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Modeling the Intrinsic Safety of Unstructured and Layered Airspace Designs

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***Abstract*—Previous research relating airspace structure and capacity has shown that a decentralized layered airspace concept, in which each altitude band limited horizontal travel to within a predefined heading range, improved safety when compared to unstructured airspace. However, the extent of the safety benefits of such layered airspace designs were not quantified. To this end, in this paper, conflict rate models are developed to determine the intrinsic safety of unstructured and layered airspace designs. In comparison to previous work, the present models consider conflicts between aircraft in different flight phases. Thus, conflicts for climbing and descending traffic, as well as for cruising aircraft, are taken into account when computing the total conflict rate. To validate the models, fast-time simulations were performed for several different layered airspace concepts, and for unstructured airspace. The results indicate that the models are able to estimate the conflict rate for high traffic densities using a model fit for low densities. When comparing the different layered airspace concepts tested, the model predicted, and the simulation results confirmed, a clear safety improvement when the permitted heading range per altitude band is reduced. Thus the models can be used to study the effect of airspace design parameters on the safety of unstructured and layered airspace concepts.**

***Keywords*—airspace safety; conflict rate model; conflict probability; unstructured airspace; layered airspace; Free-Flight; airspace capacity; airspace structure; self-separation; BlueSky ATM simulator**

I. Introduction

Air traffic demand has been growing rapidly in many parts of the world over the last decade, and this growth is expected to continue. The increased demand has stressed the current 'centralized' Air Traffic Management (ATM) system to near saturation levels [1], [2]. To keep pace with demand, many studies have suggested some degree of 'decentralization' of traffic separation responsibilities, from ground based air traffic controllers to each individual aircraft, to increase en route airspace capacity [3]–[5]. To support decentralization, numerous airborne Conflict Detection and Resolution (CD&R) algorithms [6], and accompanying display interfaces [3], [7], have been developed.

While CD&R algorithms are necessary to implement decentralization, results from the Metropolis project have indicated that the structuring of traffic also plays an important role on the capacity of decentralized airspace [8], [9]. In that study, four airspace concepts of increasing structure were compared. The results showed that a decentralized layered airspace concept, in which a vertical segmentation of airspace was used to separate traffic with different travel direction at different flight levels, led to the highest capacity when compared to other concepts that constrained the horizontal motion of aircraft. The increased capacity for 'layers' was found to be a result of the reduction in relative velocities between aircraft cruising at the same altitude, which in turn improved safety when compared to completely unstructured airspace.

To model the intrinsic safety benefits of layered airspace, the understanding gained from the Metropolis project was used to develop probabilistic conflict rate models for level flying aircraft [10]. In this paper, conflict rate models for both unstructured and layered airspace designs are extended to take into account conflicts between aircraft in different flight phases, i.e, conflicts between pairs of cruising aircraft, between cruising and climbing/descending aircraft, and between pairs of climbing/descending aircraft, are treated to determine the overall conflict rate.

The derived models are tested using three fast-time simulation experiments. The first experiment focused on testing the conflict rate models for unstructured and layered airspace designs under ideal conditions, and investigated the effect of heading range per altitude layer on safety. The second and third experiments considered the effect of variations in flight path angle and airspeed, respectively, on conflict rate.

This paper begins with an overview of the previous research on conflict rate modeling for unstructured and layered airspace designs in section II. Next, in section III, the conflict models are extended to take into account climbing and descending traffic. This is followed with the design of simulation experiments used to validate the models in section IV. The results of these simulations are presented and discussed in section V. The paper ends with a summary of the main conclusions.

II. Previous Research

Conflicts are defined as predicted losses of separation, and conflict rate is defined as the number of conflicts per unit time. The conflict rate *without conflict resolution* can be used to measure the intrinsic safety of an airspace design concept, i.e., to measure the ability of an airspace concept to prevent conflicts from occurring. This section describes the conceptual design of the 'Layers' airspace design concept, and also discusses previous work on modeling conflict rate for unstructured and layered airspace.

A. The Layers Airspace Design Concept

Several different layered airspace designs have been discussed in literature [11]–[13]. The concept under consideration in this work was developed in the Metropolis project [8], [9], and is known as the 'Layers' concept.

The Layers concept was developed as an extension to the hemispheric/semicircular rule [14]. It uses a vertical segmentation of airspace to separate traffic with different travel directions at different flight levels. This is achieved using so called 'heading-altitude' rules which describe the headings permitted per altitude band. Consequently, operators have the freedom to select their preferred horizontal trajectories and airspeed. Climbing and descending aircraft are exempted from the heading-altitude rules, and can violate them to reach their cruising altitude or destination.

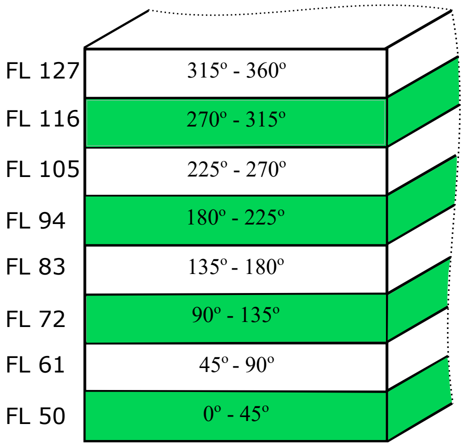

Fig. 1. Schematic view of an example Layers concept with an allowed heading range of 45^o per flight level. The airspace volume and Flight Levels (FL) pictured are also used in the fast-time simulations performed in this study.

An example Layers topology is shown in Fig. 1. An important design requirement for the Layers concept is that the spacing between altitude bands is at least equal to the vertical separation minimum to prevent conflicts between aircraft cruising in adjacent flight levels. In this work, a vertical separation of a 1000 ft is used. Therefore, the altitude bands for the Layers concepts considered here are separated by 1100ft.

One complete set of layers is needed to specify all possible travel directions. Thus, eight altitude bands are needed to define one complete layer set when an allowed heading range of 45^o per flight level is used, as shown in Fig. 1. When multiple sets of layers are available, the total flight distance is used to determine the cruising altitude of an aircraft, i.e., short flights use lower layer sets, and longer flights use higher layer sets. This can be used to minimize the effect of predetermined altitudes on efficiency.

B. Modeling Conflict Rate for Unstructured Airspace in 2D

Unlike Layers, in unstructured airspace, no constraints are imposed on aircraft trajectories. Thus, aircraft are free to select their preferred altitudes, flight paths and speeds in unstructured airspace.

As aircraft move independently of each other without conflict resolution, the conflict rate for unstructured airspace, $C_{ss_{ua}}$, has been modeled in literature as the expected value of a binomial random variable model that is summed over all aircraft in the airspace [4], [15]:

$$C_{ss_{ua}} = \frac{1}{2}\sum_{i=1}^{N_{ss}} (N_{ss} - 1)\, p_2 = \frac{N_{ss}\,(N_{ss} - 1)}{2} p_2 \qquad (1)$$

Here, N_{ss} is the steady-state number of aircraft, and p_2 is the instantaneous conflict probability between any two aircraft. Note that the number of conflicts is divided by 2 in the above expression so that conflicts between the same two aircraft are not counted twice at a given moment in time.

To model p_2 it is necessary to take into account the method used for Conflict Detection (CD). In most studies, CD is performed through linear extrapolation of aircraft positions over a predefined 'look-ahead' time, t_l. For such CD in two dimensional airspace, [15] proposed that p_2 can be computed by comparing the area searched for conflicts by an aircraft, A_c, to the total airspace area under consideration, A. For two dimensional airspace, A_c can be approximated as a rectangular 'conflict search area' that is defined by t_l, the horizontal separation minimum, d_{sep_h}, and the average aircraft velocity, v, see Fig. 2. Since conflicts are detected if the Closest Point of Approach (CPA) of an intruder aircraft is located in A_c, p_2 is defined as [15]:

$$p_2 = \frac{A_c}{A} p_s = \frac{2\; d_{sep_h} \cdot v \cdot t_l}{A} \cdot p_s \qquad (2)$$

Here, p_s is the effect of airspace structure on instantaneous conflict probability, and it can be thought of as a scaling factor to the A_c/A term in the above expression. Since there are no limitations on aircraft trajectories in unstructured airspace, there are also no procedural mechanisms to prevent conflicts from occurring. Therefore, this kind of structure has no beneficial effect of on conflict probability and $p_s = 1$ for two dimensional unstructured airspace, i.e., there is no scaling of the A_c/A term for unstructured airspace. Substituting Eq. 2 in Eq. 1 yields the following expression for the conflict rate of unstructured airspace in the horizontal plane (2D):

$$C_{ss_{ua,2D}} = N_{ss}\,(N_{ss} - 1) \cdot \frac{d_{sep_h} \cdot v \cdot t_l}{A} \qquad (3)$$

C. Modeling Conflict Rate for Cruising Aircraft in Layered Airspace

In our previous work, a conflict rate model for the Layers concept has been derived for cruising aircraft [10]. This was done by extending the conflict rate model for unstructured airspace with the two aspects that differentiate layered and unstructured airspace: the reduction of the number of possible conflict pairs, and the reduction of relative velocity between cruising aircraft. Below, a summary of these two aspects, and the resultant conflict rate model for Layers, is given. The reader is referred to [10] for the complete derivation.

1) Conflict Pair Reduction

Since the spacing between the predefined flight levels of the Layers concept is at least equal to the vertical separation minimum, cruising aircraft at different altitude bands can not conflict with each other. Therefore, the Layers concept reduces the number of possible conflict pairs between cruising aircraft, and the corresponding conflict rate for a particular altitude layer can be expressed as:

$$C_{ss_{lay_i}} = \frac{N_{ss_{lay_i}}\,(N_{ss_{lay_i}} - 1)}{2} \cdot p_{2_{lay_i}} \qquad (4)$$

Here, the subscript lay_i indicates that the variables are for one specific layer. The expected total number of conflicts at a given moment in time in the entire airspace can be computed by summing Eq.4 over all altitude bands:

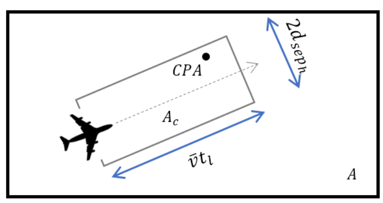

Fig. 2. Area searched for conflicts, A_c. Here A is the total airspace area under consideration. A conflict occurs if the Closest Point of Approach (CPA) of an intruder aircraft is inside A_c.

$$C_{ss_{lay,2D}} = \sum_{i=1}^{L} \frac{N_{ss_{lay_i}}(N_{ss_{lay_i}} - 1)}{2} \cdot p_{2_{lay_i}} \tag{5}$$

Here, L is the number of altitude layers. If traffic is assumed to be evenly distributed over all (predefined) flight levels, then $N_{ss_{lay_i}} = N_{ss}/L$. Furthermore, the instantaneous conflict probability between any two aircraft in a layer, $p_{2_{lay_i}}$, is equal for all layers. Therefore, this term can be generalized to the instantaneous conflict probability p_2 for all layers. Using these assumptions, Eq. 5 can be simplified to:

$$C_{ss_{lay,2D}} = \frac{N_{ss}\left(\frac{N_{ss}}{L} - 1\right)}{2} p_2 \tag{6}$$

When comparing Eqs. 1 and 6, it can be seen that the first way in which the Layers concept reduces the conflict rate over unstructured airspace is by decreasing the number of two aircraft combinations that can conflict with each other.

2) Relative Velocity Reduction

As aircraft in the Layers concept are 'sorted' into different altitude bands based on their heading, the relative velocities between cruising aircraft at a particular flight level are lowered. Therefore, the effect of a layered airspace structure on the instantaneous conflict probability between two aircraft, p_s, can be modeled by considering the effect of a predefined heading range on the relative velocities between traffic in a particular altitude layer [10], see Fig. 3.

For the conflict situation shown in Fig. 3, the relative velocity, v_{rel}, can be computed as a function of the absolute heading difference, $|\Delta hdg|$, between the two aircraft:

$$v_{rel}(|\Delta hdg|) = 2\ v \sin\left(\frac{|\Delta hdg|}{2}\right) \tag{7}$$

Here, it is assumed that all aircraft in a layer have the same true airspeed, v, and fly in the same altitude layer. The allowed heading range per layer, α, is the also the maximum heading difference between any two aircraft cruising in the same altitude band. If the headings of all aircraft in a layer are uniformly distributed within the heading range α, then the probability density function of the *heading difference* between two aircraft has a triangular shape, see Fig. 4, and can be described as:

$$P(|\Delta hdg|) = \frac{2}{\alpha}\left(1 - \frac{x}{\alpha}\right) = \frac{2}{\alpha^2}(\alpha - x) \tag{8}$$

The effect of layered airspace structure on instantaneous

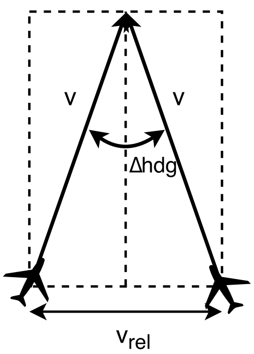

Fig. 3. Relation between heading difference between two conflicting aircraft and relative velocity

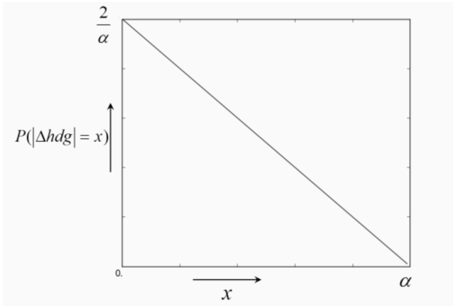

Fig. 4. The probability density function of the absolute heading difference between two uniformly distributed headings between 0 and α is triangular in shape [10].

conflict probability, p_s, can be calculated by integrating the product of Eqs. 7 and 8 for the range of heading differences between two aircraft in a layer:

$$p_s = \frac{1}{v}\int_0^{\alpha} P(|\Delta hdg = x|) \cdot v_{rel}(|\Delta hdg = x|)dx \tag{9}$$

The above equation is divided by v so that the resulting p_s is dimensionless. Finally, the conflict rate for two dimensional layered airspace can be determined by substituting Eq. 9 into Eq. 2, and then substituting the result into Eq. 6:

$$C_{ss_{lay,2D}} = N_{ss}\left(\frac{N_{ss}}{L} - 1\right) \cdot \frac{d_{sep_h} \cdot v \cdot t_l}{A} \cdot \frac{2\pi}{\alpha}\left(1 - \frac{2}{\alpha}\sin\frac{\alpha}{2}\right) \tag{10}$$

III. Conflict Rate Models With Climbing and Descending Traffic

For a given airspace volume, climbing and descending aircraft will affect the total number of conflicts. Therefore in this section, the conflict rate models for unstructured and layered airspace designs are extended to take into account the effect of climbing and descending aircraft.

A. Modeling the Effect of Conflict Detection on Conflict Probability in 3D

For motion restricted to the horizontal plane, the instantaneous conflict probability, p_2, was shown to be dependent on the *area* searched for conflicts, A_c, and the *total airspace area* under consideration, A, see Fig. 2. Analogously, for three dimensional airspace, p_2 is dependent on the *volume* searched for conflicts, V_c, and the *total airspace volume* under consideration, V:

$$p_2 \sim \frac{V_c}{V} \tag{11}$$

Fig. 5 displays the side-view of the volume searched for conflicts by an aircraft, V_c. It shows that V_c is dependent on the horizontal separation minimum, d_{sep_h}, the vertical separation minimum, d_{sep_v}, the aircraft velocity, v, the CD look-ahead time, t_l, and the flight path angle, γ. The flight path angle of an aircraft can be described using its horizontal and vertical speeds, v_h and v_v:

$$\gamma = \tan^{-1}\left(\frac{v_v}{v_h}\right) \tag{12}$$

For most practical cases, $v \cdot t_l >> d_{sep_h}$. Therefore, V_c can be approximated using the simplified side-view presented in the bottom half of Fig. 5. Here, the distance x_1 depends on γ, d_{sep_h} and d_{sep_v}:

$$x_1 = 2\ d_{sep_h} \sin(\gamma) + 2\ d_{sep_v} \cos(\gamma) \tag{13}$$

As the vertical speed, v_v, is usually smaller than the horizontal speed, v_h, the flight path angle will also be relatively small. For small γ, the following assumptions can be used to simplify the above model:

$$2\ d_{sep_h} \sin(\gamma) = 2\ d_{sep_h}\gamma \tag{14a}$$
$$2\ d_{sep_v} \cos(\gamma) = 2\ d_{sep_v} \tag{14b}$$

Using the above simplifications, V_c can be formulated as:

$$\begin{aligned} V_c &= 2\ d_{sep_h} v\ t_l\ x_1 \\ V_c &= 2\ d_{sep_h} v\ t_l\,(2\ d_{sep_h}\ |\gamma| + 2\ d_{sep_v}) \end{aligned} \tag{15}$$

Combining Eqs. 15 and. 11 results in the following relation for p_2 for three dimensional airspace. This relation will be used to model the conflict rates for unstructured and layered airspace designs.

$$p_2 \sim \frac{2\ d_{sep_h} v\ t_l\,(2\ d_{sep_h}\ |\gamma| + 2\ d_{sep_v})}{V} \tag{16}$$

B. Modeling the Total Conflict Rate for Unstructured Airspace

As mentioned earlier, for unstructured airspace, there is no a priori separation of traffic or prevention of conflicts. Consequently, the instantaneous conflict probability, p_2, is independent of aircraft flight phase, and it is not necessary to consider differences between cruising and climbing/descending aircraft. Therefore, the two-dimensional conflict rate model for unstructured airspace can be extended to three dimensions by simply using the 3D version of p_2, i.e., by substituting Eq. 16 into Eq. 1:

$$C_{ss_{ua,3D}} = \frac{N_{ss}\,(N_{ss}-1)}{2} \cdot f(|\gamma|_{avg}) \cdot k \tag{17}$$

where $f(|\gamma|_{avg})$ is defined using Eq. 16:

$$f(|\gamma|_{avg}) = \frac{2\ d_{sep_h} v\ t_l\,(2\ d_{sep_h}\ |\gamma|_{avg} + 2\ d_{sep_v})}{V} \tag{18}$$

Here, $|\gamma|_{avg}$ is the average absolute flight path angle of all aircraft in the airspace, and k is a constant term introduced to account for any non-modeled aspects that may influence the conflict rate. The value of k is determined by fitting the model to the simulation results in a least-square sense. If $k = 1$, then the model as defined above is able to predict the conflict rate accurately. On the other hand, if $k < 1$, the model is over-estimating the conflict rate, and if $k > 1$, model is under-estimating the conflict rate. Thus, the value of k can be used to determine the accuracy of the model.

C. Modeling the Total Conflict Rate for Layered Airspace

The structure of the Layers concept prevents conflicts between aircraft cruising at different altitude bands. However, there are no procedural mechanisms in Layers to separate climbing and descending traffic from cruising aircraft. Therefore, the total conflict rate for Layers can be modeled by splitting the number of instantaneous conflicts into three types:

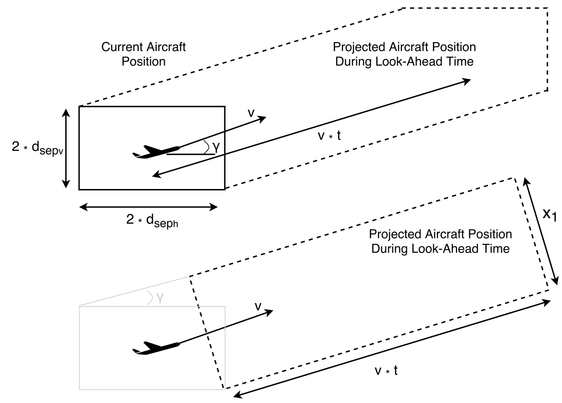

Fig. 5. Side-view of the volume searched for conflicts by an aircraft in a three-dimensional airspace. The top figure indicates the dependency on the airspace parameters, and the bottom figure represents the simplification using $v \cdot t >> d_{sep_h}$.

1) Cruising vs. Cruising
2) Cruising vs. Climbing/Descending
3) Climbing/Descending vs. Climbing/Descending

The overall conflict rate for the Layers concept for three-dimensional can be modeled as a summation of the conflict rates of the different conflict types listed above:

$$\begin{aligned} C_{ss_{lay,3D}} = &\frac{N_{cruise}(\frac{N_{cruise}}{L}-1)}{2} \cdot \frac{2\ d_{sep_h} \cdot v \cdot t_l}{A} \cdot g(\alpha) \cdot k_1 \\ &+ N_{cruise} \cdot N_{CD} \cdot f(|\gamma|_{avg}) \cdot k_2 \\ &+ \frac{N_{CD}(N_{CD}-1)}{2} \cdot f(|\gamma|) \cdot k_3 \end{aligned} \tag{19}$$

Here, $g(\alpha)$ and $f(\gamma)$ are defined as:

$$g(\alpha) = \frac{2\pi}{\alpha}\left(1 - \frac{2}{\alpha}\sin\frac{\alpha}{2}\right) \tag{20}$$

$$f(\gamma) = \frac{2\ d_{sep_h} v\ t_l\,(2\ d_{sep_h}\ |\gamma| + 2\ d_{sep_v})}{V} \tag{21}$$

In the above equations, $|\gamma|$ is the absolute flight path angle of climbing/descending aircraft, $|\gamma|_{avg}$ is the average absolute flight path angle of all aircraft in the airspace, N_{cruise} is the instantaneous number of cruising aircraft, and N_{CD} is the instantaneous number of climbing/descending aircraft. Note that the second term on the right hand side of Eq. 19 considers combinations of cruising and climbing/descending aircraft. Since a particular aircraft can not be cruising and climbing/descending at the same time, it is not required to divide this term by 2. Also note that k-constants have been introduced into Eq. 19. As for unstructured airspace, these constants are used to to determine the accuracy of the three components of the model when it is fitted to data from simulation experiments.

IV. Fast-Time Simulation Design

To validate the conflict rate models derived for three-dimensional airspace, three fast-time simulation experiments were performed for unstructured and layered airspace designs. This section describes the design of these experiments.

A. Simulation Development

1) Simulation Platform

The BlueSky open-source ATM simulator was used as the simulation platform in this research. It was developed at the Delft University of Technology (TU Delft) using the Python programming language[1]. BlueSky has numerous features including the ability to simulate more than 5000 aircraft simultaneously with CD&R. For more information on BlueSky, the reader is referred to [16].

2) Conflict Detection

Conflicts were detected using the so called 'state-based' Conflict Detection (CD) method. In this CD method, conflicts are detected if separation violations are predicted when aircraft positions are linearly extrapolated over a predefined 'look-ahead' time. In this study, a 'look-ahead' time of 5 minutes, as well as separation requirements of 5 nautical miles horizontally and 1000 ft vertically, were used.

3) Airspace Concepts and Concept Implementation

Four different layered airspace concepts and an unstructured airspace concept were used in the fast-time simulations. Table I displays the properties of these concepts. Additionally, all concepts were defined between FL50 and FL127, see Fig. 1. This figure also shows the altitudes of the eight flight levels used by all layered airspace concepts. The altitude bands for layered concepts are separated by 1100 ft. In combination with a vertical separation requirement of 1000 ft, the additional 100 ft separation between altitude bands guarantees that aircraft do not trigger conflicts with traffic cruising in adjacent layers. It should also be noted that the only difference between the L360 and UA concepts is the use of predefined cruising altitudes in L360.

The airspace concepts were implemented into BlueSky by modifying its trajectory planning functions. Aircraft in both unstructured and layered airspace concepts used the direct horizontal route. For unstructured airspace, altitude was linearly dependent on the distance between origin and destination. Since traffic scenarios with a uniform distribution of flight distances were used, this form of altitude selection resulted in a uniform vertical distribution of traffic, i.e., altitude was proportional to flight distance.

On the other hand, altitude for the Layers concept was selected based on the bearing to the destination and the matching flight level from a predefined list, i.e, by using the 'heading-altitude' rule for each layered airspace concept. When multiple sets of layers were available, the total flight distance was used to determine the cruising altitude of an aircraft: short flights used lower layer sets, while longer flights used higher layer sets. Because traffic scenarios with a uniform distribution of trip distances were used, traffic was distributed uniformly over the eight predefined flight levels used by all layered concepts.

B. Traffic Scenarios

1) Testing Region and Flight Profiles

A large square region of 480 $\times$ 480 nautical miles was used as the physical environment for the traffic simulations. A total of 289 airports were evenly distributed in a grid pattern in this region, with a spacing of 30 n miles (similar to the spacing between airports in Europe including small ones).

[1]BlueSky can be downloaded from https://github.com/ProfHoekstra/bluesky

TABLE I
EXPERIMENT AIRSPACE CONCEPTS

Symbol	Name	Heading Range Per Layer, α	Number of Layer Sets
UA	Unstructured Airspace	-	-
L360	Layers 360	360^o	8
L180	Layers 180	180^o	4
L90	Layers 90	90^o	2
L45	Layers 45	45^o	1

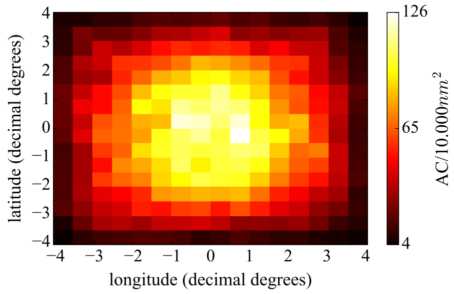

Fig. 6. Density distribution for a representative traffic scenario. To compensate for the reduced densities near the edge of the simulation area, a smaller experiment area was defined between -2^o and 2^o latitude and longitude.

Pilot simulations revealed that traffic densities near the edges of the 'simulation volume' were much lower than in its center, see Fig. 6, because origins and destinations for all traffic were located within the simulation volume. To compensate for this, a smaller 'experiment volume' of 240 x 240 n miles was defined in which traffic was more evenly distributed in the horizontal plane. As mentioned earlier, in the vertical plane, the experiment volume was defined between FL50 and FL127. Only conflicts for aircraft located within the experiment volume were used in the validation of the conflict rate models.

Aircraft were spawned at 0 ft, and subsequently took off and climbed to their assigned cruising altitudes. All aircraft climbed and descended with the same flight path angle. At a predetermined distance from their destination (which depended on the cruise altitude), aircraft descended to the ground. Since the focus of this research is on en route airspace design, aircraft were deleted from the simulation when they descended through 4000 ft. Furthermore, to avoid take-off conflicts, CD was performed for altitudes above 1000 ft.

2) Scenario Generation

A scenario generator was created to produce traffic scenarios with a desired and constant traffic density, as well as with a uniform distance distribution. Constant density scenarios were required so that the total the number of conflicts logged during a simulation run could be attributed to a particular density. Uniform distance distributions were required to ensure a uniform vertical distribution of traffic, as altitude was selected based on distance for unstructured airspace, and if multiple layer sets were available for the Layers concept.

Since aircraft were deleted from the simulation as they exited the sector, to realize constant density scenarios, aircraft were introduced into the simulation at rate, ω_{ac}, equal to:

$$\omega_{ac} = \frac{\rho_{ac}\ A\ v}{s} \tag{22}$$

TABLE II
SIMULATION PARAMETERS FOR PRIMARY EXPERIMENT

Parameter	Value	Description
A	$57.6{\cdot}10^3$ n miles^2	Experiment Area
V	$1.64{\cdot}10^{16}$ ft ^{3}	Experiment Volume
s	345 n miles	Average distance
v	500 kts	Speed of all aircraft
t_l	5 mins	CD look-ahead time
d_{sep_h}	5 n miles	Horizontal separation
d_{sep_v}	1000 ft	Vertical separation
L	8	Number of altitude layers
$\|\gamma\|$	2.8^o	Flight path angle of climbing/descending aircraft
$\|\gamma\|_{avg}$	0.39^o	Average flight path angle of all aircraft

TABLE III
TRAFFIC DEMAND SCENARIOS

#	Density[3] [ac/10,000 NM^2]	Number of Instantaneous AC[3]
1	2.0	46.1
2	2.7	62.2
3	3.8	87.6
4	5.4	124.4
5	7.6	175.1
6	10.6	244.2
7	14.8	341.0
8	20.7	476.9
9	29.0	668.2
10	40.6	935.4
11	56.9	1311.0
12	79.6	1834.0
13	111.5	2569.0

Here, A is the airspace area used for simulation, v is average aircraft speed, s is average flight distance, and ρ_{ac} is the desired traffic density, defined as $\rho_{ac} = N_{ss}/A$. These and other constant simulation parameters are listed in Table II. Using this approach, thirteen traffic demand scenarios of increasing density were defined, see Table III. Note that the values in Table III are for the total simulation area, which is larger than the experiment area.

To ensure that aircraft had a minimum cruise phase during their flight, the minimum distance between origin and destination was selected to be 240 n miles. The maximum flight distance was set to 450 n miles. Using these settings, scenarios showed a uniform distribution of flight lengths.

C. Independent Variables

Three separate experiments were performed. The independent variables of each experiment are discussed below.

1) Primary Experiment

The focus of the primary experiment was to validate the conflict rate models derived for unstructured and layered airspace concepts under ideal conditions. Additionally, this experiment investigated the effect of heading range per altitude band on the safety of the layers concept. The independent variables for this experiment were:

- 5 *airspace concepts*, see Table I.
- 13 *traffic demand densities* ranging between 2.0 and 111.5 aircraft per 10,000 square nautical miles, see Table III. Note that this relates to a current en route density[2] [17] of approximately 21.6 aircraft per 10,000 square nautical miles.

For each traffic demand scenario, two repetitions were performed using different traffic realizations. This resulted in a a total of 130 simulation runs for the primary experiment, involving a total of 257,300 flights.

2) Flight Path Angle Variation Experiment

Since flight path angle, γ, was an important parameter that affected the instantaneous conflict probability between two aircraft in three dimensional airspace, see Eq. 16, a experiment was performed with two different values of γ. The independent variables for this experiment were:

- 2 *airspace concepts* namely, Unstructured Airspace (UA) and Layers 45 (L45), see Table I
- 11 *traffic demand densities* ranging between 2.0 and 56.9 aircraft per 10,000 square nautical miles, see Table III
- 2 *flight path angle settings* for climbing and descending traffic, namely 2.8^o (standard) and 1.4^o (non-standard)

Two repetitions were performed for each traffic demand scenario. Therefore, a total of 88 simulation runs were performed for this experiment, using a total of 103,736 flights.

3) Airspeed Variation Experiment

The third and final experiment focused on the effect of airspeed variations on the conflict rate of layered airspace. This experiment compared simulations in which all aircraft flew at the same airspeed to simulations were airspeed was uniformly distributed. The independent variables were:

- 1 *airspace concepts* namely, Layers 45 (L45), see Table I
- 11 *traffic demand densities* ranging between 2.0 and 56.9 aircraft per 10,000 square nautical miles, see Table III
- 2 *airspeed* settings; 1) airspeed of 500 kts for all aircraft; 2) uniformly distributed airspeed between 450 kts and 550 kts

Two repetitions were performed for each traffic demand scenario. Therefore, a total of 44 simulation runs were performed for this experiment, using a total of 51,868 flights.

D. Dependent Variables

The conflict rate models derived for unstructured and layered airspace concepts, described by Eqs. 17 and 19 respectively, were validated using the instantaneous number of conflicts logged during the simulation experiments.

E. Simulation Procedure and Data Logging

To minimize unsystematic variation in the results, standardized simulation conditions were used. For a particular repetition of a traffic demand scenario, the creation times of aircraft and the origins and destinations for aircraft were kept constant across all airspace concepts. Additionally, scenarios had a duration of 2 hrs, consisting of a 1 hr traffic volume buildup period and a 1hr logging period during which the traffic density was kept constant.

To compute the conflict rate, the properties of active conflicts, and the states of all aircraft in the simulation, were logged periodically every 30 seconds. As mentioned earlier,

[2]Based on traffic densities in upper airspace for an area centered around Brussels that includes five large TMAs, the positions of which are approximated to Brussels, London, Frankfurt, Paris and Amsterdam.

[3]In simulation area, which is larger than experiment area

only conflicts for aircraft within the experiment area were used for model validation, as traffic was more evenly distributed in this region, see Fig. 6.

V. Results and Discussion

In this section, the results of the three simulation experiments are presented and discussed.

A. Primary Experiment

The goal of the primary experiment was to validate the conflict rate models for both unstructured and layered airspace concepts, and to investigate the effect of heading range per altitude band on the intrinsic safety of the layers concept. These two aspects are discussed below.

1) Model Accuracy

The conflict rate for unstructured airspace is shown in Fig. 7, and the corresponding conflict rate model is given by Eq. 17. The conflict rate results for the Layers 45 concept is shown in Fig. 8. In addition to the total conflict rate, Fig. 8 also shows the results for the three different types of conflicts considered by the conflict rate model for layered airspace, see Eq. 19.

From Figs. 7 and 8, it can be seen that model fitting at low densities yields accurate conflict rate predictions at high densities. This suggests that the overall structure of the model is sound, and that the binomial random variable approach used for modeling conflict rates in this work is a good way

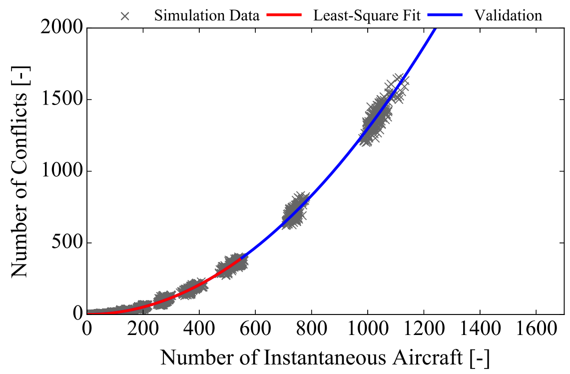

Fig. 7. Total conflict rate for unstructured airspace (primary experiment). Scatter: simulation data. Red line: least-square fit to Eq. 17. Blue Line: validation for higher densities

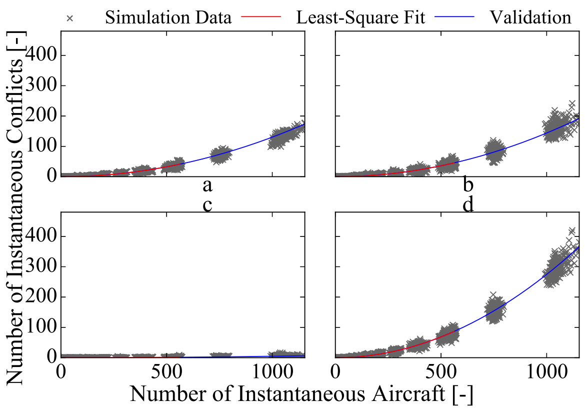

Fig. 8. Conflict rate for the Layer 45^o concept (primary experiment). a) cruising vs. cruising b) cruising vs.C/D c) CD/ vs. C/D d) total conflict rate. Scatter: simulation data. Red line: least-square fit to Eq. 19. Blue Line: validation for higher densities

TABLE IV
Model Accuracy (Unfiltered)

	Unstructured Airspace	Layers 360	Layers 180	Layers 90	Layers 45
k	1.03	-	-	-	-
k_1	-	1.30	1.44	1.66	2.18
k_2	-	1.77	1.73	1.45	1.23
k_3	-	1.23	1.24	0.96	0.73

to analyze the intrinsic safety of unstructured and layered airspace designs. Similar trends were found for the other layers concepts (not shown).

To quantitatively assess model accuracy, the values of the 'k'-constants introduced to the conflict rate models can be examined, see Table IV. The 'k'-constants can be thought of as a scaling factor. Therefore, the closer 'k'-constants are to 1, the more accurate the models are. The values shown in Table IV, as well as for all other results figures and tables, take into account the two repetitions performed for every traffic demand density scenario.

Table IV shows that the k value for unstructured airspace is very close to 1. This indicates that Eq. 17 is a very good at predicting the conflict rate of unstructured airspace. However for layers, the k values deviate significantly from 1. Moreover, the results show that the model accuracy decreases when the heading range per altitude layer is reduced, and that the model underestimates the conflict rate in most cases ($k > 1$). This means that the layers conflict rate model is not very accurate at estimating the number of conflicts, even though it is able to predict the shape of the conflict rate curve well.

To determine why the conflict rate model for layered airspace is not as accurate as expected, two hypotheses are tested.

The first hypothesis is concerned with differences in the definitions used for Conflict Detection (CD) by the model and by the simulation. In the model, a conflict is defined to occur at a time t_{cpa} when the minimum distance point between two aircraft is located within a rectangular 'conflict search area', see Fig. 2. However, in the simulation, the first moment of conflict detection occurs at time $t_{in_{conf}}$ when the separation requirements are about to be violated. Consequently, conflicts are detected earlier in the simulation than for the approach used by the model, see Fig. 9. Furthermore, since the magnitude of the difference between these two times increases with decreasing conflict angle, this hypothesis also explains why the accuracy of the conflict rate model decreases when the heading range per altitude layer is reduced.

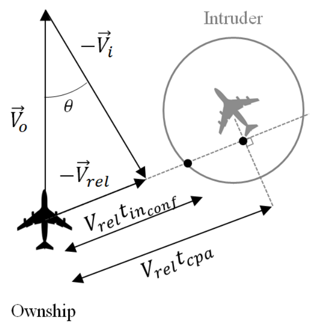

Fig. 9. Difference between t_{cpa}, the time to closest point of approach, and $t_{in_{conf}}$, the first moment of a predicted loss of separation

TABLE V
MODEL ACCURACY (CONFLICTS FILTERED BASED ON t_{cpa})

	Layers 360	Layers 180	Layers 90	Layers 45
k_1	1.15	1.21	1.23	1.35
k_2	1.65	1.61	1.34	1.12
k_3	1.05	1.09	0.82	0.64

TABLE VI
MEASURED AVERAGE CONFLICT ANGLE

	Average Conflict Angle [deg]
Layers 360	112
Layers 180	82
Layers 90	41
Layers 45	22

To test this hypothesis, a filtering of conflicts was performed during post-processing: only conflicts with a t_{cpa} less than the CD look-ahead time were considered since these types of conflicts can be predicted by the model. The corresponding results are shown in Table V.

When comparing the results before and after filtering the conflicts based on t_{cpa}, it can be seen that the accuracy of the model has improved significantly. However, in absolute terms, the model still lacks accuracy.

The second hypothesis regarding the accuracy of the conflict rate model for Layers is related to the heading distribution of cruising aircraft. The model is derived assuming a uniform distribution of aircraft headings *within the range permitted for each altitude band.* A uniform distribution of headings should lead to a triangular distribution of conflict angles between 0^o and the allowed heading range per layer, α, see Fig. 4. Accordingly, the mean conflict angle should be equal to $\frac{1}{3}\alpha$. Table VI shows that this assumption was not satisfied for any of the layers concepts. This strongly suggests that the headings for aircraft in the traffic scenarios used to validate the model were not uniformly distributed within the required range per layer.

To account for the actual heading distribution in the traffic scenarios, a new model fit was performed after correcting the allowed heading range, α, to match the measured conflict angle for each layered concept using $\alpha = 3 \cdot \theta$, where θ is the measured conflict angle. For example α for the Layers 45 concept is taken to be 66^o based the data presented in Table VI. This resulted in the k values displayed in Table VII. Note that in Table VII only values of $k1$ are shown since this correction only affects conflicts between pairs of cruising aircraft. The table shows that the k values are very close to 1 for all layered concepts after correcting for conflict angle, and filtering conflicts based on t_{cpa}.

To summarize, the above analysis revealed that the accuracy of the conflict rate model for unstructured airspace is high. However, the accuracy of the conflict rate model for Layers is negatively affected by the mismatch between the CD definition used by the simulation and by the model. Since the CD definition used in the simulation reflects reality better, model accuracy could be improved by using a larger (trapezoidal) 'conflict search area' so that conflicts with a t_{cpa} greater than, and a $t_{in_{conf}}$ less than, the look-ahead time can also predicted by the model. Additionally, the results for layered airspace indicated that the heading range per layer was not distributed within the expected range. While this also led to a reduction in accuracy, it should be noted that this was caused by the scenarios used in the simulation, and not due to the structure of the model itself. When conflicts were filtered based on t_{cpa} and corrections were applied to compensate for the heading range in the scenario, the accuracy of the model was found to be high. This suggests that the current conflict rate model for Layered airspace can be altered as described above to improve its absolute accuracy.

TABLE VII
MODEL ACCURACY (CONFLICTS FILTERED BASED ON t_{cpa}, AND α CORRECTED BASED ON MEASURED CONFLICT ANGLE)

	Layers 360	Layers 180	Layers 90	Layers 45
k_1 (not corrected)	1.15	1.21	1.23	1.35
k_1 (corrected)	1.15	0.99	0.93	0.93

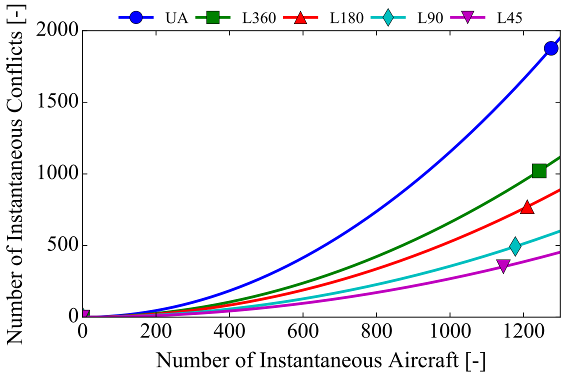

Fig. 10. Total conflict rate for all concepts (primary experiment). The curves represent the least-square fit of the simulation data to Eq. 17 for Unstructured Airspace (UA) and to Eq. 19 for the layered airspace concepts.

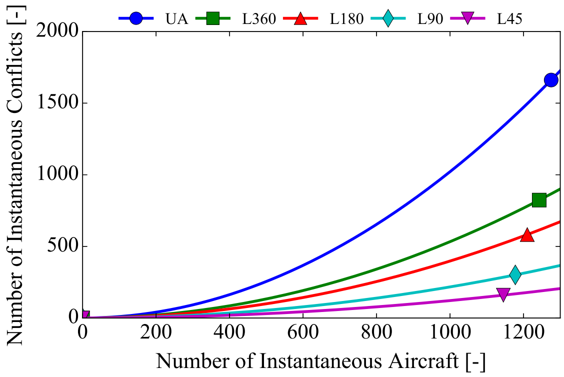

Fig. 11. Conflict rate for cruising aircraft (primary experiment). The curves represent the least-square fit of the simulation data to Eq. 3 for Unstructured Airspace (UA) and to Eq. 10 for the layered airspace concepts.

2) Effect of Heading Range Per Altitude Layer

Fig. 10 shows the conflict rate results for all five airspace concepts used in the primary experiment. As predicted by the conflict rate model for layered airspace, this figure shows that decreasing the heading range per altitude layer leads to a reduction of the total conflict rate. Further analysis showed that this safety improvement was mainly due to a reduction in the number of conflicts between cruising aircraft when the allowed heading range per layer was decreased, see Fig 11.

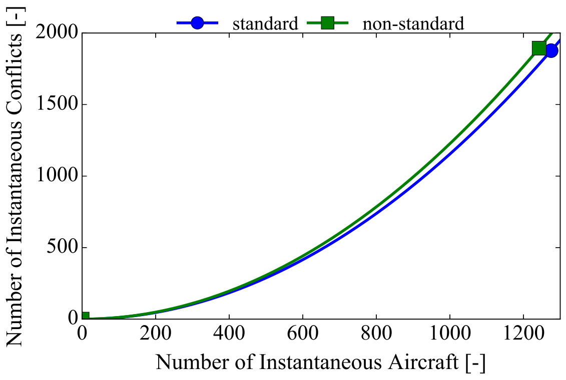

Fig. 12. Effect of variation in flight path angle on conflict rate for unstructured airspace. Here *standard* represents the simulations with a γ of 2.8^o, and *non-standard* represents a γ of 1.4^o. The curves represent the least-square fit of the simulation data to Eq. 17

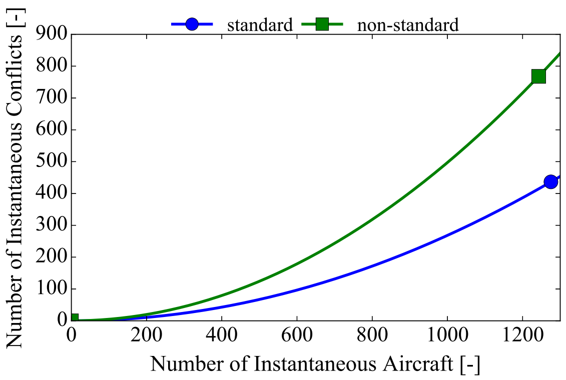

Fig. 13. Effect of variation in flight path angle on conflict rate for Layers 45^o. Here *standard* represents the simulations with a γ of 2.8^o, and *non-standard* represents a γ of 1.4^o. The curves represent the least-square fit of the simulation data to Eq. 19

Since all layered airspace concepts used the same number of flight levels, based on the structure of Eq. 19, this increased safety can be attributed to the reduction of relative velocities between cruising aircraft when the permitted heading range per altitude layer is decreased.

When comparing the layered concepts to unstructured airspace, Fig. 10 shows that the conflict rate is always higher for unstructured airspace. It is interesting to note that this is also true for the Layers 360 concept. Since there are no heading-altitude constraints, and therefore no reduction in relative velocities, for either of these two concepts, the increased safety of Layers 360 can be attributed to the a priori vertical separation of traffic that prevents conflicts between aircraft cruising at different flight levels. Therefore, in this case, safety was improved by reducing the number of possible conflict pair combinations for layered airspace when compared to unstructured airspace.

B. *Flight-Path Angle Variation Experiment*

The effect of flight path angle on conflict rate has been analyzed for unstructured airspace and for the Layers 45 concept, see Figs. 12 and 13, respectively. The same traffic scenarios are used as for the primary experiment, but the flight path angle, γ, during the climbing and descending phases of flight is varied; simulations are performed for a γ of 2.8^o and for a γ of 1.4^o.

Although the origins, the destinations and the cruising altitudes for traffic are the same, a change in γ changes the ratio between the number of cruising vs. climbing/descending aircraft at any given moment in time. A reduction in γ causes an aircraft to take more time to reach its cruising altitude. Therefore, a reduction in γ also increases the proportion of climbing/descending aircraft in the simulation.

The conflict probability between aircraft in unstructured airspace is not significantly affected by their flight phases. Consequently, Figure 12 only shows a small effect of a change in γ on conflict rate. The slight increase in conflict rate for $\gamma = 1.4^o$ can be explained by the fact that aircraft spend more time climbing/descending, and less time cruising, for a lower γ. This slightly increases average flight path angle over the course of a flight, which in turn slightly increases the conflict probability between aircraft as described by Eq. 16.

In contrast, Fig. 13 shows that γ has a drastic effect on the conflict rate for layered airspace. The safety benefits offered by layered airspace applies only to cruising aircraft as there are no procedural mechanisms to separate climbing/descending aircraft from each other or with cruising aircraft. Therefore, a reduction in γ increases the amount of time needed for an aircraft to reach its cruising altitude, and benefit from the reduction in conflict probability between cruising aircraft in at the same flight level for Layers. This explains why the conflict rate is significantly higher when γ is reduced to 1.4^o for the Layers 45 concept.

Based on the above analysis, it can be concluded that conflict rate is inversely proportional to flight path angle because it changes the ratio between cruising and climbing/descending aircraft. Moreover the safety of Layers is more sensitive to flight path angle changes than for unstructured airspace.

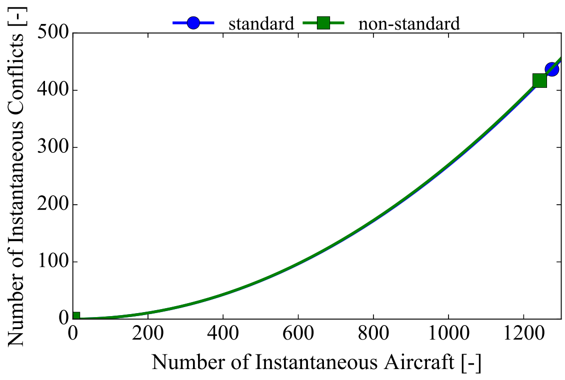

Fig. 14. Effect of variation in true airspeed on conflict rate for Layers 45^o. Here *standard* represents the simulations with a constant airspeed of 500 kts, and *non-standard* represents a uniformly distributed airspeed between 450 kts and 550 kts.

C. *Airspeed Variation Experiment*

The final experiment investigated the effect of airspeed variations on conflict rate. To this end, two sets of simulations were performed for the Layers 45 concept. In the first set of simulations, all aircraft flew at 500 kts, while in the second set, the speed of aircraft was uniformly distributed between 450 kts and 550 kts.

The conflict rate results for airspeed variations are displayed in Fig. 14. The figure shows no difference in the conflict rate between the two airspeed cases, since the average speed of all aircraft in both cases is the same and equals 500 kts. This suggests accurate estimates of conflict rate can be computed using the models derived in this work as long as the average traffic speed, or the distribution of speeds, is known.

VI. Conclusions and Recommendations

In this paper, conflict rate models for unstructured and layered airspace designs were developed. The models derived in this work take into account conflicts between aircraft in different flight phases; conflicts between cruising aircraft, between climbing/descending aircraft, and between cruising and climbing/descending aircraft are considered. Fast-time simulation experiments were conducted to validate the models, and to compare unstructured and layered airspace designs in terms of safety. The following conclusions can be drawn:

- A model fit at low densities produced accurate conflict rate estimates for high densities. Therefore, the binomial random variable approach used for modeling conflict rates in this work is a good way to analyze the intrinsic safety of unstructured and layered airspace designs.
- The safety of layered airspace increases when the heading range per altitude layer is decreased. This effect is predicted by the presented conflict rate model, and it is because the relative velocities, and therefore the conflict probabilities, between cruising aircraft are proportional to the heading range per flight level.
- Layered airspace was found to be safer than unstructured airspace for the entire range of densities considered in this work. This was also true for a layered concept that did not restrict the headings of aircraft, but did use predefined flight levels for cruising aircraft. This is because the a priori vertical separation of traffic in the layers concept reduces the number of possible conflict pairs, and also reduces the conflict probability between cruising aircraft.
- Conflict rate is inversely proportional to flight path angle. The safety of the Layers concept was found to be more sensitive to changes in flight path angle compared to unstructured airspace. This is because the safety benefits of layered airspace are only applicable to cruising aircraft, while conflict probability is not significantly affected by flight phase for unstructured airspace.
- The absolute accuracy of the conflict rate models, particularly for layered airspace, can be further improved by relaxing model assumptions related to conflict detection. This will be the focus of future work.

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Martijn Tra received the MSc degree in Aerospace Engineering from TU Delft in 2016, for modeling the effect of layered airspace on conflict rate and capacity. During his MSc, he performed an internship at Schiphol Group, where he developed a tool to assess the competitiveness of Schiphol airport. He is currently working as an engineer at ADB Safegate, working with advanced airport solutions.

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Jacco Hoekstra obtained his MSc, PhD and private pilot license from TU Delft. He has worked at the Dutch National Aerospace Laboratory (NLR) for 16 years, and has co-operated with NASA, the FAA and many European organizations. He founded the Association for Scientific Development of ATM, was the founding director of AT-One and was the head of NLR's Air Transport Division. After serving two terms as dean of the Aerospace Engineering faculty of TU Delft, he is now a full professor at this faculty, and holds the chair in CNS/ATM. His research topics include 4D trajectory based ATM, airborne separation assurance and controller-pilot data link communication. Next to research, he teaches courses on CNS/ATM, programming in Python and aeronautics.