAS is a computerized avionics device which is designed to reduce the danger of mid-air collisions between aircraft (FAA, 2000). It monitors the airspace around an aircraft, independent of air traffic control, and warns pilots of the presence of other aircraft which may present a threat of mid air collision. It offers TA (Traffic Advisory) and RA (Resolution Advisory), the former warns the pilot that another aircraft is in near vicinity and the latter offers the pilot direct, vocalized instructions to avoid danger. TCAS is a commercially available version of what are generically known as Airborne Collision Avoidance Systems (ACAS) which reduces the probability of mid-air collision effectively.

3. SYSTEMIC MODEL
The assessment of traffic safety in relation to ATM management is addressed in this section, which is based on the mathematical model. The collision risk model determine the correlation between elements such as collision risk, separation minima, airspace design, air route network characteristics, flow parameters, intervention capability and communication, navigation and surveillance equipment performance.

The model developed here is a systemic approach. To distinguish the model from the Reich model and Event model, it is referred to here as the systemic model. This model is built and has not been used before elsewhere, but it is applied in an example to verify its practicability and merits in the next section. Because of the complexity of each factor and combinations of all factors, it is very difficult to accurately estimate some parameters. However, it is often possible to make a cautious estimate of the risk so that the result is receivable.

3.1 Systemic Collision Risk Model
Collisions can not happen instantly: the aircraft pair concerned would have to move from a safe state to one that is hazardous. In the transformation process, STCA and TCAS would
generally detect imminent collisions if they are available, and air traffic controller have enough time to intervene, so the collision risk would be eliminated, but on the other hand, if the prevention fails, collision occurs.

James Reason proposed the image of "Swiss cheese" to explain the occurrence of system failures (Reason, 1990), which is used to analyze the mid-air collision in the paper. In the complex ATM system, mid-air collisions are prevented from occurring by a series of barriers - separation minima, air traffic controller and avoiding system, etc. Each barrier has unintended weaknesses, or holes – hence the similarity with Swiss cheese. These weaknesses are inconstant – i.e., the holes open and close at random. When by chance all holes are aligned, the hazard reaches the aircraft and causes mid-air collision.

The systemic model (Figure 1) is founded in the perspective of Reason model, which takes into account not only the CNS system, but also the effects of defensive barrier and the human factors. Nowadays the collision avoidance systems are assembled in the almost commercial air transport aircraft, so the relationship between the collision risk and the collision avoidance systems must be taken into account. ATC intervention process plays a major part in preventing gross losses of separation. This is why the new model focuses on human factors, rather than just only the system errors.

Figure 1 Systemic collision risk model

Figure 1 is a picture of the systemic collision risk model. Five sheets are described in the model, which are CNS sheet, STCA sheet, ATC sheet, TCAS sheet and Pilot sheet, and the five sheets are independent. When the separation is lost, there is collision risk. On each sheet there are holes those present failures or errors which would lead to collision. Once the collision risk pass through the five sheets, the collision occurs.
Nowadays defensive barriers (STCA/TCAS) are fitted entirely, so that the influence of defensive barriers on the collision risk must be considered. If the STCA gives an alert, the air traffic controller must intervene to prevent the loss of separation and ensure the safety flight. If the prevention is appropriated, the collision risk is eliminated. Contrarily if the prevention is fail, there is a TCAS alert if the aircraft fitted with TCAS and the pilots perform TCAS RAs to prevent the collision from occurring. If the pilots execute successfully, the collision is avoided, otherwise the collision occurs.

As noted above, a collision would occur if the collision risk passes through the five sheets, in other words, the collision occurs. Treating the CNS system, defensive barrier and ATC/Pilot intervention independently case, we can approximate the collision risk by the product of the probability of separation loss in CNS environment, the probability of the defensive barrier is not given an alert timely and the probability ATC/Pilot cannot prevent the collision.

### 3.2 Collision Probability

The probability calculations in CNS, STCA, ATC, TCAS and Pilots can be carried out separately because the motions in the five sheets can be taken as independent. The event tree of collision process is illustrated in figure 2. Then the collision risk is:

\[
CR = N_{SLCNS} \times (P_{STCA} \times P_{UNATC} \times P_{TCAS} \times P_{UNPILOT} + P_{STCA} \times P_{UNATC} \times P_{UNTCAS} + P_{UNSTCA} \times P_{TCAS} \times P_{UNPILOT} + P_{UNSTCA} \times P_{UNTCAS})
\]

\[
CR = \text{collision risk} \\
N_{SLCNS} = \text{frequency of separation loss in CNS system} \\
P_{STCA} = \text{probability of STCA give alerts to the controllers} \\
P_{UNSTCA} = \text{probability of STCA do not give alerts to the controllers} \\
P_{ATC} = \text{probability of ATC intervene successfully} \\
P_{UNATC} = \text{probability of ATC intervene unsuccessfully} \\
P_{TCAS} = \text{probability of TCAS give alerts to pilots} \\
P_{UNTCAS} = \text{probability of TCAS do not give alerts to pilots} \\
P_{PILOTS} = \text{probability of pilots intervene successfully} \\
P_{UNPILOTS} = \text{probability of pilots intervene unsuccessfully}
\]

Figure 2 Collision event tree
The seven scenarios are illustrated here, and No.3, 4, 6, 7 scenarios make collision occur.

1. STCA appears to prevent many encounters from producing TCAS RAs.
   There is a variety of reasons for that there is an STCA alert but not a TCAS RA: the alert is a cautious ‘nuisance’ type; the aircraft flight paths quickly go out of conflict; the controller resolves a conflict before TCAS comes into operation; aircraft does not have TCAS fitted. Among the reasons the third is in the majority. The controller communicates with pilots after STCA give alerts and pilots react in time so that the conflict is avoided.

2. TCAS proves its worth.
The controller did not resolve the conflict before TCAS RAs. Pilots Manoeuvre aircraft according to the RAs and make aircraft return the safety state. Pilots are requested to obey the RAs in TCAS monitoring but not conform the instructions of the controllers.

3. Pilots do not execute the RAs successfully.
   Because TCAS does not provide the pilots with sufficient information about the Resolution Advisory, pilots may not execute RAs well and lead to a collision when executing the RAs. Sometimes the pilots execute the RAs to avoid a collision course but get into a collision course with the third aircraft unintentionally.

4. TCAS do not give alerts in time
   TCAS system is failure or not fitted so that no appropriate TAs and RAs are given to pilots. Then the pilots and controllers miss the best chance to avoid the collision. The probability of no TCAS alerts is approximate to the frequency of no TCAS alerting successfully which derives from the relative data collected.

5. TCAS plays a great role in the conflict.
   Although STCA does not alert, there are TCAS alerts to pilots about 15 seconds to 35 seconds before the CPA (closest point of approach). TCAS give TAs in time and appropriate RAs to pilots, and then Pilots execute TCAS RAs and lead aircraft to safety separation again.

6. Pilots do not resolve the collision.
Pilots response too low to execute RAs timely, and then the collision occurs. The probability of this scenario is decided mainly by the pilot respond time. If the pilot respond time is less than the required time from the RAs to the collision, the collision can be avoided; otherwise the collision occurs.

7. Collision occurs without defensive barrier function.
   It assumes that there are all SSR are fitted with STCA and there are all aircraft are fitted with TCAS. But the defensive barriers both do not function. This scenario is similar to the situation without defensive barrier and the collision risk is decided just by the errors of CNS system.

3.2.1 Separation loss in CNS
   The limitations of the preliminary models are generally in the accuracy of the tails of the probability functions that drive the final risk values. The collision risk is not only derived from navigation errors but the gross errors which are the majority lead to collision. The function $N_{\text{SLCNS}}$ can be derived from the statistic data, which is the number of the separation loss divided by the corresponding flight hours.
3.2.2 STCA
STCA is concerned with potential conflicts in projected flight paths. STCA is a computer system continually monitors secondary surveillance radar (SSR) data and alerts air traffic controllers if it detects a situation where two aircraft are in danger of approaching too close to one another. Thus the goal is to provide a warning around 90 to 120 seconds before the Closest Point of Approach (CPA) of the two aircraft.

3.2.3 ATC intervention
Then the probability of ATC intervention is calculated. The total intervention time comprises three individual response times - controller response time, communication delay time, and pilot/aircraft response time (FAA/EUROCONTROL, 1998). Air traffic control response time is the time between when a STCA alert occurs and the time required for an air traffic controller to observe the alert, decide on a corrective action, obtain a clear radio channel, and convey instructions to the flight crew. It depends on the number of aircraft being monitored by the controller, the skill level of the controller, the scan rate and display capability of the ATC equipment, the nature of the threat, random factors, etc.

Flight crew response time is the time required between the moment that instructions are conveyed by the controller and the moment that controls in the cockpit are moved appropriately. This time depends on the type of aircraft, the skill level of the pilots, the time required to disengage automatic controls (if necessary), the interference of other flight control activities, random factors, etc.

\[ T_{ATC} = T_{CR} + T_{CD} + T_{PR} \]  

\( T_{ATC} \) = ATC intervention time  
\( T_{CR} \) = controller response time  
\( T_{CD} \) = communication delay time  
\( T_{PR} \) = pilot response time

Controller response time \( (T_{CR}) \), communicational delay time \( (T_{CD}) \), and pilot/aircraft response time \( (T_{PR}) \) are independent so that the probability distribution of the total intervention time is computed by taking the convolution of the three individual distributions. \( P_{ATC} \) is the probability that ATC interventions cause the aircraft to modify its course in time to avoid a collision after the STCA alert occurs.

\[ P_{ATC} = \text{Prob}(T_{ATC} < T_{STCA}) \]  

\( T_{STCA} \) = time between STCA gives alert and the collision occurs

3.2.4 TCAS
TCAS is an aircraft system using SSR transponder signals to provide advice to the pilot on potential conflicting aircraft that are equipped with SSR transponders, either Mode C or Mode S. TCAS II provides vertical Resolution Advisories (RAs) in addition to Traffic Alerts (TAs). Threshold times of TCAS RAs depend on the flight level of the aircraft: details are set out in FAA (2000). If the closing intruder is assessed as a threat, TCAS II system proposes an RA to the pilot as a vertical avoidance manoeuvre. Corrective RAs require the pilot to change the flight path of the aircraft: preventive RAs require the pilot to keep the aircraft on that flight
path. It is supposed that all aircraft are fitted with TCAS. This probability can be collected by
the data statistic, see Peter (2005b).

3.2.5 Pilots manoeuvre
The TCAS RAs logic requires a climb/descent to resolve the conflict. It assumes that a pilot
reacts within 5 seconds of receiving the RA and then accelerates at 0.25 g to a vertical speed
of ±1500 feet/minute. Again, this is a simplification, but it does show that the total time from
receipt of the RAs to resolution is about 10 seconds. Furthermore the probability density
function of pilots manoeuvre time can be collected by the data statistic. 

$P_{PILOTS}$ is the probability that pilots manoeuvre will cause the aircraft to modify its course in
time to avoid a collision after the TCAS RAs alert occurs.

$$P_{PILOTS} = \text{Prob}(T_{PILOTS} < T_{TCAS})$$ (4)

$T_{PILOTS} =$ time pilots Manoeuvre 
$T_{TCAS} =$ time between TCAS gives alerts and the collision occurs

4. EXAMPLE OF SYSTEMIC MODEL CALCULATIONS

The research of collision risk composes of two steps - collision risk calculation and risk
evaluation, the farmer is calculated by the model and relative methods and the latter is to
analyze the safety level through compared to the TLS.

4.1 Collision Risk Calculation
There are five factors in the collision risk calculation - $N_{SLCNS}, P_{STCA}, P_{ATC}, P_{TCAS}$, and $P_{PILOTS}$. 
The famous REICH model and the EVENT model are used to calculate the $N_{SLCNS}$, which is
not main subject and not be presented in detail. $P_{STCA}$ and $P_{TCAS}$ are approximated by data
collected and addressed by Peter (2005b). $P_{ATC}$ and $P_{PILOTS}$ are obtained by the above
methods.

The reader is reminded that this is only a hypothetical example, to illustrate use of the model. 
The ATC intervention time is presented by Cassella and the pilot response time distribution is a
Rayleigh distribution (Cassell, et al 1996). Here it is assumed air traffic controller
intervention time obey the normal probability density function. The expression is:

$$f(x) = \frac{1}{\sqrt{2\pi} \sigma} e^{-\frac{(x-u)^2}{2\sigma^2}} \quad -\infty < x < +\infty$$ (5)

$T_{STCA}$ is supposed to be between 90 and 120 seconds and $T_{TCAS}$ is between 15 and 35 seconds,
and then $P_{ATC}$ and $P_{PILOTS}$ can be calculated. The collision risk can be calculated by the above
parameters, then which is compared with TLS.

ATC intervention time can be approximated well by the normal distribution. Controller
response time fit to N(10,6$^2$), communication delay time is too small to be consolidated with
pilot response time , and pilots response time fit to N(3,6$^2$), $P_{ATC}$ is calculated according to
(3), the $T_{STCA}$ is assumed to be 120 seconds, so

$$P_{ATC} = \int_{90}^{120} f(t)dt = 0.9522$$

$$P_{ATC} = \int_{0}^{120} f(t)dt = 0.9522$$
Therefore, $P_{ATC}$ is about 0.9522.

$P_{PILOTS}$ is calculated according to (4), so

$$P_{PILOTS} = \int_{0}^{15} f(t)dt = 0.6687$$

$$P_{PILOTS} = \int_{0}^{35} f(t)dt = 0.6915$$

Therefore, $P_{PILOTS}$ is about between 0.6687 and 0.6915.

Collision risk is calculated according to (1). $P_{PILOTS}$ and $P_{ATC}$ are analyzed on the above part, and $P_{STCA}$ and $P_{TCAS}$ are approximate to be 0.85 and 0.97 by reference Brooker (2005b) because there are no domestic relative data. Therefore the collision risk reduced by defensive barrier is between 0.0628 and 0.0669. We can know the safety improvement is provided by the defensive barrier and the human intervention - collision risk is reduced to lie in the range of 0.0628 ~ 0.0669 compared to collision risk for just including the system error.

$N_{SLCNS}$ is calculated to be $0.43 \times 10^{-8}$, then the safety of separation provision is equal to $0.43 \times 10^{-8}$. If the avoiding system is included by the systemic model, the whole collision risk should be between $0.27 \times 10^{-9}$ and $0.29 \times 10^{-9}$.

### 4.2 Risk Evaluation

There is an Achieved Level of Safety (ALS) - the risk level being achieved in the system under examination. If the ALS is lower than TLS, the safety of the given separation minima meet safety level required, or else not.

Here the ALS is $0.43 \times 10^{-8}$ by separation provision, and the whole risk of ATM system is between $0.27 \times 10^{-9}$ and $0.29 \times 10^{-9}$. TLS is $1.5 \times 10^{-8}$ established by ICAO-NATSPG. So we can just the separation minima is able to meet TLS and the separation minima is safe. Furthermore the whole risk including avoiding system is lower than collision risk of separation provision, and then we can judge the safety level is very prominent.

### 5. CONCLUSIONS

Systemic collision risk model provides a framework for evaluating the relationship between aircraft separation standards, avoiding system and safety. It makes use of systems perspective and event trees. These appear to be good tools for collision risk estimation of present ATM system. In this way, this model remains useful as the aviation safety community imports new separation minimum and target level of safety.

Systemic model organizes sufficient indicators of the ATM system without requiring elaborate modeling of the internal processes of complex technologies. Future uses of systemic model will require the careful quantification of empirical data and scientific refinement.

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