Transportation Research Part C 95 (2018) 295–319

Contents lists available at ScienceDirect

Transportation Research Part C

journal homepage: www.elsevier.com/locate/trc

Three-dimensional conflict count models for unstructured and layered airspace designs

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ARTICLE INFO

Keywords:
Airspace safety
Airspace design
Conflict probability
Conflict rate
Air Traffic Management (ATM)

ABSTRACT

This paper presents analytical models that describe the safety of unstructured and layered en route airspace designs. Here, 'unstructured airspace' refers to airspace designs that offer operators complete freedom in path planning, whereas 'layered airspace' refers to airspace concepts that utilize heading-altitude rules to vertically separate cruising aircraft based on their travel directions. With a focus on the *intrinsic* safety provided by an airspace design, the models compute instantaneous conflict counts as a function of traffic demand and airspace design parameters, such as traffic separation requirements and the permitted heading range per flight level. While previous studies have focused primarily on conflicts between cruising aircraft, the models presented here also take into account conflicts involving climbing and descending traffic. Fast-time simulation experiments used to validate the modeling approach indicate that the models estimate instantaneous conflict counts with high accuracy for both airspace designs. The simulation results also show that climbing and descending traffic caused the majority of conflicts for layered airspaces with a narrow heading range per flight level, highlighting the importance of including all aircraft flight phases for a comprehensive safety analysis. Because such trends could be accurately predicted by the three-dimensional models derived here, these analytical models can be used as tools for airspace design applications as they provide a detailed understanding of the relationships between the parameters that influence the safety of unstructured and layered airspace designs.

1. Introduction

The sustained growth of air traffic in recent years has stressed several components of the current Air Traffic Management (ATM) system to near saturation levels. This is particularly true for en route airspace design where continued reliance on the fixed airway network has significantly reduced flight efficiencies (Doble et al., 2008). This is because airway navigation often force aircraft to deviate from direct trajectories, which during peak demand periods can trigger artificial traffic concentrations and increased delays (Magill et al., 1998; Dell'Olmo and Lulli, 2003). Their use in Europe, for instance, has been linked to the 20% increase in en route delays in 2016, even though traffic demand grew by only 2.4% during the same time period (Performance Review Commission, 2016). Similar statistics reported in many other parts of the world have motivated several studies to explore alternate options for organizing en route traffic (Rebollo and Balakrishnan, 2014; SESAR Consortium, 2007; Joint Planning and Development Office, 2007).

To overcome the capacity limitations posed by airway routing, some researchers have proposed a transition to less rigid route

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https://doi.org/10.1016/j.trc.2018.05.031
Received 23 December 2017; Received in revised form 24 April 2018; Accepted 30 May 2018

Nomenclature

Greek letters

α	heading range per flight level [°]
β	no. of flight levels in 1 layer set
γ	flight path angle [°]
κ	number of layer sets
ψ	aircraft heading [°]
ρ	density [ac/NM^2]
ε	proportion of cruising aircraft
ζ	vertical spacing between layers [ft]

Roman letters

A	airspace area [NM^2]
B	airspace volume [NM^2·ft]
C	no. of instantaneous conflicts
D	trip distance [NM]
k	model accuracy parameter
L	total no. of flight levels
N	no. of instantaneous aircraft
p	average conflict probability between any two aircraft
S_h	horizontal separation requirement [NM]
S_v	vertical separation requirement [ft]
t_l	conflict look-ahead time [mins]
V	aircraft velocity [kts]
V_r	relative velocity [kts]
Z	altitude [ft]

Subscripts

h	horizontal
i	aircraft i
j	flight level j
v	vertical
$2d$	two dimensional
$3d$	three dimensional
cd	climbing/descending aircraft
$cruise$	cruising aircraft
lay	layered airspace
max	maximum
min	minimum
$total$	total
ua	unstructured airspace

structures for en route airspace (Hoekstra et al., 2002; Green et al., 2001; Bilimoria et al., 2000; Krozel et al., 2001; Barnett, 2000). This approach has been adopted in some low-density areas of Europe with the creation of so called 'Free Route Airspaces' (FRAs) since 2008 (NMD/NSD Operations Roadmap Team, 2015). FRAs aim to emulate the route selection flexibility offered to aircraft flying in unmanaged airspace, while continuing to provide air traffic controllers with control of the traffic within them. Analysis by Eurocontrol has shown that the limited use of FRAs thus far has yielded an average route efficiency increase of 1.6% per flight, with gains of up to 4% in some areas (Performance Review Commission, 2016). Further extending FRAs into more dense airspace sectors could, therefore, lead to substantial reductions in total delay, fuel consumption and emissions. As such, FRAs demonstrate the potential of utilizing procedural mechanisms to reorganize and improve the performance of en route airspace operations, without large capital investments in new hardware.

While reducing structural constraints can increase en route airspace capacity relative to airway routing for current traffic demand levels, a recent study has found that offering operators *complete* freedom in path planning is not optimal in terms of safety for higher densities (Sunil et al., 2017). In that study, several unmanaged en route airspace concepts, which varied in terms of the number of constrained degrees of motion, were compared qualitatively using simulation experiments. The results clearly showed that a layered airspace concept, which used a vertical segmentation of airspace to separate traffic with different travel directions at different flight levels, led to the highest safety. The increased safety for 'layers' was found to be a result of the reduction of relative velocities between cruising aircraft at the same altitude, which in turn reduced the number of conflicts when compared to a completely unstructured airspace design.

Using the qualitative understanding gained from Sunil et al. (2017) as a starting point, the current paper aims to develop quantitative models that describe the intrinsic safety provided by unstructured and layered en route airspace designs. Here the notion of intrinsic safety refers to the ability of an airspace design to reduce the occurrence of conflicts due to the constraints that it imposes on traffic motion. As such, the intrinsic safety provided by an airspace design is irrespective of whether or not conflicts are actually detected by aircraft; instead this aspect of safety considers the effect of the route structure imposed by a particular design on the number of 'truly occurring' conflicts. Consequently, intrinsic safety is directly proportional to the workload experienced by pilots and/or air traffic controllers in resolving any remaining conflicts that could not be prevented by a particular airspace design.

The modeling approach used in this work treats aircraft conflicts similar to the collisions that occur between ideal gas particles to determine instantaneous system-wide conflict counts as a measure of intrinsic safety. In comparison to previous studies, the models considered here take into account the effect of the horizontal *and* the vertical motion of aircraft on conflict counts. This is done by grouping the considered aircraft according to flight phase, while also considering the proportion of aircraft in different flight phases. This approach allows conflicts involving climbing and descending traffic, as well as those between aircraft, to be taken into account. Because the resulting three-dimensional analytical models use measurable airspace characteristics, such as traffic demand and separation requirements, as inputs, they lend themselves well for airspace design applications as the interactions between the factors affecting safety can be directly understood from the structure of the models. Moreover, their analytical nature makes it possible to easily compare different airspace concepts, and to also fine-tune the parameters of the selected airspace design.

To assess the accuracy of the derived models, three separate fast-time simulation experiments have been performed, encompassing almost three million flights. The first experiment measures the accuracy of the models under ideal conditions, and analyzes