Collision risk-capacity tradeoff analysis of an en-route corridor model

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Abstract

Flow corridor is a new class of trajectory-based airspace which derives from the Next Generation Air Transportation System Concept of Operations. Reducing the airspace complexity and increasing the capacity are the main purpose of the en-route corridor. This paper analyzes the collision risk-capacity tradeoff using combined discrete-continuous simulation method. A basic two-dimensional en-route flow corridor with performance rules are designed as the operational environment. A second order system is established by combing Point Mass Model and Proportional Derivative controller together to simulate the self-separation operations of the aircrafts in the corridor and the operation performance parameters from the User Manual for the Base of Aircraft Data are used in this research in order to improve the reliability. Simulation results indicate that the aircrafts can self-separate from each other efficiently by adjusting their velocities, and rational setting the value of some variables can improve the rate and stability of the corridor with low risks of loss of separation.

Keywords: air traffic control; corridor; self-separation; simulation, risk-capacity tradeoff

1. Introduction

A corridor is defined as a long “tube” of airspace, in which groups of flights fly along the same path in one direction and accept responsibility for separation from each other. Multiple (parallel) lanes, self-separation and dynamic activation rules are three of the prominent attributes of corridors. The well-designed corridor may reduce the airspace complexity, increase the airspace capacity and decrease the workload of air traffic controllers [1].

Previous research has looked at the initial design concept, optimal placement of corridors, and the topology of the network. John et al. [2] initially proposed and evaluated the conception of Dynamic Airspace Super Sectors (DASS), which is thought of as a network of one-directional, high density highways in the sky. Safety, performance and cost are three primary criteria used to measure design alternatives. Yousefi et al. [3] conducted a statistical analysis of city-pair traffic and the placement of a network of High-Volume Tube-Shape Sectors (HTS). Velocity vectors for small volumes of airspace were calculated and vector fields of the fluid velocity were created. After the analysis of vector fields’ topology, the geometry and location of potential corridors are determined. Sridhar et al. [4] grouped airports into regions, and modeled a series of tubes connecting major regions. A network connecting the top 18 regions was designed, and the top 250 busy airports with the appropriate region were associated by clustering techniques. Hoffman et al. [5] constructed a tube network and made an estimate of capacity-enhancing effects of tubes for airspace. A comprehensive list of design issues and some potential alternatives are created to enhance the tube design and tradeoffs. Xue et al. [6] [7] studied the complexity of traffic in a selected corridor using simulation. A space-time map was developed to examine and visualize the utilization of corridor, suggest the number of lanes, and show the possibility of deploying corridors dynamically. Yousefi et al. [8] [9] developed an initial operational procedure to implement flow corridor operations, and proposed a flow-based modeling approach to cluster 4DTs into potential corridors. A sliding time window is implemented to dynamically create and optimize corridor’s coordinates based on the changes in preferred trajectories. The objective of this research is to develop models and methods for constructing collision risk-capacity tradeoff curves in the corridor.

2. Model Description

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2.1. Structure and assumptions of corridor

A two-dimensional en-route flow corridor is presented to be a tube of parallel high altitude Q-routes structure which is assumed to be 80 nm long and 16 nm wide with the route centerlines 8 nm apart where located at the FL350 as shown in Figure 1.

Aircrafts usually travel in the same direction from left to right by self-separation in the corridor. The aircraft may adjust its velocity and separation with the leading one, switch lanes for overtaking, or in extreme cases exit the corridor along paths that are divergence angle by 30 degrees before the exit. Detailed movements of each aircraft are assumed as follows:

1) All aircrafts initially enter the corridor with random types, velocities and separations with their leading ones;

2) Each aircraft is under conditions of level fight that fly along the middle line of each corridor and self separates with aircraft in front according to a self-separation model by adjusting its acceleration and velocity;

3) Any time the velocity of an aircraft is larger than the average velocity of the leading one by some velocity threshold, it attempts to switch the lane;

4) Any time an aircraft gets within minimum separation of aircraft in front (loss of separation), it switches lane or breaks out;

5) The first aircraft in each lane and the aircraft whose separation with its leading aircraft is larger than some threshold value, it flies towards the target velocity.

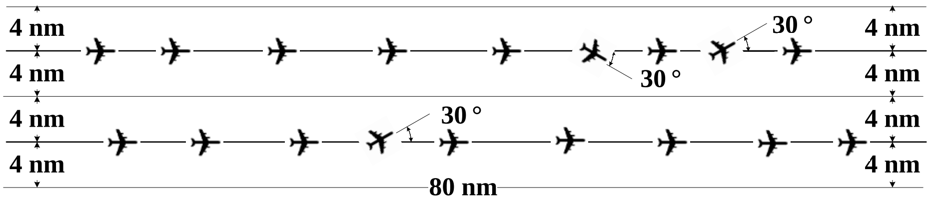

Figure 1 Structure of Corridor

2.2. Aircraft Performance Model

2.2.1. Aircraft model

In this paper, an aircraft is modeled by using Point Mass Model (PMM). This model is adapted from Glover and Lygeros [10]. Some key elements of the model are summarized here. The states of the model are the horizontal position (x and y) and altitude of the aircraft (z), the true airspeed (v), the flight path angel (γ) and the heading (ψ). Table1 illustrates the description and primary dimension of the state variables.

Table 1 State variables

Variables	Description	Primary dimension
x	Along-track position	Along-track
v	True airspeed	Along-track
y	Across-track position	Across-track
ψ	Heading	Across-track
z	Altitude	Vertical
γ	Flight-path angle	Vertical

The control inputs to the model are the engine thrust (T), the angle of attack (ϕ) and the bank angle (α). Table 2 outlines the description and primary dimension of the control variables.

Table 2 Control variables

Variables	Description	Primary dimension
T	Thrust	Along-track
ϕ	Bank angle	Across-track
α	Angle of attack	Vertical

Eq. (1) is the Newtonian dynamics equations of motion used in this paper:

$$\begin{cases} \dot{x} = v\cos\psi\cos\gamma \\ \dot{v} = \dfrac{1}{m}(T\cos\alpha - D - mg\sin\gamma) \\ \dot{\psi} = \dfrac{1}{mv}(L + T\sin\alpha)\sin\phi \\ \dot{\gamma} = \dfrac{1}{mv}[(L + T\sin\alpha)\cos\phi - mg\cos\gamma] \end{cases} \quad (1)$$

m is the mass of the aircraft and g is the gravitational acceleration. L and D denote respectively the lift and drag forces, which are functions of the state and angle of attack as outlined in Eq. (2).

$$\begin{cases} L = \dfrac{C_L S\rho}{2}(1 + c\alpha)v^2 \\ D = \dfrac{C_D S\rho}{2}(1 + b_1\alpha + b_2\alpha^2)v^2 \end{cases} \quad (2)$$

S is the surface area of the wings, ρ is the air density and C_D, C_L, c, b_1 *and* b_2 are aerodynamic lift and drag coefficients whose values generally depend on the phase of the fight. During the cruising phase, all commercial airliners are usually assumed operating near trimmed flight condition ($\gamma = \dot{\gamma} = 0$ and $\alpha \approx 0$), then the lift is represented by the Eq. (3).

$$\begin{aligned} &\dot{\gamma} = \frac{1}{mv}[(L + T\sin\alpha)\cos\phi - mg\cos\gamma] = 0 \\ &\Rightarrow L = mg\frac{\cos\gamma}{\cos\phi} - T\sin\alpha = \frac{mg}{\cos\phi} \end{aligned} \quad (3)$$

Assume that the coefficient of lift C_L is set so that lift exactly balances the weight of the aircraft. Combining the previous relationships, C_L can be calculated by Eq. (4):

$$\begin{aligned} &L = \frac{mg}{\cos\phi} = \frac{C_L S\rho}{2}(1 + c\alpha)v^2 \\ &\Rightarrow C_L = \frac{2mg}{S\rho v^2\cos\phi} \end{aligned} \quad (4)$$

The drag coefficient is computed as a function of phase of flight as Eq. (5), and C_{D0} and C_{D2} are two constants.

$$C_D = \begin{cases} C_{D0,AP} + C_{D2,AP}C_L^2 & \text{Approach} \\ C_{D0,LDG} + C_{D0,\Delta LDG} + D_{D2,AP}C_L^2 & \text{Landing} \\ C_{D0,CR} + C_{D2,CR}C_L^2 & \text{Other} \end{cases} \quad (5)$$

This further implies the lift and drag functions as Eq. (6):

$$\begin{cases} L = \dfrac{C_L S\rho}{2}(1 + c\alpha)v^2 = \dfrac{2mg}{S\rho v^2\cos\phi}\dfrac{S\rho}{2}(1 + c\alpha)v^2 = \dfrac{mg}{\cos\phi} \\ D = \dfrac{C_D S\rho}{2}(1 + b_1 a + b_2\alpha^2)v^2 = \dfrac{C_D S\rho}{2}v^2 \end{cases} \quad (6)$$

2.2.2. Discrete states

Discrete states are used for describing the self-separation performance of the aircrafts in the corridor. Five different discrete states are defined in the corridor: Velocity Adjusting State (VA), Target Velocity Flying State (TVF), Lane Changing State (LCS), Breakout State (BS) and Locking State (LS). Different than other four types of states, LS is a combined state which cannot exist without TVF and VA. Figure 2 illustrates the state transition diagram of the aircrafts, and TVF, VA, LCS, BS are all represented by the solid circle while LS is represented by a dashed circle outside the TVF and VA.

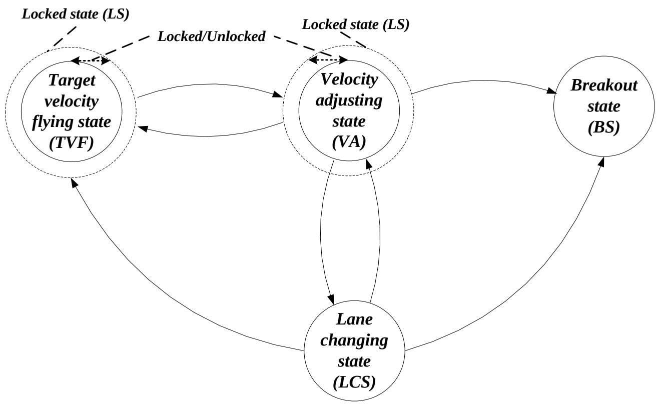

Figure 2 State Transition Diagram

a) Velocity Adjusting State (VA)

VA is a state which an aircraft attempts to adjust its velocity, acceleration and separation with the leading aircraft according to the Proportional Derivative (PD) controller below. An aircraft is in this state if the separation with the leading one is less than the *distance threshold* (that is, the leading aircraft is not too far in front) but larger than the minimum separation. This state can transfer from/to the target velocity flying state and the corridor changing state, locked or unlocked, or transfer to the breakout state (be aware that this is a unidirectional transition). For the point mass model, combine the equations of time derivatives of along-track positions and velocities.

$$\begin{cases} \dot{x} = v\cos\psi\cos\gamma \\ \dot{v} = \dfrac{1}{m}(T\cos\alpha - D - mg\sin\gamma) \end{cases}$$

Because the aircrafts are assumed straight (ψ = 0 or small) and level flight ($\gamma = \dot{\gamma} = 0$, α = 0) in the corridor, substitute the drag into the equations.

$$\begin{cases} \dot{x} \approx v \\ \dot{v} = \dfrac{1}{m}T - \dfrac{C_D S\rho}{2m}v^2 \end{cases}$$

This is equivalent to a second-order equation:

$$\ddot{x} = \frac{T}{m} - \frac{C_D S\rho}{2m}v^2 = \frac{T}{m} - \frac{C_D S\rho}{2m}\dot{x}^2$$

Using a proportional plus derivative control:

$$T = k_1(x_{ref} - x) + k_2(v_{ref} - v) + T_{ref}$$

T_{ref} is the thrust of the aircraft to balance the drag, x_{ref} is the target position along track, v_{ref} is the target velocity, k_1 and k_2 are tuning parameters. This leads to the second order system [11] as Eq. (7):

$$\ddot{x} = \frac{k_1(x_{ref} - x) + k_2(v_{ref} - v)}{m} + \frac{C_D S\rho}{2m}v^2 - \frac{C_D S\rho}{2m}v^2$$

$$\Rightarrow m\ddot{x} + k_2\dot{x} + k_1 x = k_1 x_{ref} + k_2 v_{ref} \tag{7}$$

Un-damped natural frequency:

$$\omega_n = \sqrt{\frac{k_1}{m}}$$

Damping ratio:

$$\zeta = \frac{k_2}{2\sqrt{mk_1}}$$

To achieve a time constant of τ:

$$\tau = \frac{1}{\zeta\omega_n} = \frac{2\sqrt{mk_1}}{k_2}\frac{\sqrt{m}}{\sqrt{k_1}} = \frac{2m}{k_2}$$
$$\Rightarrow k_2 = \frac{2m}{\tau}$$

To achieve a damping ratio of ζ:

$$\sqrt{mk_1} = \frac{k_2}{2\zeta}$$
$$\Rightarrow k_1 = \frac{k_2^2}{4m\zeta^2}$$

Using τ and ζ as input, the acceleration of aircraft can be calculated as Eq. (8):

$$\ddot{x} = \frac{k_1(x_{ref} - x) + k_2(v_{ref} - v)}{m} \tag{8}$$

b) Target Velocity Flying State (TVF)

TAF is a state which an aircraft attempts to fly at its preferred target velocity without regard to the position or velocity of the aircraft in front of it. An aircraft is in this state if either (a) it is the first aircraft in the corridor, or (b) its leading aircraft is sufficiently far ahead so that it does not currently need to adjust its velocity to maintain separation. This state can transfer from/to the velocity adjusting state, locked or unlocked, or transfer from the lane changing state (unidirectional transition).

Different from the VA state, using a derivative control:

$$T = k_2(v_{ref} - v) + T_{ref}$$

This leads to the following first order system as Eq. (9):

$$\ddot{x} = \frac{k_2(v_{ref} - v)}{m} + \frac{C_D S\rho}{2m}v^2 - \frac{C_D S\rho}{2m}v^2$$
$$m\ddot{x} + k_2\dot{x} = k_2 v_{ref} \Rightarrow m\dot{v} + k_2 v = k_2 v_{ref} \tag{9}$$

The acceleration of aircraft can be calculated as Eq. (10):

$$\dot{v} = \frac{k_2(v_{ref} - v)}{m} \tag{10}$$

c) Lane Changing State (LCS)

Before introducing the LCS state, the *lane switch requirement* should be defined first. *Lane switch requirement* is a criterion to decide whether the aircraft can switch its lane for overtaking or avoiding conflicts. Some research has been done on constructing resolution trajectories and relative rules in the single-lane [12] [13], the detailed contents of lane changing criterion in the corridor will be developed here: (a) the potential lane-switch flight should be in either the VA state or TVF state but not locked; (b) make a projection of the target flight onto the other lane (assuming a 30 degree path) to find its new leading and trailing aircraft in the other lane. Both the distances between the new leading and the new trailing aircraft must be larger than the lane-switch separation; (c) the trailing aircraft in the new corridor should also be in VA state or TVF state.

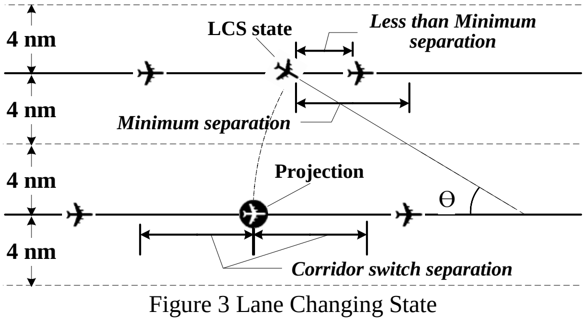

Figure 3 Lane Changing State

LCS is a state which the target aircraft flies a 30-degree (θ) path to the other lane with constant velocity as Figure 3. An aircraft switches lanes under the following two situations: (a) the separation with its leading aircraft is less than the minimum separation and also the *lane switch requirement* is satisfied; (b) the velocity is larger than the average velocity of its leading aircraft by *velocity threshold*, the separation with its leading aircraft is less than the *distance threshold* and also the *lane switch requirement* is satisfied. This state can transfer from/to velocity adjusting state, and transfer to target velocity flying state or breakout state (unidirectional transition).

When an aircraft starts to change its lane, the fly-pass method is adopted to simulate the turning procedure. The aircraft starts turning before it reaches the point and “cuts the corner”, this is the preferred method for most modern aircraft. To determine how long it takes an aircraft to switch the lane, the radius (r) and distance (d) should be calculated first, as in Figure 4.

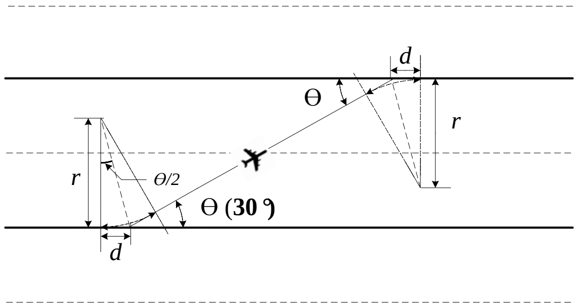

Figure 4 Geometry of Fly-pass Method

Assume the aircraft remains level throughout the LCS state, and turns are executed at a fixed bank angle $\pm\phi_{nom}$. So the component of the lift in the vertical direction are equated to the weight of the aircraft, and the turn rate can be calculated as Eq. (11):

$$\begin{aligned}\dot{\psi} &= \frac{1}{mv}(L + T\sin\alpha)\sin\phi \\ &= \frac{1}{mv}\left(\frac{mg}{\cos\phi_{nom}}\right)\sin\phi_{nom} = \frac{g\tan(\phi_{nom})}{v}\end{aligned} \tag{11}$$

Assuming that the aircraft starts the turn at time 0 with heading ψ_0, at time t the heading angle $\psi(t)$ and distance travelled by the aircraft are as Eq. (12):

$$\begin{cases}\psi(t) = t\dfrac{g\tan(\phi_{nom})}{v} + \psi_0 \\ r(\psi(t) - \psi_0) = vt\end{cases} \tag{12}$$

Dividing the two equations leads to the radius as Eq.(13):

$$r = \frac{v^2(t)}{g\tan(\phi_{nom})} \tag{13}$$

The distance d can be obtained by Eq. (14):

$$d = r\cot\left(\frac{\theta}{2}\right) = \frac{v^2}{g\tan(\phi_{nom})}\cot\theta \tag{14}$$

d) Breakout State (BS)

An aircraft breaks out of the corridor if the separation with its leading aircraft is less than the *minimum separation*, and also the *lane switch requirement* cannot be satisfied. BS is a terminal state which the target aircraft follows a route to breakout to the side of a corridor as Figure 5. The breakout aircraft keeps its velocity and adjusts its 2D position until out of the corridor region. The trailing aircraft in the original corridor will be locked for one time step to avoid two consecutive aircraft changing to the BS state or the LCS state at the same time. This state can transfer from the VA state or LCS state (unidirectional transition).

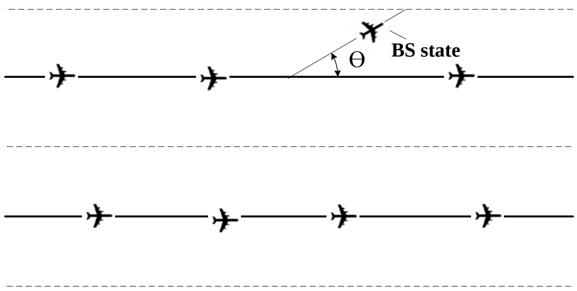

Figure 5 Breakout State

e) Locking State (LS)

LS state is a combined state used for safety and efficiency consideration. This state always works with VA and TVF states to prevent simultaneous lane changes or breakouts. For example, when an aircraft is in the LCS state, the trailing aircraft in the original corridor will be in LS (be locked) for one time step in order to avoid two consecutive aircrafts changing to the LCS or BS state at the same time. Further, the leading and trailing aircraft in the new corridor is locked until the corridor switch procedure is finished for safety. This is to prevent two aircrafts from “crossing” in the middle while changing lanes. Figure 6 illustrates a scenario of locking states.

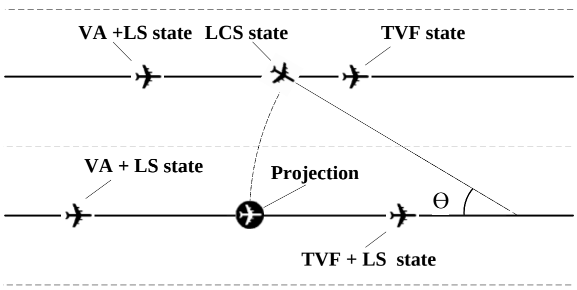

Figure 6 Locking States

2.2.3. Algorithm

In order to determine the throughput of the corridor, an aircraft performance model is established to capture the stochastic range of the problem. Table 3 defines some key variables in the main algorithm. Figure 7 shows the pseudo code for the main algorithm. The core outline of the algorithm is briefly described. Specific details will be explained later.

Table 3 Parameters for algorithm

Variables	Description
Velocity Difference	The velocity difference between an aircraft and its adjacent leading one.
Velocity Threshold	A threshold value of velocity used for triggering the transition of discrete state.
Current separation	The longitudinal separation with its adjacent leading aircraft at current time.
Minimum separation	The minimum separation requirement between adjacent aircraft for saftey
Distance threshold	The threshold value of separation used for trigging transition of dicrete state.
Lane switch requirement	Some clear requirement if an aircraft wants switch its lane to another
Discrete states	Describe the movement of aircraft in the corridor, including target velocity flying, velocity adjusting, lane switch, breakout and locking state.

```
INPUT           Number of aircrafts, simulation replications, corridor structure,
                time step, etc
INITIALIZE      Aircraft types and initial attributes, minimum separation, target
                separation, etc
LOOP            WHILE not all aircrafts passed the corridor DO
   SIMULATE     Performance the movement simulation for all aircrafts in the
                corridor.
   UPDATE       Aircrafts discrete states as the following rules:
                If (velocity difference > velocity threshold)
                    If (current separation > separation threshold)
                        Target velocity flying state
                    Else if (current separation > minimum separation)
                        If (lane switch requirement is satisfied)
                            Lane switch state
                        Else
                            Velocity adjusting state
                    Else
                        If (lane switch requirement is satisfied)
                            Lane switch state
                        Else
                            Breakout state
                Else
                    If (current separation > separation threshold)
                        Target velocity flying state
                    Else if (current separation > minimum separation)
                        Velocity adjusting state
                    Else
                        If (lane switch requirement is satisfied)
                            Lane switch state
                    Else
                        Breakout state
   UPDATE       The queue length of aircrafts in the corridor, and the simulation
                time.
END OF LOOP
```

Figure 7 Pseudo code for the main algorithm

In the loop, the algorithm checks the velocities difference and separations between the aircrafts and their leading ones. If the velocity difference is equal to or greater than the velocity threshold, and also the current separation is less than distance threshold, then the lane switch requirement will be checked. This represents a scenario where the trailing aircraft is traveling faster than the leading aircraft and the leading aircraft is not too far in front of the trailing aircraft, so the trailing aircraft wants to surpass the leading one. If the lane switch requirement is satisfied (the other lane is sufficiently clear etc.), the trailing aircraft transfers to the lane switch state. If the trailing aircraft cannot switch lanes due to congestion, it transfers to the target velocity flying state, velocity adjusting state or breakout state on the basis of different separations.

If the velocity difference is smaller than the velocity threshold, and also the current separation is larger than the distance threshold, the trailing aircraft changes to the target velocity flying state. Or else, the trailing aircraft will transfer to velocity adjusting state when the current separation is between distance threshold and minimum separation. This represents a case where the trailing aircraft is traveling at a velocity that is either slower or only slightly faster than the leading aircraft. If the leading aircraft is sufficiently far in front, the trailing aircraft simply will be in target velocity flying state, but otherwise transfers to velocity adjusting state to maintain separation with leading one.

When the current separation is less than the minimum separation, the aircraft will be in lane switch state if the lane switch requirement is satisfied, or else transfers to breakout state.

3. Methodology for simulation

The en-route corridor model established above is neither completely discrete nor completely continuous. In order to analyze the risk-capacity tradeoff of the en-route corridor, a combined discrete-continuous simulation method is used to estimate the performance of the aircrafts in the corridor [14] [15]. The simulation was implemented in C++ language and displayed with Google Earth[16]. The simplified flowchart of the simulation is illustrated in Figure 8.

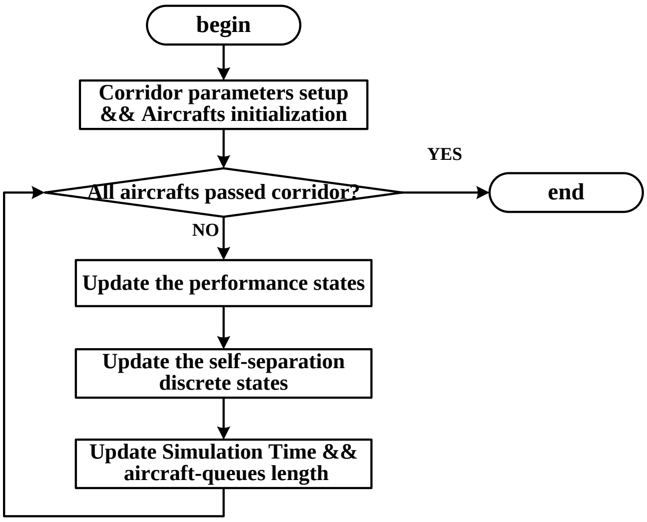

Figure 8 Flowchart of Simulation

3.1. Data process

Both practical data and Pseudo-random number are used in the simulation. The aircrafts operation performance parameters used in this research comes from the User Manual for the Base of Aircraft Data (BADA) [17] published by EUROCONTROL. Eight typical aircraft types which are A320, A332, A345, A380, B737, B742, B743 and B764, are selected for simulations. The initial separations with the leading aircrafts and the initial velocities of the target aircraft are generated randomly.

3.2. Key variables

The computer simulation program includes 4 types of 68 different variables in total. Some of them have significant impact on the performance of the corridor. Table and Table define the key input and output parameters associated with the algorithm [18].

3.2.1. Key input parameters

The key input parameters are the key static parameters that the user selects to run the simulation (Table 4). Note that additional input parameters such as the target separation and buffer separation are defined in Table 3 and not shown here.

Table 4 Key Input Parameters

Parameters	Description
Aircraft number	The number of aircrafts generated for each lane to test the performance of the corridor.
Replication times	The number of simulation iterations to analyze the risk-capacity tradeoff.
Time Step	The simulation time step for updating the state of the aircrafts in the corridor.
Initial Separation	The initial separation with the leading one when an aircraft entering the corridor.
Target Separation	The separation aim of each aircraft attempts to keep with the leading one.
Switch Threshold	The minimum gap between the projection and the new leading /trailing aircrafts for safety lane switching

3.2.2. Output Metrics

These variables are the measures of system performance [19] [20]. Currently, capacity, conflict rate, breakout rate and lane switch rate are selected as the Outputs Metrics (Table 5). The collision risk is measured by the conflict rate, breakout rate and lane switch rate.

Table 5 Output Metrics

Parameters	Description
Capacity	The inverse of the average of the corridor passing time interval.
Breakout rate	The fraction of aircraft that breakout from the corridor
Switch rate	The fraction of aircraft that switch from one corridor to another
Conflict rate	The fraction of aircraft that either breakout or switch corridors.

4. Simulation results

4.1. Case study

4.1.1. An aircraft flying by itself

Figure 9 illustrates a sample scenario in which an aircraft flies by itself in the corridor. The *x*-axis corresponds to the time horizon when the aircraft is in the corridor. The *y*-axis corresponds to the velocities and accelerations during this time. This aircraft is a B737. It enters the corridor with a velocity of 456.25 knots and an acceleration of 0 knots/s. It maintains these values until it exits the corridor at simulation time 600 seconds.

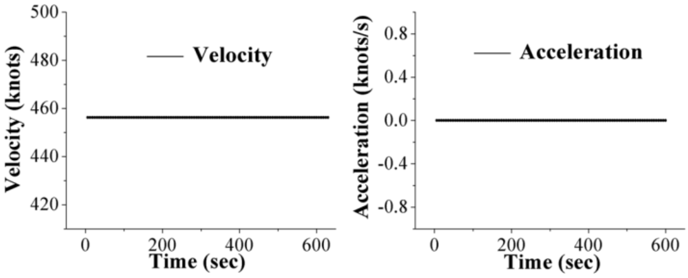

Figure 9 B737 Flying by Itself

4.1.2. An aircraft following another

Figure 10 illustrates a typical scenario which an aircraft following another in the corridor. This aircraft is an A345. It enters the corridor at simulation time 2814 seconds with a velocity of 476.85 knots. Since the initial separation with the leading aircraft is large, it tries to reduce the gap by speeding up to 495.46 knots. Then it attempts to keep the target separation with the leading aircraft by slowing down. Once it becomes the first aircraft in the lane, it starts to fly towards its target velocity until exiting the corridor at simulation time 3402 seconds. The jump of the acceleration at simulation time 2800 is caused by the starts of self-separation with leading aircraft in the corridor, and the jump at simulation time 3312 seconds is caused by the leading aircraft exiting from the corridor which makes the state of this aircraft changing from VA to TVF, As the aircraft reach its initial target velocity, the acceleration jumps back to 0 at simulation time 3366 seconds finally.

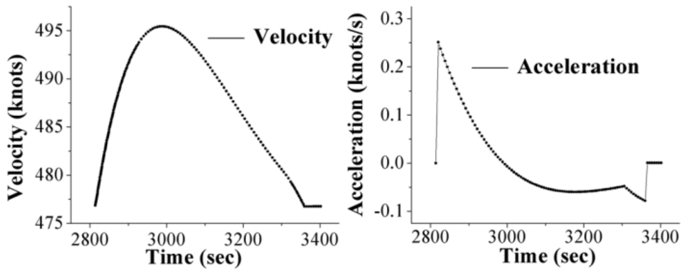

Figure 10 A345 Following another Aircraft

4.1.3. An aircraft passing another

Figure 11 illustrates a complex scenario which an aircraft passing another by changing lane. This aircraft is a B742. It enters the corridor at simulation time 936 second with a velocity of 513.4 knots. Because the initial velocity is so large, it tries to slow down to keep the minimum separation with the leading aircraft. At the simulation time 984 second, it starts to switch lanes to pass the leading aircraft with the constant velocity. After the lane changing, this aircraft adjusted its velocity and separation with the new leading aircraft until exit of the corridor at simulation time 1518 second. The first jump of the acceleration is caused by changing the state from VA to LCS and the second jump is caused by changing back to VA. The reason of the third jump is caused by changing state from VA to TVF as above.

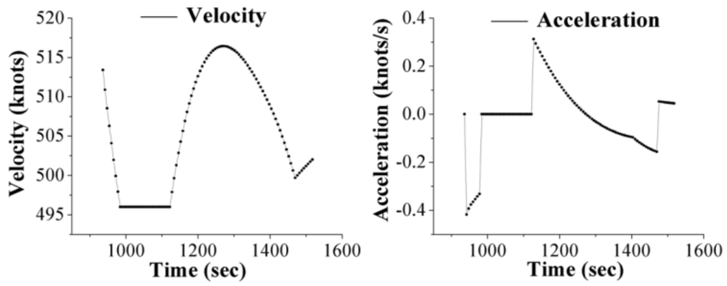

Figure 11 B742 Passing another Aircraft

4.2. Sensitivity analysis

4.2.1. Initial separation

The initial separations for the aircrafts equal the sum of minimum separation plus initial buffers which are independent and identically distributed (IID) exponential random variables. Figure 12 illustrates the 95% confidence interval of the four output metrics by increasing the mean of initial buffer from 1 nm to 10 nm (this also indicates the mean of initial separation increasing from 6 nm to 15 nm) with 1 nm per step. The capacity is monotone decreasing from 150.4 to 62.3 aircrafts per hour while the switch rate has a very slight increasing to 0.31%. The conflict and breakout rates drop rapidly by almost 71% when the initial separation increasing to 7 nm, after that they reduce slowly and decrease to 0.58% and 0.27% respectively. Please note that the units of conflict rate, switch rate and breakout rate are in fractional representation in all figures.

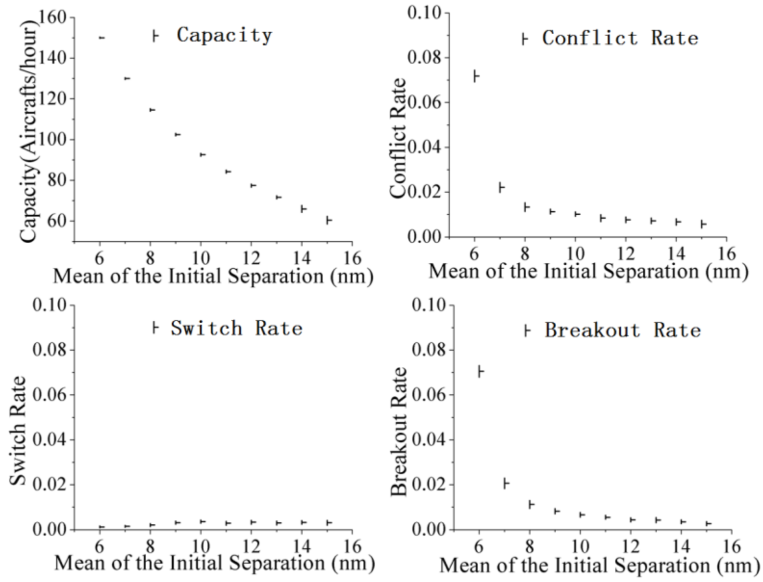

Figure 12 Sensitivity Analysis of Initial Separation

4.2.2. Target separation

The target separation for each aircraft equals the sum of the minimum separation plus a target buffer which is a constant. Figure 13 illustrates the 95% confidence interval of the four output metrics by increasing the target buffer from 0.5 nm to 5 nm (this also indicates the target separation increasing from 5.5 nm to 10 nm) with 0.5 nm per step.

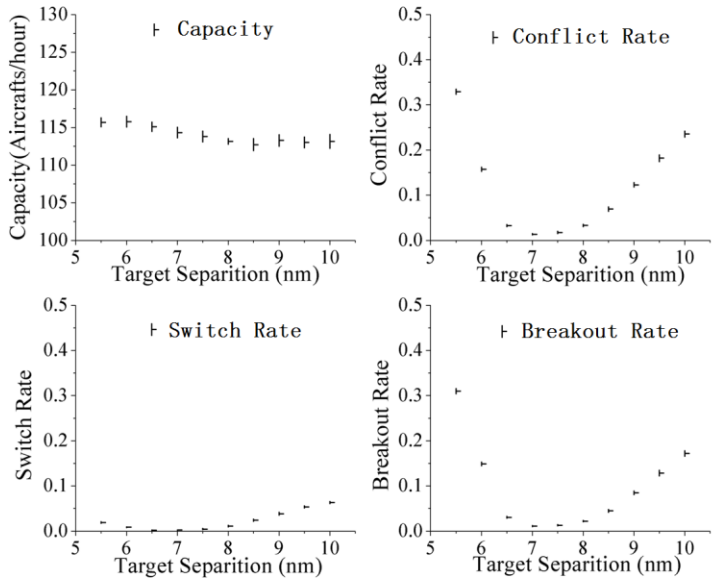

Figure 13 Sensitivity Analysis of Target Separation

The capacity fluctuates slightly around 114.5 aircrafts per hour while the other three metrics fluctuate dramatically during the changing. Both the conflict and breakout rates decline sharply by almost 90% when the target separation increases to 7 nm. After that they begin rise gradually and reach 23.5% and 17.2% respectively. The switch rate has similar trend and increases to 6.3% in the end. The changes of difference between initial separation and target separation are the main reason of these trends. The corridor cannot accommodate so many aircrafts within corridor as the target separation increases, so the conflicts grow up again after reaching the bottom.

4.2.3. Distance threshold

The distance threshold for each aircraft is set as a constant. Figure 14 illustrates the 95% confidence interval of the four output metrics by increasing the distance threshold from 7 nm to 16 nm with 1 nm per step. The capacity remains stable around 114 aircrafts per hour. Conflict rate, switch rate and break out rate fall moderately all the time and reach 1.45%, 0.325% and 1.13% respectively.

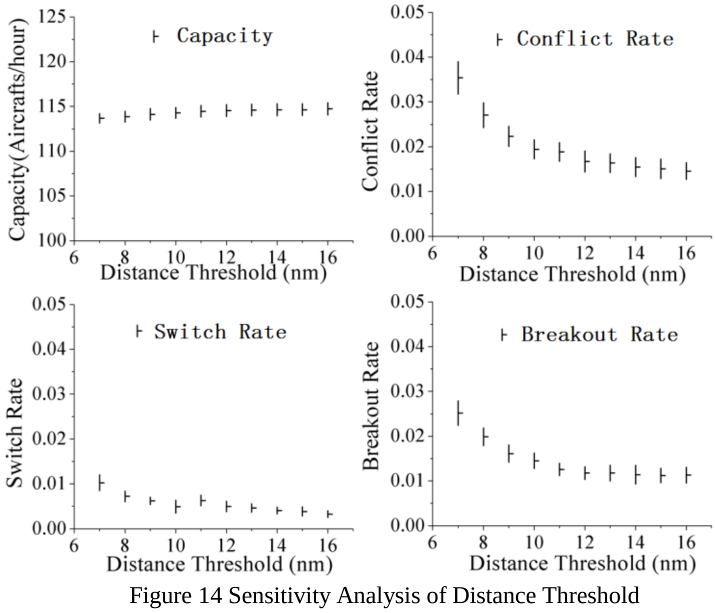

Figure 14 Sensitivity Analysis of Distance Threshold

4.2.4. Switch threshold

The switch threshold for each aircraft is also set as a constant. Figure 15 illustrates the 95% confidence interval of the four output metrics by increasing the switch threshold from 5.5 nm to 10 nm with 0.5 nm per step. The capacity remains stable at 114.5 aircrafts per hour. The conflict rate and switch rate have similar decline trends and reduce to 1.42% and 0.125% respectively while the breakout rate reaches a plateau at 1.3%.

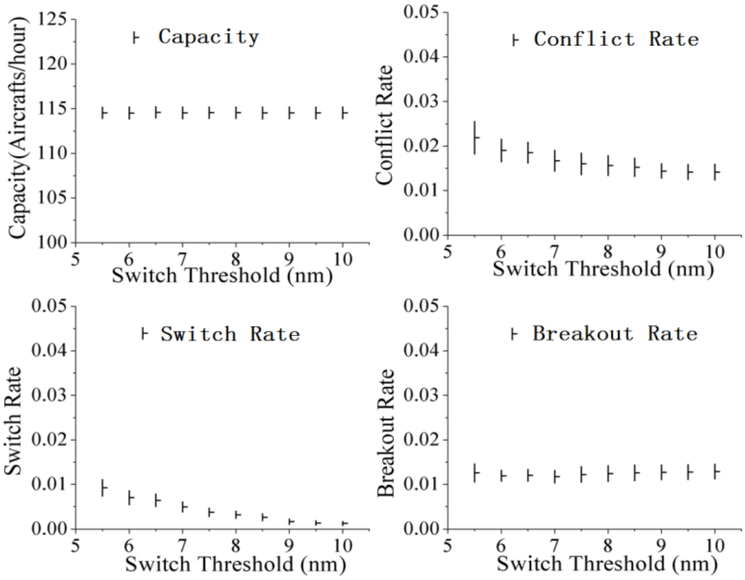

Figure 15 Sensitivity Analysis of Switch Threshold

5. Conclusions

The corridor concept is a revolutionary changing of the current ATM system which can reduce complexity, restructure the airspace to provide more system capacity. This paper conducted a reliability combined discrete-continuous simulation of the aircrafts flying in a self-separation corridor with two parallel routes, filled up the research gap of new procedures initialization and safety analysis. According to the point mass model with proportional derivative controller, each aircraft is simulated to adjust its acceleration, velocity and discrete state etc. to fly through the corridor with safety, order and high efficiency. Key insights from the model are:

1) The initial separation between the aircrafts has a significant effect on the capacity, conflict rate and breakout rate of the corridor. As the mean of the initial separation increases, both the capacity and collision decreases non-linearly. A good design of aircraft inter-arrival separation can lead to a high capacity with low risk of conflict.

2) The target minimum separation between pairs of aircraft is a very important variable. It’s one of the key parameters in realizing aircraft self-separation in the corridor. Either too small or too large may lead to a high risk of conflict with no obvious improvement in capacity.

3) The distance threshold is an effective variable in reducing conflict rate by limiting the chance of the aircrafts flying at their preferred target velocities. A good distance threshold value may improve the rate and stability of the traffic flow in corridor with low risk of loss of separation.

4) The switch threshold is a useful way in adjusting the switch rate of the corridor. However, no obviously effect has been found in improving the capacity and reducing the Breakout rate.

5) According to the experiments, when the mean of the initial separation is 8 nm, the target separation is 7 nm, the distance threshold is 12 nm, the switch distance is 7 nm, the capacity and collision risk will get a best tradeoff for the corridor structure in the paper.

6) The main factor for the “system balance point” is relative to the discrete states transition rules which are established in 2.2.2 and the parameters setting of Proportional Derivative Controller. And with the reasonable target separation, distance threshold, and switch threshold, the collision risk may decreases without serious impact on the capacity of the corridor.

7) Some side routes or transition region should be carefully designed for avoiding small probability event risk in the corridor.

The corridor structure presented in this paper is relatively basic. Future work includes extending the corridor structure to two or more levels, introducing the vertical movement of aircraft with time lag and random error. The interactions between different parameters is another work to be done.

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