Nationaal Lucht- en Ruimtevaartlaboratorium
National Aerospace Laboratory NLR

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Overview of NLR Free Flight Project 1997-1999

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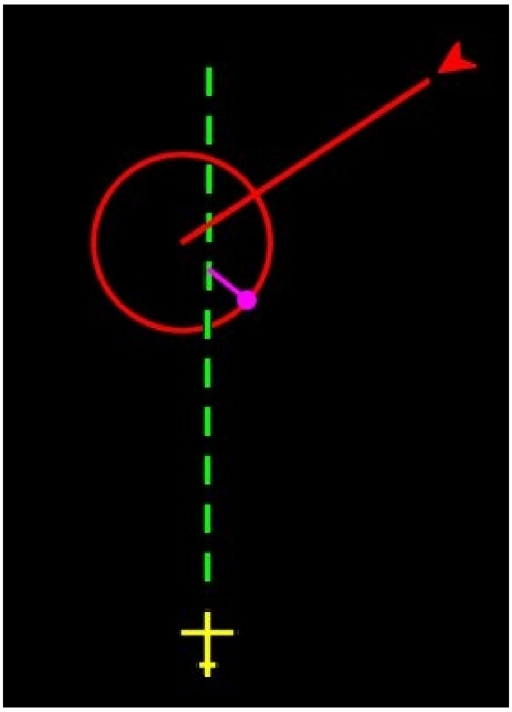

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ABSTRACT

NLR has investigated the feasibility of Free Flight concepts with airborne separation during several years of research in collaboration with NASA, the FAA and the RLD (Dutch Civil Aviation Authorities). Issues that have been addressed are:

- conflict detection & resolution methods
- complex conflict geometries
- pilot workload
- pilot acceptability
- display symbology
- safety (both objective & subjective)
- mixed equippage procedures
- transition issues

These issues have been investigated using different techniques, tools and simulations.

Off-line traffic simulations comprising up to 400 aircraft simultaneously were used to validate several methods for conflict detection and resolution. This simulated traffic densities up to ten times today's average Western European density. The resolution method that proved to be most effective was based on a publication of Martin Eby of Lincoln Laboratories(MIT). Additionally, complex geometries and restrictions were used to test the robustness of the method. This method has been developed further into an Airborne Separation Assurance System. This ASAS includes a human-machine interface that has been tested in several flight simulator trials. Air line pilots have been exposed to three times the Western European density and nine time the number of conflicts. No significant increases in workload were found during the cruise phase. The subjects' acceptability proved high and the subjective safety was rated equal or better when compared to today's situation.

Further analysis indicated that using this co-operative airborne separation method decreases the collision risk significantly.

All studies in the project made use of a resolution method based on exchanging position and velocity information only. No flight plan information, co-ordination procedures, priority rules or ground based systems proved to be required in order to allow effective separation assurance in the scenarios that were tested. An extra conflict prevention system called predictive ASAS has been developed, which could alleviate a possible need for exchanging flight plan information in the cruise phase. Retrofitting aircraft with such a system is facilitated by the limited requirements for system integration. Because of the simplicity of the architecture and the resolution method, the system proved to be transparant to the crew, allowing a straightforward display design. The traffic display, which is integrated in the navigation display, depicts a horizontal and vertical resolution advisory to the pilot to choose from. Bands on the heading, vertical speed and speed scale show which maneuvers would cause a possible conflict alert.

This report describes mainly the airborne perspective. Initial experiments with air traffic controllers in the loop indicated that controllers could collaborate with such a system in order to gain full gate-to-gate coverage. This aspect is described in separate publications.

None of the studies could refute the feasibility of airborne separation using such a concept in the cruise phase, even under extremely dense and constrained traffic situations.

More detailed information can also be found at the NLR Free Flight Web Site: http://www.nlr.nl/public/hosted-sites/freeflight

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Summary

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[1] 'Air traffic controller strategies in resolving free flight traffic conflicts: the effect of enhanced controller displays...', W.D. Pekela, B.G. Hilburn, Paper World Aviation Congress (WAC) 1998
'Overview of ATC Free Flight studies' , NLR Contract Report, to be published in 2000

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0 Free Flight

In the early days of flying, all pilots navigated using ground features such as roads, rail tracks and coastlines. Since there were not many aircraft flying around in those days, collision avoidance was only an issue near airfields. By keeping a sharp look out, collisions were avoided by the pilot. In case of an aircraft nearby a set of rules indicating who had right of way were used. Flying was very much restricted by weather conditions allowing the visibility of the ground and the other aircraft.

Later on, radio navigation enabled flying in and above clouds without getting lost. Radar and radio communication allowed control towers to separate traffic near the airports in weather conditions previously inhibiting flight. With beacons placed all over the country, a route in instrument meteorological conditions (IMC) consisted of flying from one beacon to another. This created a route structure in the sky consisting of so-called airways (see figure below).

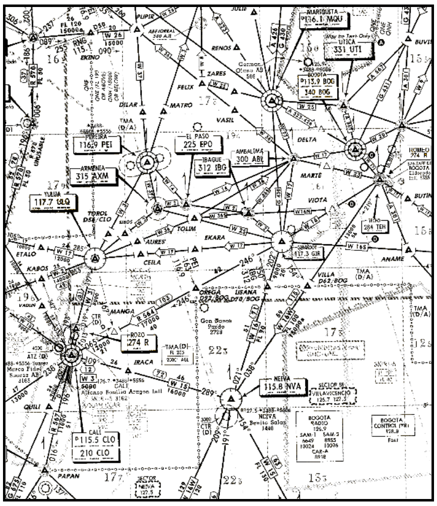

Figure 0.1 Example of airway structure

This increased the local traffic density and thereby the probability of mid-air collisions on these airways. Therefore to maintain a safe separation of the traffic, air traffic control was now no longer restricted to the area around an airport . Air Traffic Control became responsible for the separation of aircraft during the complete flight except for some general aviation, which still uses visual separation today.

The route structure of airways is still being used today. Modern navigation however, no longer relies on flying to and from a beacon. Any route can be flown by the automatic pilot using a variety of navigation aids such as omni-directional radio beacons, inertial navigation systems and satellite navigation.

In many situations, aircraft are allowed to ‘fly direct’ and cut off turns of their route. This so-called ‘direct routing’ yields time and fuel savings. Direct routing is currently only applied in relatively quiet airspace. In high traffic densities, the airways aid the air traffic controller in sequencing the traffic and in maintaining a mental picture of the complete traffic situation. This mental picture is essential to ensure the separation of the traffic.

Free Flight is a concept where direct routing is achieved by moving the separation task to the cockpit. This changes the ATM system from a centrally controlled system to a distributed system. Whether is it is feasible and safe to decentralise this task of separation is the central question in this study.

1 Introduction free flight study

1.1 Background

A lot of research has been devoted to improving Air Traffic Management. There are two main goals driving this research:

- increasing the efficiency by more efficient routes and reducing costs due to delays
- increasing the capacity to be able to facilitate the predicted air traffic growth

The challenge from a safety point of view is to maintain or increase the level of safety while increasing the efficiency and capacity.

ATM research has often aimed at improving the tools the air traffic controller has. This has involved automating traffic sequencing, detecting problems and advising solutions and more advanced man-machine interfaces for the air traffic controller. In some cases, provisions on the airborne side to downlink flight plans, performance parameters or even complete automatic negotiation processes between airborne and ground equipment were foreseen. Still most air traffic control centers have been operating in much the same way for the last twenty or thirty years.

A different and particularly interesting program with respect to Free Flight is the National Route Program (NRP) which was implemented experimentally in January 1995. As part of the NRP airlines were allowed to request direct routes above a certain altitude in the upper airspace of the USA. If the traffic was not too busy, these aircraft were allowed to fly more efficiently this way. This direct routing has been the goal of several studies. The difficulty with direct routing is maintaining the situational awareness of the air traffic controller with high traffic densities. The National Route Program may have been an inspiration to the Free Flight concept.

In all predictions traffic is predicted to grow exponenetially. For instance in the Global Market Forecast 1997-2016 by Airbus [2] the demanded air traffic capacity is predicted to have an annual growth of 5.6%. This means the capacity will nearly triple in twenty years. Though this may be good news for an aircraft manufacturer, it means a real challenge for the ATM concept and airspace structure as we use it today. For ATM research it means that high-density traffic scenarios should be used to simulate the future environment in which the tool or concept might be used.

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[2] *'Global Market Forecast 1997 – 2016 Confirming Very Large Demand' March 1997 PART 2,* http://www.airbus.com/gmf97/gmf97_2.html

1.2 Definition of the Free Flight concept

The Free Flight concept is a joint initiative of the global aviation industry and the FAA. The implementation of the Free Flight concept has been recommended by the RTCA Task Force 3 in their Final report on Free Flight implementation[3]. In that report Free Flight is defined as:

"... a safe and efficient flight operating capability under instrument flight rules (IFR) in which the operators have the freedom to select their path and speed in real time. Air traffic restrictions are only imposed to ensure separation, to preclude exceeding airport capacity, to prevent unauthorized flight through Special Use Airspace (SUA), and to ensure safety of flight. Restrictions are limited in extent and duration to correct the identified problem. Any activity that removes restrictions represents a move toward free flight. "

In the section on the Free Flight definition in the Initial Program plan of Flight 2000[4] by the FAA it further states:

" This suggests that each user is granted both maximum flexibility and guaranteed safe separation. The goal is not only to "optimize" the system but to open the system for each user to "self-optimize". Self-optimization is the key to understanding the extent of free flight's reach as well as free flight's challenges. "

The Free Flight definition has been applied to anything that improves user flexibility. However, a key element in the Free Flight concept is the traffic separation. If traffic separation is self-optimized, a key element of the RTCA definition, this means airborne separation. The notion of airborne separation assurance is a controversial issue. In a lot of documents this option is only mentioned for clear skies or relatively quiet areas[5]. This assumes Free Flight with Airborne Separation is inherently more dangerous than conventional Ground Controlled Separation. Moreover this assumes high traffic densities require central co-ordination and low densities permit a distributed approach. The question is whether this is in line with reality. Which system will be able to handle high-density traffic better: a distributed system or a centrally organized system?

To answer this and other questions some experimental data is required. During the NLR study described in this report some indications have been found which may give insight into those issues.

Though Free Flight has been defined in several ways, within this project the focus is on airborne separation assurance combined with self-optimized (direct) routing. This true Free Flight definition, with both airborne separation and direct routing will be used throughout this report. The transition to this mature Free Flight

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[3] *Final Report of the RTCA Task Force 3, Free Flight Implementation*, RTCA, Inc., Washington, D.C., October 26,1995

[4] *Flight 2000 Initial Program Plan*, Federal Aviation Authority, US department of Transportation, Washington, D.C., July 16, 1997

[5] http://www.faa.gov/freeflight/ff_ov.htm Flexibility only increases when weather and traffic density permit. In bad weather and dense area Free Flight flexibility will be restricted.

concept will be evolutionary and may require many phases. However, to know whether these transitions are necessary it is important to know more about the end goal. That is the main focus of this study. Within this study the transition issue is being addressed in the 'mixed equipage' procedures.

1.3 NASA/NLR Free Flight study

NASA is coordinating a large US government funded program called the Advanced Air Transport Technology (AATT) program In this program several US companies perform research on, among other topics, Free Flight. NLR was invited to propose a Free Flight study at the AATT meeting and the result was a separate co-operation with NASA, the Federal Aviation Authority (FAA) and the Dutch Civil Aviation Authority (RLD). In this co-operation NASA and the RLD sponsor NLR to perform a proposed five-year program to investigate the human factors and feasibility of Free Flight with Airborne Separation.

The NLR Free Flight study officially started in January 1997, though some initial concept definition and design was already in progress in 1996.. As NLR is now being considered to have a leading position in the Free Flight research, members of the project team are now participating in several panels and consortia (RTCA, ICAO, European consortia, avionics industry, FAA, Eurocontrol) advising the authorities and industry on airborne separation assurance and standards. This dissemination of the project result is an ongoing process.

1.4 Distribute or Centralize Control?

Free Flight is a distributed alternative for today's centralized Air Traffic Management system. The structure of today's ATM system is that of a centrally controlled system. ATC is the central node, sequentially processing all actions required to prevent and resolve conflicts.

In Free Flight the ATM system has become a distributed system. All conflict are prevented and resolved by interactions of the elements of the system simultaneously. Free Flight is therefore more than the introduction of a new tool or new procedure. It is a revolutionary change of the structure of the system.

On top of this system structure change, it also changes the responsibility of the people involved (pilots and controllers). Moving a responsibility is harder and takes a longer time than a technological improvement alone.

Both the decentralisation and the resulting shifted responsibilities make Free Flight a drastic change. Changes always require better arguments than the arguments required for keeping a system in place. This means research should address replace the prejudice and fear of the changes with facts and data from analysis, experiments and simulations. The studies described in this report try to address the conceptual issues involved with this revolutionayr change of the ATM system. Chapter 14 deals with this (de)centralisation topic for ATM research and other characteristics of distributed vs. centralised systems in general.

2 Free Flight Issues

2.1 Today's Air Traffic Management concept

2.1.1 Air Traffic Services Overview

To understand the concept of Free Flight and the profound change that it means, a general understanding of today's Air Traffic Management is essential. The notion that most flights are under air traffic control from gate to gate is required to see the difference with the Free Flight concept.

Air-traffic control (ATC) is a complex of international measures under responsibility of local administrations for traffic and defence to accomplish air-traffic safety in assigned Flight Information Regions (FIRs). Air-traffic authorities have a controlling and advisory task with respect to air-traffic.

The services they provide consist of:

- Air-traffic control (ATC)
- Flight information
- Alerting of authorities

The main goals of providing air-traffic services are:

- Airborne aircraft collision avoidance (part of ATC)
- Collision avoidance for aircraft on the ground (part of ATC)
- Initiating and maintaining orderly processing of air-traffic (part of ATC)
- Providing flight information for a safe and efficient traffic flow (Flight Information)
- Alerting and assisting necessary authorities for aircraft in need of search and rescue (Alerting)

ATC services are further divided by the sector they control :

- Area Control Centre (ACC) - Providing ATC to controlled flights in general ATC areas
- Approach Control (APP) - Providing ATC to controlled flights entering or leaving aerodromes
- Aerodrome Control (TWR) - Providing ground control and flight control below 1500 feet

A Flight Information Centre (FIC) is an air-traffic centre providing flight information and, if required, the alerting of other authorities. Flight information is information necessary for safe and efficient flights such as dangerous weather situations, changes in availability of navigation aids, condition of airports, etc.

Capturing the goal of air-traffic control in one sentence gives:

Air Traffic Control is responsible for safe, orderly and expeditious flow of traffic.

In Europe and several other areas the airlines, which are users of the Air Traffic Services, are charged for these services. The height of the fee is calculated using a formula based on route, aircraft weight and/or number of passengers.

2.1.2 Instrument Flight Rules

When flying under Visual Flight Rules (VFR) aircraft are responsible for maintaining their separation. Typical VFR traffic is the general aviation flying at low altitudes. Commercial aircraft continuously fly under the complementary set of rules called Instrument Flight Rules (IFR). These rules allow the aircraft to operate even when the visibility is low. Because under IFR Air Traffic Control is responsible for maintaining the separation, the IFR procedures are generally also used in good visibility. Relying on maintaining separation visually would be dangerous during most phases of the flight, because of the high speeds of most commercial airlines.

When flying IFR, the complete route is requested and a route clearance is received from ATC before take-off. This route information is then sent out via the Aeronautical Telecommunications Network (ATN) to all air traffic control centres, which will have the flight under control in their sector.

When there is a need for a route change this has to be requested during the flight and, if the traffic and weather situation permits, the aircraft will receive a clearance for this route change. Further, any altitude change (e.g. to climb to a higher, more economic flight level) requires a clearance from ATC. Therefore, there is no freedom for the crew to change their route to a more optimal route without negotiation with the ground.

Apart from the requests for a route or altitude change, there are several other procedures requiring communication with the ground: when crossing a sector boundary, the controller of the previous sector 'hands off' the aircraft to the next controller. This requires a new position and/or route report to the new controller as a confirmation or log-on to the sector. Maintaining the separation of all traffic under his/her control is the responsibility of the controller of the sector.

Since World War II, radar has been used to monitor the traffic situation. At first it was only used around the airport, but with the increasing amount of air traffic, also en-route traffic is monitored via the radar. Aircraft today are also equipped with a transponder that broadcasts extra information to the radar such as an identification code (squawk) and the altitude (mode C) for the air traffic controller. The result is a complete overview of the three-dimensional traffic situation. Trailing blips on the screen even provide an impression of the direction and magnitude of the ground speed. Using the mode C transponder ensures an accurate vertical position estimate however the angular nature of the radar may not provide a very accurate horizontal position estimate especially at larger distances. Typical separation minima in these circumstances are therefore 5 nautical mile horizontally and 1000 feet vertically.

In areas, where there is no radar surveillance (e.g. large areas of Africa and Asia) procedural separation replaces radar-controlled separation. Procedural separation means that every aircraft reports its position and by issuing the appropriate clearances, the separation is ensured by ATC. The situational awareness of the controller is clearly less in this situation compared to radar surveillance. The result is the use of larger margins and therefore less optimal flights as well as an inherently more dangerous situation.

A special form of procedural separation takes place over the Atlantic Ocean. Here so-called 'tracks' work similar to a railway system: aircraft are positioned, already separated, at the beginning of a track with intervals of 10 minutes and will arrive at the end of that same track. So lateral route changes are inhibited over the ocean. These tracks are changed regularly based on the weather situation and labelled for reference. The distance between the tracks is one degree latitude, meaning 60 nautical miles. The vertical separation used to be 2000 ft but has recently been reduced to 1000 ft over the Atlantic Ocean due to the increased traffic density between Europe and North America. This enormous difference between the vertical and horizontal separation is due to possible (different) navigation errors caused by the inertial navigation system during the long flight over the ocean, while the altitude is determined via the same reference (air pressure) ensuring a very accurate estimation of the *relative* vertical position. Using satellite navigation to enhance and replace inertial navigation might improve the *relative* lateral navigation and provide a way to reduce the distances between the tracks.

Under radar coverage, traffic flows are normally structured into airways. Airways originally consisted of routes flying from one beacon to the next one. In the old days, this was the easiest way to navigate under IFR. Although today's navigation equipment no longer requires flying from one beacon to the next, the airways are still in place. One reason for this is that a structured traffic pattern enables one controller to monitor a complete sector. Possible separation problems are limited to intersections, aircraft changing altitude or overtaking each other in an airway. Apart from this benefit there are clearly some drawbacks as well: (1) the airways might not be the most optimal or direct route, (2) the local traffic density is artificially increased by concentrating the traffic lines instead of using the full airspace, (3) flying on the same route might inhibit flying the optimal flight level or speed as a result from the traffic concentration in the airway.
When the traffic density is low (e.g. during the night) aircraft are often cleared for direct flights to a waypoint further along the route.

The air traffic controller's highest priority is safety. Most of the time actions are based on preventing conflicts far before they could become imminent. For instance keeping two aircraft that are flying in the same airway in the same direction at a different altitude (always a value rounded to a multiple of 1000 feet) even when they will not overtake each other, ensures he/she will not have to monitor for a possible conflict between those two aircraft. If not adequately anticipated, more than one dangerous situation might develop simultaneously, all of which might require instantaneous action. The preventive actions allow the controller to keep his workload at an acceptable level even during high-density traffic situations. The price for this safety is the less than optimal airspace usage.

2.2 Free Flight concept

Though currently relatively safe, the separation concept as described in the previous section is often not the most optimal way of flying from an airline point of view. When the traffic situation allows it, the controller will allow the traffic to optimise their flight based on their requests. Airlines would prefer a more optimal way of flying with respect to fuel and time within the safety margins. Self-optimisation therefore might provide a more optimal, while still safe, traffic pattern. This idea forms the basis of Free Flight.

In Free Flight, the separation task is moved to the cockpit. By using a system that broadcasts not only identification and altitude but also the position, velocity and maybe even a part of the intended route, every aircraft could use these data to ensure the separation themselves. Such a system is becoming available: the so-called ADS-B (Airborne Dependent Surveillance - Broadcast). The effect of this system is that all aircraft in range receive the data broadcast by all other aircraft in the area. The data of the other aircraft are processed by an on-board system and this is displayed on the Cockpit Display of Traffic Information (CDTI). Several display formats are currently being developed to present the traffic situation to the crew in an optimal way.

Free Flight might also provide a more efficient airspace usage for instance over the ocean or areas without radar coverage and maybe even in the areas currently controlled using radar. In general (except maybe in the terminal area around airports) the separation assurance method as described above, and not the airspace volume itself, is the limiting factor on capacity.

ADS-B could potentially be used to perform airborne separation, the key element of the Free Flight concept. However, several design choices need to be made regarding how the concept should be implemented. Within the conceptual design phase of this study several choices have been made that formed the basis for the definition of Free Flight in the remainder of the study: These choices will be discussed in the next chapter.

3 Free Flight Initial Conceptual Design

3.1 Introduction

In commissions, working groups and panels that deal with Free Flight a lot of time is spent on discussing the operational concept. How much of the separation task and separation responsibility should be transferred to the airborne crew? What are the system requirments of the tools? For how long should this be? For which flight phases? Should every action be co-ordinated with the controller? These questions are not easy to answer. Many factors influence these discussions including politics, legal aspects and interests of authorities and unions. In the NLR Free Flight study several choices have been made, which would be beneficial for the meaning of the results of the study and not necessarily the direction one should proceed in. The factors mentioned above did not influence the choice within this study but will in reality. The sections in this chapter deal with these questions and describe the choices made at the beginning of the study.

3.2 Airborne Separation

One of these choices was to investigate Free Flight with full airborne separation. This means Air Traffic Control is no longer in control of the separation assurance process but the aircrew is. In this scenario the aircraft are equipped with sufficient equipment to perform separation assurance autonomously. The quality of ground based air traffic control varies enormously globally. Investigating a concept that requires a high degree of interaction between equipment on the ground and in the cockpit will limit the possible application. A global concept should therefore preferably be independent of ground equipment. An added advantage is that the concept can be tested and applied in areas without radar coverage first where an immediate benefit is to be expected in terms of the airspace capacity in relation to the safety.

Taking into account that air traffic control is normally responsible for a ‘safe and efficient traffic flow’, one might question whether the resulting Free Flight traffic flow will be efficient. This is in fact related to the very basic question whether a central controlling node is required for an overall optimisation. The only way to find out whether this central controlling element is required is to try it without in simulations both off-line (no human-in-the-loop) and on-line (with humans-in-the-loop).

Not having a central element requires a common set of so-called rules-of-the-sky. They could be used by the crew or electronically implemented in a system. The possible sets of rules can be divided in two classes: with right of way (‘priority rules’) or without right of way(‘co-operative rules’). When applying rules, it might require a mechanisation of some kind of arbitration to enforce the rules. This could be implemented as a ground-based station, listening to, monitoring and recording the ADS-B position messages of the aircraft and registering anomalies. These anomalies include breaching the rules like non-co-operative manoeuvring, turning into short-term conflicts, reacting at the last moment, etc. Another option, for instance for areas with no ground stations, would be to record the last few hours of received and transmitted ADS-B messages on-board allowing analysis of incidents.

Without these measures, not obeying the rules and relying on for example the fail-safe aspect of a co-operative concept (= forcing the other conflicting aircraft to manoeuvre) might be beneficial for the execution of the flight, since this yields some fuel and time benefits. This might therefore be tempting in a commercial situation. This is however not specific to Free Flight. Today not obeying to air traffic control (or late) or declaring an emergency will also yield these benefits. As long as there is a mechanism that allows checking for any breach of the rules, this does not have to be a hurdle for the introduction of airborne separation assurance.

3.3 Tools

With today's cockpit technology, Free Flight with airborne separation assurance would probably be unsafe in IMC. Depending solely on radio calls and visual acquisition of traffic is not sufficient for airborne separation without excessive margins, which in turn would inhibit an efficient use of airspace. Even in good visibility (VMC) only in low traffic densities, during the approach, slow speeds and the high amount of radiotelephony might allow this. To perform Free Flight safely and efficient, in low visibility avionics modifications are required to enable the crew to view traffic, to detect conflicts and to solve the conflict efficiently.

The extra tools required are:

- communication system to receive and transmit aircraft identification, position, velocity and some auxiliary data periodically, like the Automatic Dependence Surveillance Broadcast (ADS-B) system
- Cockpit Display of Traffic Information (CDTI)
- Conflict Detection module (CD)
- Conflict Resolution module (CR)
- optional: auxiliary tools aiding the pilot in maintaining traffic awareness

These tools together form the Airborne Separation Assurance System (ASAS). This function can be integrated in the flight management system or separately installed.

The ADS-B receiver receives the traffic data. These data are at least the identification, position and velocity vector of the aircraft. The ADS-B messages could also contain flight plan data. The conflict detection module checks for possible problems using the ADS-B received data. The resulting conflict data are then transferred to the conflict resolution module, which calculates the advised resolution manoeuvre. Traffic data, conflict data and resolution data are all shown integrated on the Cockpit Display of Traffic Information (CDTI). The traffic information display does not have to be a dedicated display but is typically integrated in the navigation display.

In figure 3.1 an overview of a basic ASAS system architecture is given.

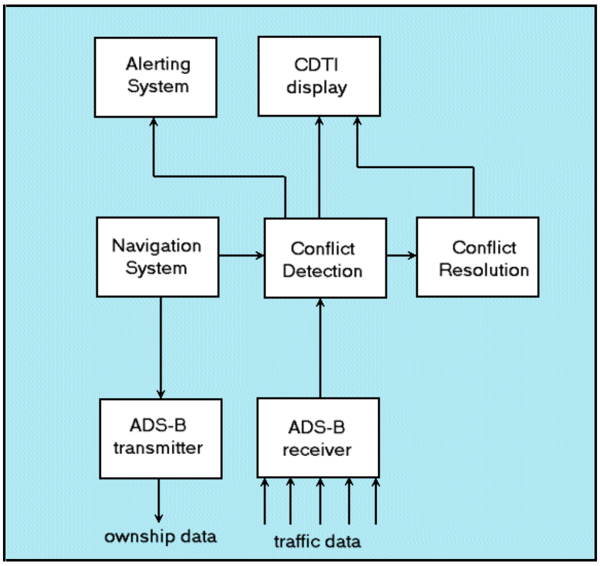

figure 3.1 ASAS system architecture

In the case that existing transmitters and receivers are used, a software modification could be sufficient for a glass cockpit. At the other extreme, for general aviation a simple device including a LCD display, GPS (for position and ground velocity) and ADS-B transceiver could be sufficient.

3.4 Priority and Resolution coordination

When establishing the rules of the sky, one important choice is which type of rules should be used: priority rules (using the 'right of way' principle) or co-operative rules (in which both aircraft maneuver). Analogous to the rules-of-the-road, priority rules only establish which aircraft has right of way and which aircraft has to manoeuvre. This obviates the need for further co-ordination, since counteracting manoeuvres are not possible when only one aircraft manoeuvres.

Priority rules decide which aircraft should move and which aircraft should not manoeuvre. This can prevent the effect that is often observed when two pedestrians meet. Both move in the same direction, creating an impasse. Unlike pedestrians, aircraft can not "wait". To avoid counteractive behaviour rules are required to co-ordinate the maneuver or to establishing a priority.

Several studies have used priority-type rules. However, NASA Ames has found in a simulator study[6], that crews, even when they had right of way, felt uneasy when waiting for the other aircraft to resolve a conflict. Consequently, they would often initiate some resolution manoeuvre, although they did not have to. This means there clearly still is a need to co-ordinate and confirm the agreement on the priority situation even in unambiguous situations. Without this co-ordination, using priority rules might not be acceptable to pilots. This means the priority

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[6] Free Flight and Self-Separation from the Flight Deck perspective, Sandra Lozito et al, ATM '97 paper, June 1997

rules may still require co-ordination, even though they are aimed at replacing this co-ordination.

Another drawback of using priority rules is that this takes away a fail-safe element, which is present in a non-priority system. Assume both aircraft manoeuvre co-operatively and monitor the situation while resolving the conflict. This would mean both aircraft manoeuvre at the same time and one aircraft could compensate when the other aircraft fails to execute the resolution manoeuvre, due to a non-nominal situation like a system failure.

When both aircraft manoeuvre there is a risk of counteracting manoeuvres. Ideally, this should be avoided without *explicit co-ordination*. By implementing compatible resolution rules in the conflict resolution advisory this can be avoided as long as the crew does not manoeuvre opposite to the direction indicated by the conflict resolution module (*implicit co-ordination*).

Negotiation and explicit co-ordination, either by humans or computers, should be minimised for several reasons. It would make the system more complex and prone to failure when the co-ordination fails. The extra complexity would also make the process less transparent to the crew. Therefore it becomes harder to monitor the process. In addition, a more complex system with co-ordination/negotiation provides problems for the global compatibility.

Similar compatibility problems arise with the use of flight plan data. Different brands of flight management systems are nowadays not compatible in the way trajectories are stored, constrained and generated. A standard flight plan format would be required in case of the exchange of flight plan information. This data might require a high bandwidth in high-density traffic scenarios.

In general, it is assumed the look-ahead time for conflict detection will be so large that using flight plan data is inevitable. Initially this was also the view in this study, though all the advantages of not using flight plan data suggested that this option justified exploring a concept based on state data only. Due to the distributed nature of airborne separation, Free Flight research typically needs a lot of simulation to avoid jumping to conclusions. In this study a concept not using any flight plan data has been investigated.

At this stage and based on these observations, the following choices were made for the initial conceptual design:

- Both aircraft should resolve conflict co-operatively, allowing a fail-safe mechanism if one of the aircraft fails to execute the resolution manoeuvre
- Priority rules should be avoided
- Negotiation and/or co-ordination should be minimised
- System complexity should be minimised to avoid compatibility problems
- Exchange of flight plan data should be used only when required, but the possibility of avoiding this exchange should be studied.

3.5 Flight Phase and Airspace

The way a flight is constrained differs per flight phase. During a descent with idle power it is not possible to descend with a higher rate of descent, without sacrificing the flight efficiency by adding drag (e.g. spoilers). In the same way it is not possible to accelerate in a climb with already maximum power without losing airspeed. These constraints influence the applicability of airborne separation assurance. For example during final approach, aircraft might need to know the sequence in which they have to land. The runway forms a single resource for all airspace users. This central resource therefore might need central co-ordination. Per flight phase, the operations differ.

The main topic of the study is airborne separation. If this is feasible at all, it is expected to be feasible in the cruise phase. Therefore, the focus for the conflict detection and resolution has been on upper airspace in the first phase research. This airspace does contain climbing and descending traffic but most of the traffic will be cruising. In a mature free flight environment with freedom to fly at any level, this means during cruise the aircraft will continuously try to fly at the optimal altitude. The nominal altitude increases as the weight of the aircraft decreases due to fuel consumption. The result is therefore a very shallow climb, known as the cruise-climb. Only special weather situations like the jetstream can favour another altitude.

If airborne separation is shown to be feasible in this flight phase, the research will focus on applicability in other flight phases. Typically, Free Flight Airspace will be limited by an altitude and/or distance to the destination airport will probably result from this. This will allow an airspace architecture as shown in figure 3.2: managed airspace around the airports and Free Flight airspace in between. This Free Flight Airspace might contain corridors for unequipped aircraft. Special Use Airspace (SUA) will still be in place inhibiting complete direct routing.

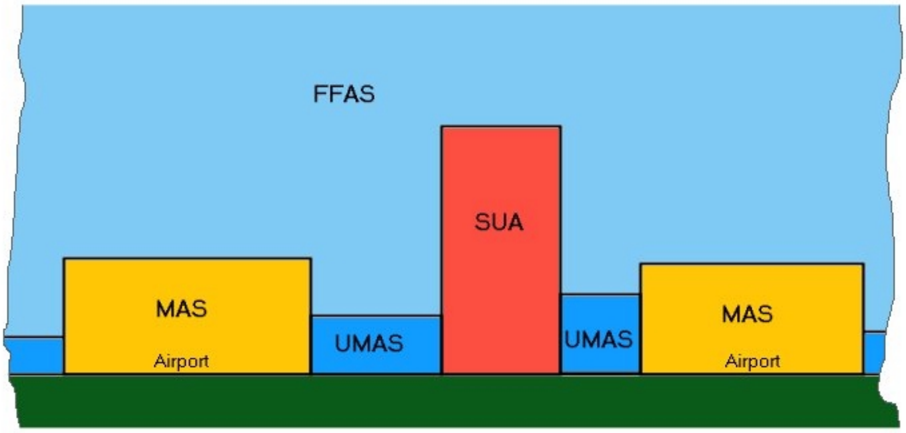

figure 3.2 Eurocontrol ATM 2000+ airspaces: Managed Airspace (MAS), Unmanaged Airspace (UMAS), Special Use Airspace (SUA) and Free Flight Airspace (FFAS)

Free Flight Airspace is already designated in this way in the document that describes the future European ATM system[7] and in several documents containing recommendations of the RTCA Special Committees[8] and other advising committees.

To avoid transition problems when introducing Free Flight, applying Free Flight over the Atlantic Ocean or Pacific Ocean should be considered first. The track system for procedural separation allows unequipped aircraft to fly conventionally on routes known to the equipped aircraft. Assigning Free Flight Airspace here first will immediately be beneficial and can be used to build trust in the system. The traffic density over the Ocean is low compared to traffic over Europe and the US East coast.

3.6 Zones and Separation minima

In the original RTCA Free Flight[3] document, two zones have been defined: a protected zone and an alert zone (figure 3.3).

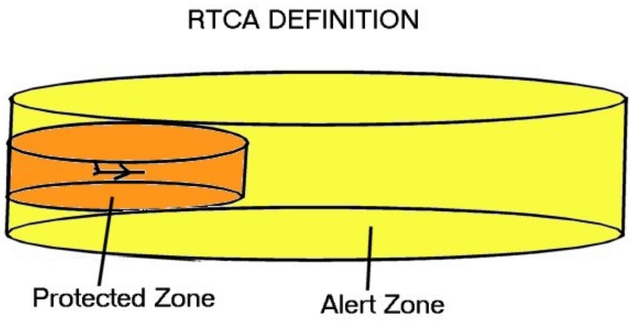

figure 3.3 RTCA definition of zones

In the RTCA definition, the protected zone is the zone that should not be touched by the protected zone of other aircraft. It is a 'hockey puck'-shaped zone determined by the position determination accuracy. The radius is half the required separation minimum. The height is equal to the required separation.

In this project, the protected zone is defined slightly differently: It is defined as the zone that should remain clear of the other aircraft. This makes the zone twice as big as in the definition above (in case of a cylinder). The radius is then equal to the required separation. The height of this zone is twice the required vertical separation (figure 3.4).

Operationally there is no difference. The advantage of this definition is that it is easier to handle by the crew, the algorithms and the display designers. The

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[7] ATM Strategy for 2000+, EATCHIP Doc: FCO.ET1.STO7.DEL02, Issue 2.0, 1/05/98

[8] Operational Concept for Conflict Detection & Resolution, RTCA SC-186, CD&R Working Group

conflict resolution problem is now changed into the problem of a point mass avoiding obstacles with a certain size in a 4 dimensional space.

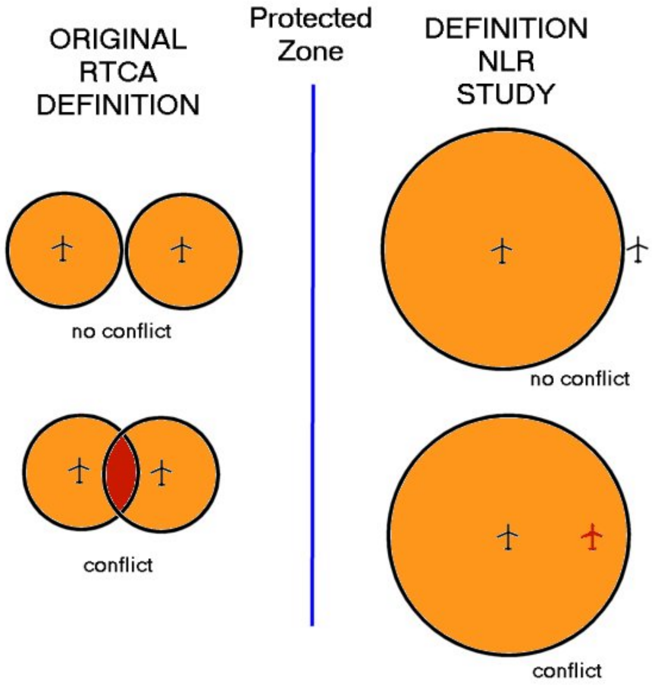

figure 3.4 Same situation with two definitions of protected zone.

In the RTCA definition, the alert zone is used to indicate a condition requiring intervention. The size of this zone is determined by aircraft speed and performance and by the CNS/ATM situation. The zone is also determined by the look-ahead time. The idea is that this alert zone spans that part of the airspace where the ownship could be within the look-ahead time.

In this study, the only alert zone that exists is the so-called look-ahead time. Its value is determined by the quality of the path prediction, the resulting number of alerts and the stability of the traffic situation. The limited ADS-B range also poses a physical limitation in the order of 100-180 nm (in case of loose of sight).
Using the 100nm means with today's cruise speeds that the maximum guaranteed look-ahead time based on the worst case (head-on conflict) is about 5 1/2 minutes. In this study the look-ahead time has been set at 5 minutes.

The protected zone in this study is defined as cylinder with a radius of 5 nautical mile and a height of 2000 ft. This reflects the currently used separation minima of 5 nautical mile horizontally and 1000 ft vertically. These numbers are based on the accuracy of radar tracking. Therefore, they may not be applicable to the Free Flight situation using the navigation data as sent out by the aircraft with ADS-B. If the navigation performance is better, an accuracy of 1 nautical mile is no longer uncommon, this could probably be decreased. Decreasing the protected zone will increase the capacity of an airspace under Free Flight conditions. In this study, the current 'radar'-values (5 nm and 1000 ft separation) are still used to be able to separate the effect of airborne separation from the effect of ADS-B based surveillance and to be able to use today's situation as a reference.

The odd, extremely flat shape of the protected zone is in fact a strong argument for the use of ADS-B. The relatively small vertical separation, as used by ATC today, is caused by the fact, that ATC uses the altitude as determined by the aircraft that received via mode-C. Although the barometric altitude may not be correct, both aircraft use the same reference and therefore the relative altitude can be determined with a high accuracy. If the lateral position is also determined via the same reference, for example GPS or the same ground based navaid, the relative lateral position will also be more accurate. In a way GPS is turned into differential GPS, even over the ocean, getting more accurate as the aircraft get closer to each other. This navigated position is sent out via ADS-B, thereby improving the lateral surveillance in much the same way as the vertical separation already is. The 1 to 30 ratio of vertical to horizontal separation minima therefore indicates the apparently accepted advantage of relative navigation, which is used of airborne separation.

Both the airborne separation and the increased surveillance accuracy are a result of the use of ADS-B. The benefits in terms of airspace capacity of equipping aircraft will therefore probably be more than indicated by this study that investigates only the effect of airborne separation.

3.7 Traffic Density

In the RTCA document, Free Flight is only foreseen for airspace with a relatively low traffic density. This assumes that a high traffic density or complexity requires central co-ordination.

The traffic densities used in this study often refer to the average Western-European traffic density. This refers to an average number of aircraft per area. This is been estimated as about 13 aircraft per area of 10,000 nm^2. One source for this is a scenario used in the PHARE[9] program, which was chosen to replicate an average Western-European traffic density. This was confirmed by a paper presented at the CEAS Free Flight symposium[10] describing the traffic density over Western Europe above 10,000 ft. These data came directly from Eurocontrol as recorded in the spring of 1996. Another Eurocontrol report[11] describing traffic simulations based on real data mentions a flow of 40 aircraft per hour in an area equal to a circle with a radius of 175 nm for upper airspace. Using an average ground speed of 500 nm/hr at these high altitudes, this indicates 14 aircraft per area of 10,000 nm^2 and thereby confirms the order of magnitude.

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[9] Programme for Harmonised Air traffic management Research in Eurocontrol – see also http://www.eurocontrol.fr/public/partners/phare/public/qds.cgi

[10] Trajectory Predictability and Frequency of Conflict-Avoiding Action – S.A.N. Magill, ATC Systems Group, DERA UK, CEAS Free Flight Symposium 1997

[11] Report of Continental RVSM Real Time Simulation – N.B. Sylvester-Thorne, Eurocontrol Experimental Centre Report 294, February 1996

In the flight simulator trials, airline pilots have flown in densities up to three times the average Western-European traffic density of 1996. Traffic densities for Western Europe are predicted to grow 2.5 times in twenty years. Scenarios with ten times the Western-European density have also been flown in the flight simulator.

The resulting conflict rates from these sources as well as from traffic simulations based on these densities, is about once per hour above 10,000 ft[12]. In the flight simulator trials this has been increased, both to due the higher densities as well as artificially for practical reasons, up to nine times per hour.

3.8 Role of Air Traffic Control

In the case of airborne separation, the separation task is moved to the cockpit completely. There is a range of concepts with shared responsibilities between complete ground controlled separation and airborne separation. These include techniques like station keeping, merging, collaborative separation, etc. These are however not the focus of this study. In the operational scenario that forms the basis for this study, there is no air traffic control and no radar coverage required in the Free Flight airspace.

3.9 Initial Conceptual Choices

Based on the goal of this study and the considerations described in the previous sections, the following choices and assumptions were made:

NO ATC TASK IN FREE FLIGHT AIRSPACE
An extreme form of Free Flight was chosen with no air traffic controller on the ground. The idea behind this concept is to probe the limits of the concept. By first shifting all tasks to the cockpit to where problems might occur, it will also show where ATC might be needed.

ALL AIRCRAFT FULLY EQUIPPED IN FREE FLIGHT AIRSPACE
All aircraft in the scenario are assumed to be fully equipped with ADS-B transmitter & -receiver and conflict detection & resolution advisory modules. The transmitter sends the aircraft's position and other information needed by the conflict detection, maybe even intent knowledge, to all other aircraft. The ADS-B receiver collects all the information of the traffic within a certain range in the free flight sector.
The scenarios of mixed equipage represent the transition to Free Flight and pose specific problems, which have been addressed in the second flight simulator trials. For the feasibility of the concept the far (?) future is studied in which the transition has taken place.

DIRECT ROUTING (horizontally & vertically)
All aircraft use direct routing and cruise climb without steps. So both horizontally and vertically the flight is 'free'. Considerations for this choice are similar to the

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[12] On the Applicability of Free-Flight Mode in European Airspace – Pierre Faure, Vu Duong, Eurcontrol Experimental Center, ATM'98 paper

NO ATC choice: probing the limits. It is also one of the benefits of applying Free Flight.

UPPER AIRSPACE ONLY

In the first phase of the study, the focus is on the upper air space to concentrate on general conceptual problems. Somewhere in the descent, a transition to controlled flight is foreseen. Where and how that transition should be implemented is not addressed in the first phase of the study. Highest gains for direct routing through applying Free Flight are expected in upper airspace, so the feasibility for this airspace is a worthy result in itself.

SEPARATION MINIMA EQUAL TO TODAY

A conflict is defined as an intrusion of the protected zone. The protected zone will be dimensioned using current ATC standards to be able to relate to existing traffic densities, even though there are indications the protected zone could be smaller. The definition of protected zone & alert zone, as it is used in this concept differs from the RTCA definition as already mentioned in the previous chapter.

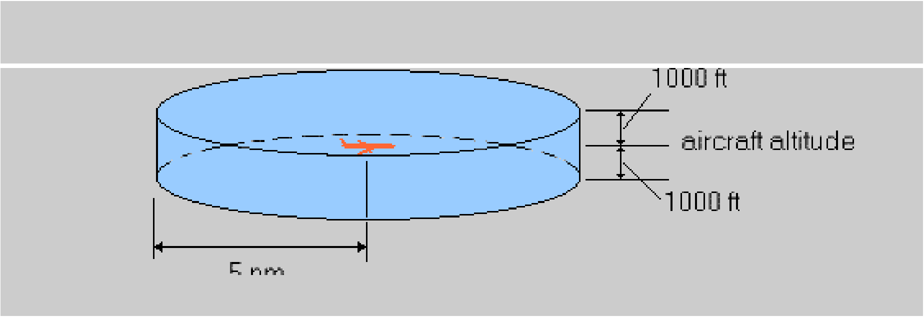

figure 3.5 Dimensions of protected zone, in reality the shape is more like a coin than like a hockey puck

The protected zone is the zone never to be entered by any other aircraft. The task of the conflict detection module is to predict an intrusion of the protected zone. This protected zone was chosen to reflect current ATC separation standards: 5 nautical mile radius and a height of 2000 feet (altitude-1000ft to altitude+1000 ft, see also figure). This means the ratio diameter to height is about 30 to 1. This zone is often referred to as the "hockey puck" but the shape is actually flatter than most coins.

LOOK-AHEAD TIME AS ALERT ZONE

In this conceptual design the alert zone does not exist in a purely spatial from. There are two aspects of the alert zone: interrogation & alerting. The interrogation is limited to a (large) maximum number of aircraft and within a certain (large) range. These limits are rarely limiting the airborne separation function when chosen large enough. (Limits used in this study are: a range of 100 - 200 nautical mile, maximum number 300 aircraft for system, 100 aircraft for traffic display) The alerting of a detected conflict is limited by the look-ahead time. This look-ahead time is the maximum time-to-intrusion for which a conflict is detected. This look-ahead time could be regarded as a time-based implementation of the alert zone and has been determined in the off-line traffic simulations. It has been set to five minutes. Two levels of urgency were established: amber for which the loss of separation would occur between five and three minutes ahead, and red for a loss of separation within three minutes. In worst case geometries with high cruise speeds, conflicts can no longer be solved laterally without exceeding limits that would require manual control and decrease passengere comfort, if the loss of separation occurs within 2 minutes.

CONFLICT RESOLUTION ADVISORIES BY SYSTEM
From the start in this study it was assumed a resolution advisory system, comparable to TCAS, is necessary for two reasons: implementing the rules-of-the-sky in the system forms a common element in the system, which aids a consistent overall system behaviour, and to ensure the workload of the crew stays within acceptable limits.
This is a feature sometimes not foreseen in experimental concepts of airborne separation. This obviously has a great impact on the workload introduced in the cockpit and therefore is seen as critical by the authors for the acceptability of the concept by the pilots community.

RULES-OF-THE-SKY CHOICE
For the rules-of-the-sky no clear choice had been made by the aviation community. These rules were required to be able to implement them in the conflict resolution system and generate the resolution advisories of the system. It is therefore also sometime referred to as Electronic Flight Rules (EFR). These rules are commonly referred to as conflict resolution algorithm by the Free Flight community, stressing the electronic implementation of the rules.
A thorough study of other free flight studies, similar to the study by Jim Kuchar[13], and ATM studies yielded a number of possibilities for the conflict resolution method. No clear indication was found of the relative value of these methods. Therefore it was concluded that off-line traffic simulations were needed to compare the different resolution in methods for the experiment. For these off-line simulation a tool called the Traffic Manager, has been developed.

3.10 Free Flight research questions

The most important single question underlying this study is:

Is Free Flight with Airborne Separation feasible?

To answer this question an incredible amount of issues need to be investigated. Some of the more important questions are (in random order):

GENERAL ISSUES

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[13] Kuchar, J. K. and L. C. Yang, "Survey of Conflict Detection and Resolution Modeling Methods", AIAA-97-3732, AIAA Guidance, Navigation, and Control Conference, New Orleans, LA, August 11-13, 1997.

Is Free Flight safe?
Is Free Flight acceptable to all parties involved (pilots, air traffic controllers, authorities, airlines)?
What are the costs and benefits of Free Flight in terms of operating costs, fuel, time and safety?
How to evolve from today's situation to a Free Flight environment?

HUMAN FACTORS ISSUES
What type of symbology should be used?
What will happen to the workload?
How should a traffic situation, conflicts and advisories to solve conflicts be displayed to the crew?
What is the role of the automation?
Will an Air Traffic Controller be able to take in case of a global emergency?

SYSTEM DESIGN ISSUES
What is the effect of changing the system from a centrally organized system to a distributed system?
What algorithm should be used for conflict detection and resolution?
Is a Free Flight traffic situation stable or will a cascade of events lead to a catastrophical situation?
What are the risks of bottle necks due to the lack of a centrally controlling element overseeing the overall situation?
What will happen if the traffic density increases? What is the limit from a system point of view?

AVIONICS QUESTIONS
Is all the airborne equipment for communication and navigation able to perform as required for the Free Flight equipment?
How to retrofit Free Flight equipment in today's aircraft?
What are the characteristics of ADS-B and which implementation should be preferred?

The NLR study aims to explore the Free Flight concept to answer most of these questions. The study has also provided a working concept together with design guidelines and prototypes of related systems and procedures. The feasibility mainly depends on how Free Flight is implemented, therefore a safe conceptual and system design is crucial. Just as important is to keep the system simple and transparent. Reducing the system complexity, and therefore the compatibility requirements, increases the feasibility enormously.

The operational concept as used in the NLR study hopes to achieve a simple, efficient and safe Free Flight concept. In the next chapters, this operational concept as well as some alternative approaches to conflict detection and resolution will be discussed.

4 Traffic Manager

4.1 Purpose

A tool that often will be referenced in most of the following chapters describing conflict detection and resolution, off-line trials and man-in-the-loop experiments is the Traffic Manager. The Traffic Manager is the program that has been used as an off-line traffic simulator, a scenario editor, scenario player, experiment manager station and data logging.

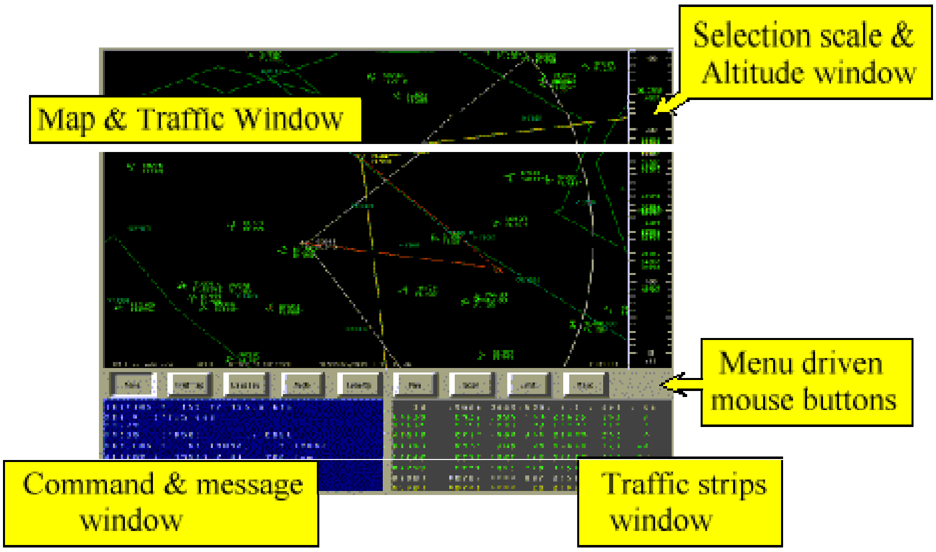

figure 4.1 Traffic Manager screen

The Traffic Manager program originated as an off-line traffic large scale traffic simulation. One of the essential elements of the Free Flight concept of airborne separation is the conflict resolution algorithm. Because of the interactive and parallel nature of the concept, the only way to analyse this is to simulate traffic patterns.

From earlier experiments a rudimentary real-time, six degrees-of-freedom traffic simulator was available. This traffic simulator could simulate 10 aircraft following prescribed heading, altitude and speed instructions. It was used to simulate traffic around the Research Flight Simulator (RFS) for the Data Link simulator trials. The simulated aircraft were visible in the out-of-the window view of the flight simulator. The aircraft model was no more than a kinematical model of aircraft motion. For the Free Flight study this traffic simulator was enhanced with a graphical user interface, optimised to be able to simulate 400 aircraft simultaneously, enhanced with BADA[14] performance models, flight management systems and fitted with pilot models able to follow a flight plan and detect and resolve conflicts. The program was first developed on a 486 PC and has been optimised to be able to simulate a large number of aircraft without overloading the CPU.

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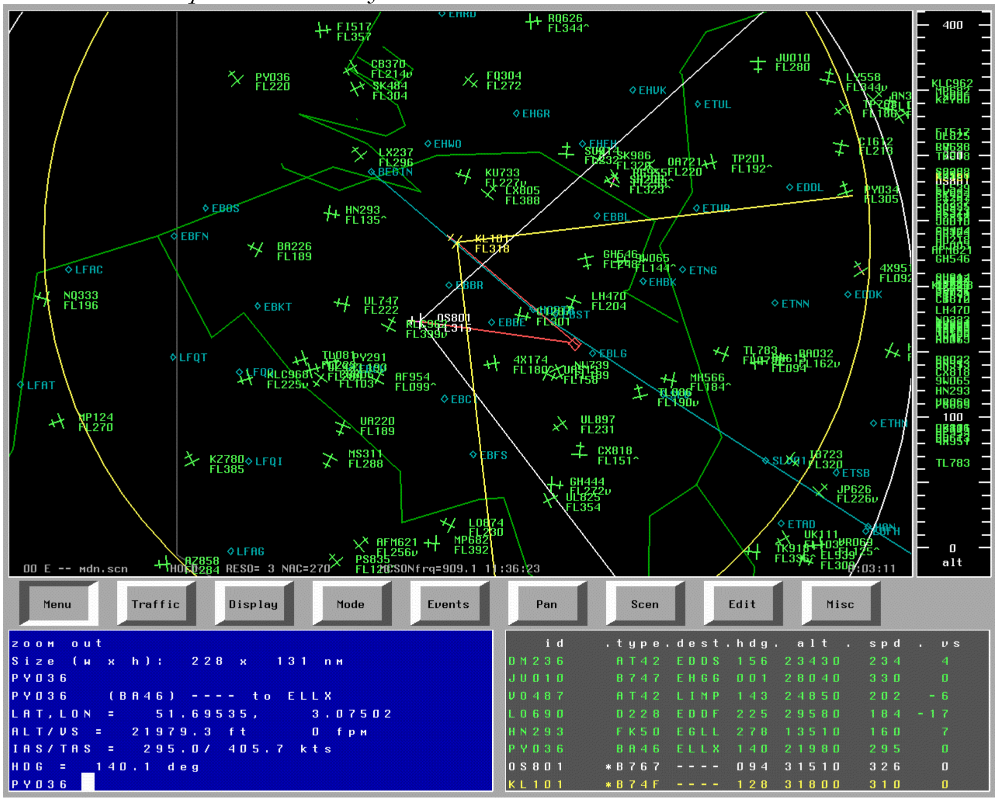
[14] User Manual for the Base of Aircraft Data (BADA) Revision 2.5, EEC Note 1/97, Eurocontrol, 1997

4.2 Features of the Traffic Manager

4.2.1 *Graphical User Interface*



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zoom out
Size (w x h):  228 x  131 nm
PY036
PY036   (BA46) ---- to ELLX
LAT,LON =    51.69535,      3.07502
ALT/VS =  21979.3 ft        0 fpm
IAS/TAS =  295.0/ 405.7 kts
HDG =  140.1 deg
PY036
```

```
    id      .type.dest.hdg. alt  .  spd  .  vs
DM236     AT42  EDDS  156  23430   234    4
JU010     B747  EHGG  001  28040   330    0
V0487     AT42  LIMP  143  24850   202   -6
L0690     D228  EDDF  225  29580   184  -17
HN293     FK50  EGLL  278  13510   160    7
PY036     BA46  ELLX  140  21980   295    0
OS801    *B767  ----  094  31510   326    0
KL101    *B74F  ----  128  31800   310    0
```

figure 4.2 Traffic Manager Graphical User Interface

The Traffic Manager's main screen is a map view on which the traffic data, the geography, navigation data are shown. This screen is also used to click on with the mouse to select aircraft, waypoints, beacons, airports, latitude/longitude positions, heading and areas. The map view can be panned and zoomed. The map window can also change to navigation display mode. In this mode, it shows the navigation display of a selected aircraft with the traffic, conflict detection and resolution and route information.

Below this view a row of multi-function buttons is available. The function of these buttons is completely configurable by the user. They depend on a menu structure described in the text file called 'buttons.dat'.

At the bottom of the screen are two windows: the command window and the strip window. The command window is an edit window and console, in which any command can be typed. After pressing ENTER this command is put on the command stack just as any command read from a scenario file, generated by the buttons or received via the network. These commands control the simulation. Implemented commands include traffic commands, display commands and simulation control. A click on the map window usually enters a value like a lat/lon position in a command, that is being edited in the command window. The system of button clicks and map clicks makes it possible to for instance create and control traffic without touching the keyboard. Also selecting a value for altitude, speed or aircraft type on the 'selection bar' next to the map view results in an entry in the command window. Any warnings or error message will also be displayed in the command window. The command reference in appendix C gives an overview of the commands. This list also provides a more detailed overview of the functionality available in the program.

4.2.2 *Scenario file recording and playing*

The first questions the user has to answer when starting the Traffic Manager is which scenario file to play and record. Playing and recording at the same time allow the cumulative editing of a scenario. In this way a taxi scenario has been developed with pre-scripted taxi-instructions. Also using background traffic and adding specific geometries uses the cumulative property of simultaneously playing and recording. The recording option enables the recording of commands to generate the scenario playback files. These scenario files were used for both the off-line comparisons of the different resolution methods as well as for the man-in-the-loop simulator experiments.

4.2.3 *Scenario Generation Functions*

The program includes the European navigation data and airports. Scheduling take-offs at airports and airspace entries at the border of a user defined experiment area enables automatic generation of realistic Free Flight traffic patterns over Europe.

4.2.4 *Environment Simulation*

This program has also been used for the man-in-the-loop simulator experiments to simulate a realistic traffic environment and control the experiment scenario. Events as weather, turbulence or failures can be recorded and triggered by the scenario files.

4.2.5 *Experiment Manager Station*

The graphical user interface allows monitoring of the scenario. Events can be introduced on-line as well as traffic. Traffic can also dynamically be handed over to a separate workstation running a flight simulation program. This allows the on-line adjustment of a scenario. The navigation display mode also enables the manual control of an aircraft in the scenario. Data logging can be monitored and controlled during the experiment. Remarks or other markers can be added to the log files while running the experiment. The configuration and other selections can be controlled by the scenario file but when required overruled by the experiment manager.

4.2.6 *Aircraft Models*

The aircraft models contain performance models, autopilot models, a flight management system and a rudimentary pilot model. Over 200 different aircraft types are supported. The pilot model contains the reaction times and scheduling effect. The update rate of the aircraft model is increased to match at least ten times per second when the aircraft is close to the 'master' simulator. This allows a visualisation of the traffic in the out-of-the-window view. Any routes defined in the scenario file are automatically loaded in the flight management system of a flight simulator that 'logs on' to the traffic manager.

4.2.7 Fast-time simulation

A real time factor can be set during run-time. Several modes allow both fixed time step as well as maximum update rate. The internal frequency related to the simulation time decreases when running fast-time due to the system's computation power and graphical performance. This frequency is shown at the bottom of the map screen. Monitoring the internal frequency on-line allows tuning the simulation to the specifications of the platform. Fast-time simulations also allow visualising moving patterns.

4.2.8 Large Scale Traffic simulations

Though the program is perfectly capable of simulating one-on-one conflicts, it was designed with large scale simulations in mind. The Traffic manager is capable of simulating up to 400 aircraft simultaneously. By switching on the automatic delete function when an aircraft lands or leaves the experiment area, even much more flights can be simulated in one scenario. This allows the simulation of extremely crowded sectors as well as the traffic around the sector that might be in reach. It also enables investigating the effect of extreme geometries involving 'walls' or 'block' consisting of a large number of aircraft. These scenarios are used to investigate 'flock' behaviour of traffic in an extremely busy airspace.

4.2.9 ASAS Test Platform

The program is very useful as an Airborne Separation Assurance System (ASAS) test platform.Various conflict detection and resolution algorithms have been implemented. Selection of the resolution algorithm can be part of the scenario file but it is also possible to select it during run-time. The ASAS indications in the flight simulator connected to the Traffic Manager are controlled by the ASAS module in the Traffic Manager.

4.2.10 Architecture

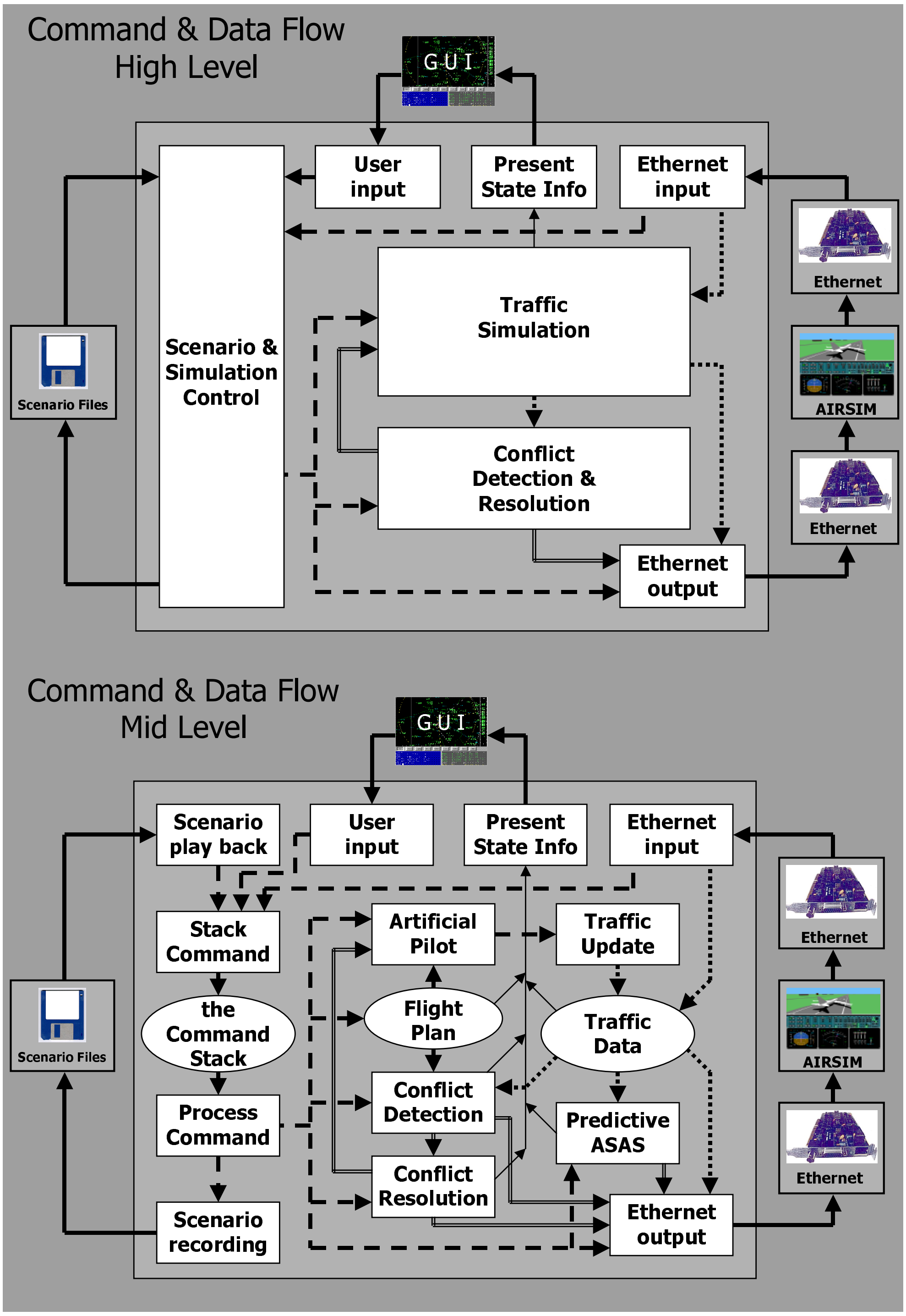

figure 4.3 Overview of architecture

The traffic manager program has a modular structure. A collection of modules is driven by commands derived from an internal command stack. This command stack is supplied with commands from various sources: the command edit window, a playback file, mouse buttons and external sources like consoles, simulators, etc. Modules can also issue commands to each other via the command stack. Next to the event driven part of the program, there is a time scheduled part: the aircraft models, pilot models, automatic scenario generation functions and conflict detection.

There are currently three versions of the Traffic Manager: a DOS version (is being phased out), a Windows (based on DirectX) version and a Unix (Iris GL) version. System dependent calls are all located in one source file with a limited size. This facilitates porting the application to any new platform.

4.2.11 Game domain

Game domains are servers connected to the internet allowing players of video games to participate in a multi-player game session via their internet connection. The same technology is currently being implemented in the Traffic Manager and in a compatible flight simulation program. This configuration aims at conducting experiments with a large number of pilots participating using PCs connected to internet. This allows the testing of the Free Flight concept with respect to human strategies in a commercial competitive environment via scoring systems.

5 Conflict Detection & Resolution

5.1 Introduction

From a literature and Internet survey, several Conflict Detection and Resolution (CD&R) methods were collected. For the conflict detection there were several options:

- State (position and velocity) based conflict detection
- Enhanced state (position, velocity and mode control panel) based conflict detection
- Route based (flight plan) based conflict detection

For the conflict resolution method three classes of methods were found:

- None (leaving it up to the pilot to change flight plan)
- Geometrical methods
- Numerical optimisation methods
- Genetic Algorithms

From the choices made in the initial conceptual design as described in chapter 3, it was decided to focus on the state based conflict detection with a geometrical resolution method (see section 5.2.2). Then to compare both options in a man-in-the-loop experiment, the route based conflict detection with a numerical optimisation resolution method would be implemented. Because of the effectiveness of the state-based system and the drawbacks of a flight plan based system (see chapter 3), this second step was never made.

The drawbacks of not using flight plan data seem to disappear when as an add-on the CD&R the so-called "predictive ASAS" is added. This provides additional data on the traffic situation to the pilot using only state-based data. This system is covered by chapter 9.

5.2 Choosing a method

5.2.1 Conflict detection

For the conflict detection three levels of intent were foreseen: (i) no intent information (ii) mode control panel (tactical) information (iii) route information.
However due to the more efficient usage of the sky when flying direct routes and optimal altitude the number of conflicts (defined as a predicted intrusion of protected zone within the lookahaead time, not a mid-air collision) already was very low when no conflict avoiding action was undertaken. Therefore, the required avoidance manoeuvres are so rare, that most flights are very predictable using current trend information alone. The accuracy of the prediction rarely changes when using track angle (no intent) instead of using route information (destination or next waypoint), because most of the times the intended route is the current track when flying direct routes. Especially with a typical look-ahead

time of five minutes, increasing the level of intent hardly improves the quality of the predictions. This notion was confirmed by the first off-line traffic simulation trials where the conflict detection & resolution already proved to be very effective without using any intent information. This of course would be different in the current ATC controlled situation where the airways might introduce sudden turns when passing a waypoint or where an altitude clearance introduces a sudden climb or descent.

To drop the requirement for intent information has huge advantages: conflict detection becomes more transparent to the pilots, reduced bandwidth of required communication, no need to solve issues concerning source and validity of intent information (FMS, MCP, separate devices), less modifications to the cockpit. Therefore, it was concluded it would be interesting to try whether the concept was feasible without using intent knowledge in the conflict detection module.

The conflict detection module now only has to look at the current state (position and altitude) and trend vector (ground speed, track, and vertical speed) to predict a conflict. Using vector calculations, the predicted minimum distance with other traffic is calculated. When less than the required separation and if the time of intrusion is within the look-ahead time, it is stored in the conflict database, together with time of intrusion, predicted positions of both own and other aircraft. This information is presented to the crew on the navigation display graphically, triggers an aural alert and is also passed on to the resolution module.
Note that when an airborne conflict detection module performs the conflict detection, each future conflict is detected twice (by both aircraft) and this means the conflict will still be detected when one of the conflict detection modules fails.

A conflict is defined as a predicted minimum distance in time-space, which is less than the required minimum separation distance. The conflict detection module only detects conflicts with aircraft for which the intrusion of the protected zone takes place in the near future. After several simulations with varying traffic densities this so-called look-ahead time was set at five minutes.

5.2.2 Resolution methods

As described in chapter 3, the option of no resolution advisory and the numerically optimised flight plan option were not further investigated in this phase of the study.

Two options remained:

- Genetic Algorithms
- Geometrical algorithms

The genetic algorithms option has been explored. Genetic algorithms are relatively new. The gene analogy is based on the effectiveness seen in the evolution of species. The idea is that applying the same mechanism that led to the evolution of animals and humans might also be an effective way to find a solution for complex problems. First, a random population of possible solutions, in this case manoeuvres or routes, is generated. Then a fitness function is applied to select solutions that are allowed to "breed". To evaluate this fitness function every solution in the sample has to be simulated yielding a high computer processor load. Mutations and crossovers are applied during the breeding of the next generation of solutions. Then the fitness function is applied again and the process starts all over. The population becomes fitter with every iteration (or generation). The fitness level of the fittest solution in the population can be used to decide to stop the process. This fittest sample is then used as the final solution. During this process, some random elements are present in the selection and mutation function to ensure a variety of solutions. Tuning the mutation and fitness function influences the solution to which the population converges.

Applying this method on conflict resolution has some important drawbacks. The process is not very transparent to the crew, since the random effects might have caused the direction in which the solution evolved. All members of the population need to be evaluated for all generations (typically 50 generations will be used). Therefore it is quite computationally intensive, while the high computing power in the cockpit is not as common as on the desktop computers. To make sure an efficient solution will result within a reasonable number of iterations (or generations), many restrictions need to be applied on the mutation process. This in fact removes the advantage of using genetic algorithms: finding a previously unforeseen solution. Very often the result of the restrictions is a very deterministic process, which results in the same solution as a less computationally intensive and safer old-fashioned mathematical algorithm.

After reading the literature on genetic algorithms, a group of experts on genetic algorithms at NLR was contacted that was looking at the feasibility of genetic algorithms assisting the air traffic controller. The demonstration of what had been developed for air traffic controllers showed that the effect of the 'genes' was very limited to ensure an effective solution. The result was a nearly deterministic process that only differed from a geometrical method in computing power requirements. This group was requested to develop a resolution module using genetic algorithms. In the end, no module has been produced because the tools developed so far were not mature enough for practical application.

Several geometrical methods for conflict detection and resolution were implemented in the Traffic Manager in the off-line study:

I. altitude step
II. cross product of speed vectors
III. extended VFR rules
IV. variations on TCAS manoeuvres
V. different implementations of the so-called voltage potential.

(i) ALTITUDE STEP & (iv) TCAS MANEUVERS

The altitude step calculates a required altitude to arrive on before the conflict occurs. By climbing or descending, the conflict is resolved. Via automatic negotiation, it is resolved which aircraft manoeuvres in which direction. This is similar to the TCAS II manoeuvres. Advantages of these methods are the effective manoeuvre, because of the shape of the protected zone (see chapter two). It also prevents large deviations from the route. Disadvantages of this method are the need for resolution co-ordination, which also requires extra hardware or sharing the same device as the TCAS module, and extra bandwidth. On top of that there is a clear lack of transparency: the pilot is out of the loop, event thought the look-ahead time of several minutes permits active decision making by the crew. Another disadvantage is that it only produces one solution in one dimension.

(ii) CROSS PRODUCT OF SPEED VECTORS

This resolution method is based on the cross product of the two vectors i.e. aircraft speed vectors. The resolution method uses the non-commutative property of a cross product combined with the result of the product to establish the direction of the adjustment in the aircraft's speed vector. Considering two speed-vectors for aircraft A and B respectively va and vb, the non-commutative property is the following: (va × vb = - (va × vb)). The effect of this is that both aircraft will manoeuvre co-operatively to prevent the conflict. The result of the cross product is a vector perpendicular to the plane defined by the aircraft's speed-vectors. This ensures an effective and clear resolution for all vertical and horizontal characteristics of the geometry of a predicted conflict. Of course there are singularities, where the cross product becomes zero: the exact head-on or exact head-tail conflict, which were covered separately to ensure an opposite sign of the avoidance manoeuvre for the aircraft involved.

The magnitude of the heading, vertical speed and /or speed adjustments depends on the distances from the aircraft to the predicted point of conflict, the size of the protected zones and the current airspeeds and not on the result of the cross product.

An advantage of this method is the co-operative manoeuvre and the transparency to the pilot. A disadvantage is that it only produces one solution in one dimension. Vertical conflicts are solved horizontally and vice versa.

(iv) EXTENDED VFR RULES

These rules basically use VFR-like system to judge, who has right of way. Eurocontrol Experiment Centre has looked in to this set of rules and constructed some variations[15], which does not only take into account the direction the other aircraft is coming from but also the current flight phase (climb, final climb, cruise, initial descent, descent) to judge which aircraft has right of way. There still is a certain freedom to choose the manoeuvre to avoid the aircraft. This complicates the automatic calculation of a resolution advisory. It needs an extra algorithm to decide upon the resolution manoeuvre. Therefore it was concluded this method could not be used on its own in an automatic resolution advisory system. Another disadvantage of the system is the concept of only one aircraft manoeuvring to avoid the conflict A typical human response of the crew who has right of way, is to still avoid the conflict instead of waiting for the other aircraft to manoeuvre. This is similar to behaviour of car traffic in cases where the right-of-way rule is not very obvious.

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[15] Duong, V. & Floc'hic, L. (1996). FREER-1 Requirement Document version 2.0. Bretigny, France: EUROCONTROL Experimental Centre

(v) VOLTAGE POTENTIAL LIKE

The voltage potential is an analogy, which compares traffic with electrically charged particles. Suppose all aircraft would be regarded as positively charged particles and the destination would be negatively charged. Summing all the repulsive forces of the traffic and the attracting force of the destination is a way to determine a vector, which maintains separation with other aircraft and will bring the aircraft to its destination. See figure 5.1 below.

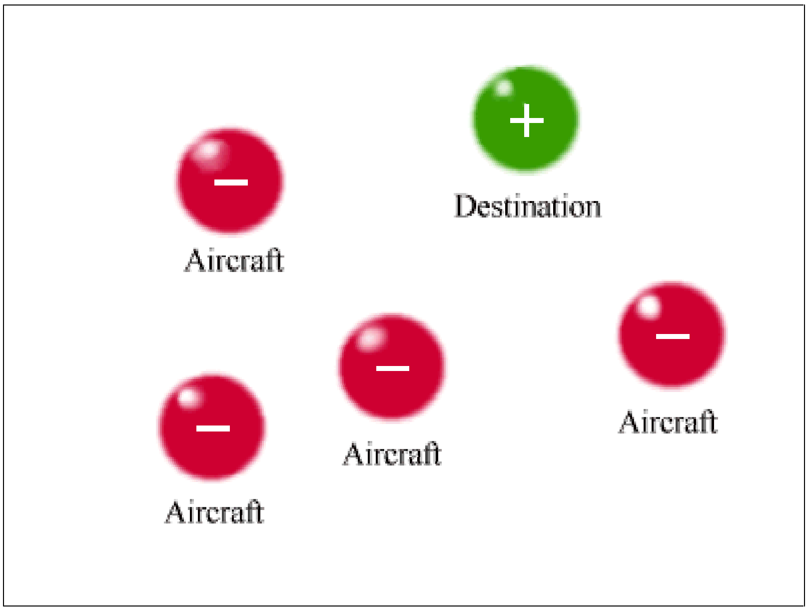

figure 5.1 Simplistic view of voltage potential

This resolution method is much too simplistic to be used in free flight. For example, no minimum separation is guaranteed and attraction to destination varies with distance to destination. It is also quite impractical to sum the repulsive forces of all aircraft even the ones with which no conflict currently is predicted.

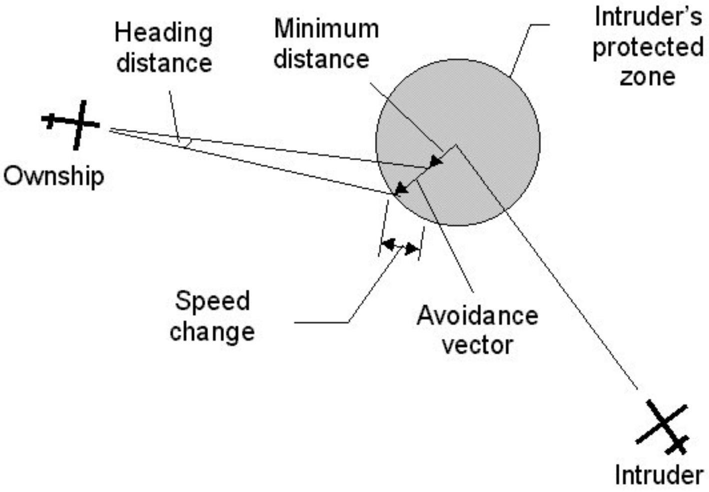

figure 5.2 Geometry of modified voltage potential resolution method

At the Lincoln Laboratory (MIT, MA, USA) an algorithm has been developed as part of an ATC tool, which retains the basic repulsion feature of the voltage potential but has a more pragmatic approach to solving conflicts (see Geometry figure). This method has been slightly modified for use in the airborne resolution module.

When a predicted conflict with traffic has been detected by the conflict detection module, the resolution module uses the predicted future position of own aircraft (will be called ownship) and the traffic or obstacle aircraft (will be called intruder) at the moment of minimum distance. The minimum distance vector is the vector from the predicted position of the intruder to the predicted position of the own ship. The avoidance vector is calculated as the vector starting at the future position of the own ship and ending at the edge of the intruder's protected zone, in the direction of the minimum distance vector. The length of the avoidance vector is the amount of intrusion of the own ship in the intruder's protected zone and reflects the severity of our conflict. It is also the shortest way out of the protected zone. Therefore, the own ship should try to accomplish this displacement in the time left until the conflict. Dividing the avoidance vector by the time left yields a speed vector which should be summed to the current speed vector to determine the advised speed vector. The result is an advised track and a ground speed. Using the three-dimensional vector, also an advised vertical speed is calculated. In case of multiple conflicts within the look-ahead time, the avoidance vectors are summed.

The same principle is used vertically. This means a horizontal and a vertical resolution manoeuvre is calculated. Because of the cylindrical shape of protected zone, these two resolution manoeuvres are independently completely solving the conflict. Both resolution manoeuvres are presented to the pilot allowing him to choose one (or both) maneuvers.

Each geometrical resolution method has its singularities in which the avoidance vector becomes zero or the sign can not be determined. Though this could be regarded as a purely theoretical problem, since in reality, noise will prevent these singularities to last long, numerical techniques like integer calculations or limited resolution in numbers could make it happen. This resolution method is no exception to the rule and several provisions are made to solve the singularities. For example in case of an exact head-on collision course on the same altitude with no vertical speed, both aircraft will be advised to turn right.

This resolution method assumes the intruder does not manoeuvre to avoid the conflict. This is part of the fail safe principle of the concept. Normally the intruder will also manoeuvre. Using the same principle will always result in an avoidance vector in the opposite direction because of the geometry of the conflict (compare the future positions with the charged particles). In this way an effective co-operation is achieved without negotiation or additional communication. This also means the initially calculated advised heading and/or speed changes will normally not be required. As soon as the conflict disappears, the current heading, speed and/or vertical speed can be maintained. This means both aircraft 'suffer' equally due to the conflict.

Both aircraft can choose whether they solve the conflict horizontally or vertically and they initially calculate the resolution advisory as if the other aircraft does not avoid the conflict. This means a total of four manoeuvres are available, which all are able to solve the conflict independently. Performance limits, weather, restricted airspace will sometimes inhibit one or two manoeuvres but rarely or almost never all four. When this would happen, the backup modes like TCAS could become critical or the crew monitoring the situation could negotiate an acceptable solution via radiotelephony. Using a look-ahead time of five minutes ensures there is time enough to identify the problem and solve it.

FINAL CHOICE: MODIFIED VOLTAGE POTENTIAL
In the off-line study using the traffic manager several methods for traffic resolution have been implemented: the Traffic Collision Avoidance System. TCAS like altitude step, a cross product of speed vectors and two different implementations of the voltage potential (one specially modified to manoeuvre without speed changes). Several were implemented and proved effective. Looking at route efficiency, time efficiency, fuel efficiency and other practical aspects related to displaying and executing the resolutions, the modified voltage potential method as described by Martin Eby[16] was chosen for the man-in-the-loop experiment. One modification on the description of Eby is that no longer the intended route is used to predict a conflict but rather the currently expected track based on current trend information.

5.3 ASAS software implementation

The traffic manager has been written in Fortran[17]. The ASAS modules are implemented as Fortran subroutines communicating via in-line arguments and so-called common blocks, grouping global variables. The different modules and the calling tree in the traffic manager are shown in the figure below.

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[16] A Self-Organizational Approach for Resolving Air Traffic Conflicts, Eby, Martin S. ,The Lincoln Laboratory Journal, MIT, Vol. 7, Nr. 2, 1994

[17] For more info on Fortran: “Fortran 77 for Engineers & Scientists”, Larry Nyhoff, Sanford Leestma, Prentice Hall, 1996, ISBN 0-13-363003-X

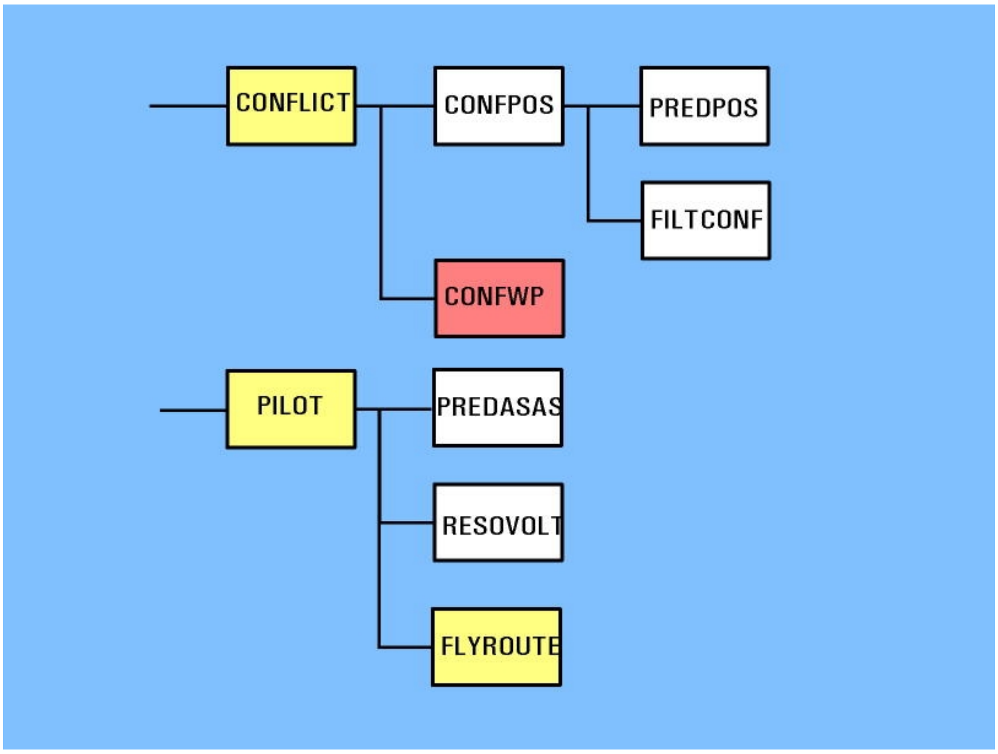

figure 5.3 Calling tree of ASAS modules in Traffic Manager program

The abbreviations in the calling tree are the names of the modules:

CONFLICT – Main module performing scheduling and selection of conflict detection method

CONFPOS – Conflict Detection based on position & velocity data. Build conflict database using traffic position and velocity data.

CONFWP – Conflict Detection based on flight plan data (see 3FMS section in chapter with alternative approaches)

PREDPOS – Module that predicts position of traffic for a given time

FILTCONF – Filter applied on conflicts to prevent conflicts for example due to turning aircraft at long range or due to data anomalies

PILOT – Scheduling and calling routine that also performs the selection of the resolution module to be called

PREDASAS – Predictive ASAS module (see chapter 9) only used for display of flight simulator

RESOVOLT – Resolution module containing the modified voltage potential algorithms variants

FLYROUTE – Flight Management and navigation model of aircraft

This calling tree represents the off-line simulation. Colour coding of the modules has been used to distinguish: traffic manager modelling & scheduling parts (yellow), ASAS modules (white) and later additions for other studies (red). The CONFPOS module contains the conflict detection that will be described in the next section. The RESOVOLT module is one of the resolution modules available in the traffic manager, containing various versions of the modified voltage potential resolution algorithm.

The data flow inside the ASAS modules is shown in the figure below.

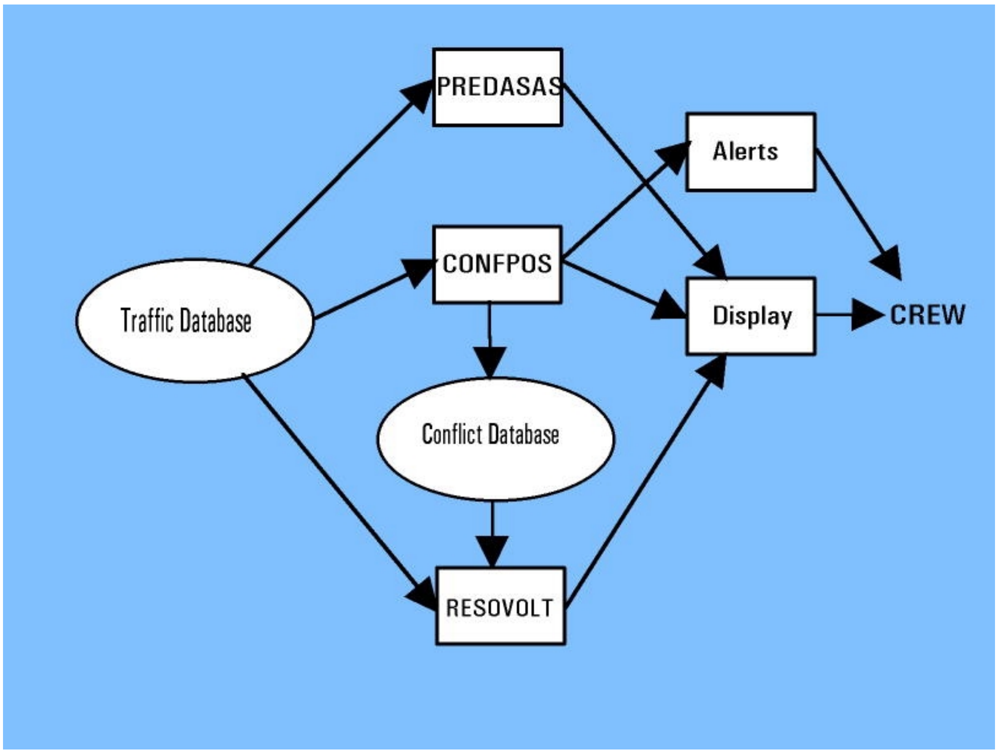

figure 5.4 Overview of modules in ASAS system

The input to the ASAS consists of data on the traffic within range derived from the traffic database:

- Traffic id (call sign)
- Position: latitude, longitude, altitude
- Velocity: ground speed, track, vertical speed

Other inputs are the position of the ownship (also from the traffic database) and the clock time.

The output of the conflict detection module (CONFPOS or CONFWP) is the conflict database for a conflict to be used by each aircraft of the conflict pair.

- Reference to the aircraft of the conflict
- Time to loss-of-separation
- Time to minimum distance point, the Closest Point of Approach (CPA)
- Positions of both aircraft at CPA: latitude, longitude, altitude
- * Velocities of both aircraft at CPA: ground speed, track, vertical speed (= actual in state based variant, only used in flight plan version)
- * Real waypoint index reference (for example 3.231) to route database (only used in CONFWP) to indicate position of conflict on flight plan

(* The last two items in the list are only used on the flight plan based variant used in the 3FMS project[18])

The minimum time to loss-of-separation is used to determine the alerting level by the alert module. It is also reflected by the colour of the conflict symbology on the display (see chapter 7).

The output of RESOVOLT is the resolution advisory:

- Advised track
- Advised vertical speed
- Advised ground speed

The output of Predictive ASAS is:

- Series of no-go track bands
- Series of no-go vertical speed bands
- Series of no-go ground speed bands

The actual algorithms and calculations are derived and described in the next sections. The predictive ASAS has been developed after the phase I man-in-the-loop flight simulator trials and is therefore described later.

5.4 Conflict Detection Module

The conflict detection module uses the position and velocity data from the traffic database. It calculates whether the separation minima (in this study 5 nautical mile and 1000 ft) will be violated within the look-ahead time. If so, it calculates the position of both aircraft at the closest point of approach (which is not necessarily within the look-ahead time) for the resolution module. Along with these data, time at which the separation is lost (protected zone intrusion time) and the time of the minimum distance point (or closest point of approach). The closest point of approach is clearly defined in the two-dimensional case as shown in figure 5.2. In the three-dimensional case, it is slightly more complex. The two-dimensional

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[18] 3FMS or Free Flight Flight Management System, a project funded by European Committee aimed at developing a future generation FMS. This project seeks to provide new capabilities, such as separation assurance algorithms, and develop existing capabilities such as terrain and weather databases. The simulation of technologies such as ADS-B, CPDLC and advanced Human Machine Interfaces (HMIs) will provide useful indications of the required performance of these technologies.

minimum distance point could even be outside the three-dimensional conflict interval (see figure 5.5). Therefore the conflict detection first calculates the conflict intervals for the horizontal and vertical dimension and then combines them (see figure 5.6).

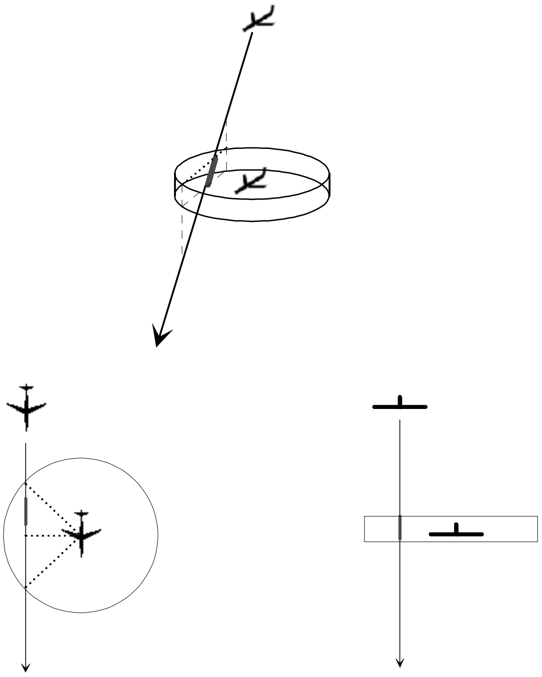

figure 5.5 Geometry of a 3D conflict with relative speed of intruder

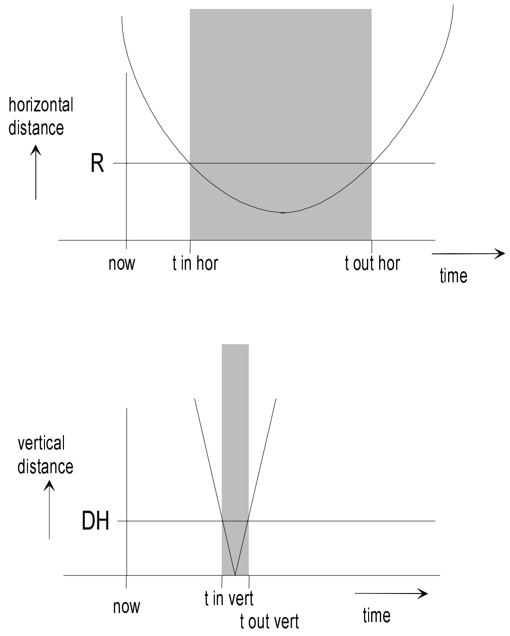

figure 5.6 Distance versus time diagrams horizontal and vertical

The conflict detection modules uses the following parameters:

DH = vertical separation, half the height of the protected zone (about 1000 ft)
R = horizontal separation, the radius of the protected zone (about 5 nautical mile)
$dtlook$ = look-ahead time in seconds, typically 300 seconds (5 minutes)

And the following input data from the traffic database:

lat_{own} = latitude of ownship
lon_{own} = longitude of ownship
h_{own} = altitude of ownship
V_{own} = speed of ownship (absolute, incl. vertical speed)
crs_{own} = track of ownship
vs_{own} = vertical speed
$lat_{intruder}$ = latitude of intruder
$lon_{intruder}$ = longitude of intruder
$h_{intruder}$ = altitude of intruder
$V_{intruder}$ = speed of intruder (absolute, incl. vertical speed)
$crs_{intruder}$ = track of intruder

And apart from this information, the module also needs a reference time which is also known to the resolution module, to enable storing the conflict data with an absolute time reference for loss of separation and minimum distance position.

t_{now} = clock time [s]

To calculate the conflict intervals the relative position and speed of the intruder is calculated in Cartesian co-ordinates for the vector calculations:

Calculate bearing of intruder: $qdr(lat_{own}, lon_{own}, lat_{intruder}, lon_{intruder})$
Calculate distance of intruder: $dist(lat_{own}, lon_{own}, lat_{intruder}, lon_{intruder})$

The calculation of bearing and distance in is performed in WGS'84 co-ordinates.

With the distance, bearing and altitudes the initial relative position $\underline{dx}$ of the intruder can be calculated:

$$dx(1) = dist \cdot \sin(qdr)$$
$$dx(2) = dist \cdot \cos(qdr)$$
$$dx(3) = h_{intruder} - h_{own}$$

The first element of $\underline{dx}$ is the relative position in the Easterly direction, the second element is the relative position in the Northerly direction and the third element is the relative altitude, positive up. The result is the right-handed reference frame with the origin at the ownship position. This reference frame will be used in the conflict detection calculations. In the conflict detection module, all elements of this vector are expressed in metres.

To calculate the relative speed, the velocities are first converted to Cartesian co-ordinates:

$$\gamma_{own} = \arcsin(\frac{vs_{own}}{V_{own}})$$
$$v_{own}(1) = V_i \sin(crs_{own})\cos(\gamma_{own})$$
$$v_{own}(2) = V_{own} \cos(crs_{own})\cos(\gamma_{own})$$
$$v_{own}(3) = vs_{own}$$

The speed vector of the intruder $\underline{v}_{intruder}$ is calculated in the same way.

Contrary to the speed in the traffic manager program, normally the speed derived from ADS-B messages will already represent the horizontal speed without the vertical component, alleviating the need for the cosine of γ in the first two formulae. Depending on the format the message may already contain the north/south and east/west velocity, facilitating the vector calculations.

The relative speed of the intruder is the obtained by subtracting the ownship speed vector:

$$dv(1) = v_{intruder}(1) - v_{own}(1)$$
$$dv(2) = v_{intruder}(2) - v_{own}(2)$$
$$dv(3) = v_{intruder}(3) - v_{own}(3)$$

The equation for the relative motion of the intruder is now:

$$\begin{pmatrix} x_1 \\ x_2 \\ x_3 \end{pmatrix} = \begin{pmatrix} dx_1 \\ dx_2 \\ dx_3 \end{pmatrix} + t \begin{pmatrix} dv_1 \\ dv_2 \\ dv_3 \end{pmatrix}$$

The time *t* in this equation is also relative, meaning *t =0* is now. The conflict detection is now simplified to straightforward vector calculations. Find the vertical conflict interval $[t_{in\ vert}, t_{out\ vert}]$ first by solving for *t*:

$$|x_3| = DH$$
$$|dx_3 + t \cdot dv_3| = DH$$
$$dx_3 + t \cdot dv_3 = DH \quad \bigcup \quad dx_3 + t \cdot dv_3 = -DH$$

$$t_1 = \frac{DH - dx_3}{dv_3} \qquad t_2 = \frac{-DH - dx_3}{dv_3}$$

$$t_{in_{vert}} = \min(t_1, t_2)$$
$$t_{out_{vert}} = \max(t_1, t_2)$$

The case where the relative vertical speed is close to zero needs special care to prevent division by zero. In this case the relative position determines the conflict and the vertical interval t_{in} and t_{out} are set accordingly. Either to from 'now' to 'eternity' or this pair of aircraft is skipped since there is no conflict if there is no vertical conflict interval.

The horizontal conflict interval is calculated as the intersection of a line and a circle in the horizontal plane. To find these times the following equation is solved for t:

$$x_1^2 + x_2^2 = R^2$$
$$(dx_1 + t\ dv_1)^2 + (dx_2 + t\ dv_2)^2 = R^2$$
$$(dv_1^2 + dv_2^2)\,t^2 + 2(dx_1 dv_1 + dx_2 dv_2)\,t + (dx_1^2 + dx_2^2 - R^2) = 0$$

$$a = dv_1^{\,2} + dv_2^{\,2}$$
$$b = 2(dx_1 dv_1 + dx_2 dv_2)$$
$$c = dx_1^{\,2} + dx_2^{\,2} - R^2$$
$$D = b^2 - 4ac$$

Note that *a* is always positive (if not equal to zero). If *a* is equal to zero, the relative speed is zero. This is handled in the same way as the vertical conflict interval with a zero relative vertical speed. If the discriminant *D* is negative there is no intersection and hence no conflict.

$$t_{in_{hor}} = \frac{-b - \sqrt{D}}{2a}$$
$$t_{out_{hor}} = \frac{-b + \sqrt{D}}{2a}$$

This is the interval of the horizontal conflict. Negative results refer to times in the past.

The vertical and horizontal interval are combined and checked for overlap. For the combined t_{in} the maximum of both values is used (it is a conflict only if it has intruded the protected zone horizontally AND vertically).

$$t_{in} = \max(t_{in_{vert}}, t_{in_{hor}})$$

For the time of leaving the zone t_{out}, the minimum time of the horizontal and vertical values is used, since the conflict ends when one of the separation minima is no longer violated.

$$t_{out} = \min(t_{out_{vert}}, t_{out_{hor}})$$

When t_{out} is before t_{in}, this means there is no overlap and hence no conflict. The beginning of the conflict interval needs to be less than the look-ahead time (if less than zero we are already in conflict).

If a conflict has been found the conflict is registered in the conflict database. The data of the conflict that is stored is:

- $t_{intru}=t_{in} + t_{now}$ = intrusion time, moment at which loss of separation occurs
- $t_{conflict}=t_{mindist} + t_{now}$ = minimum distance time or CPA time (absolute)

Data of both aircraft at minimum distance position (CPA):

- Positions of both aircraft at CPA: latitude, longitude, altitude
- * Velocities of both aircraft at CPA: ground speed, track, vertical speed (= actual in state based variant, only used in flight plan version)

The minimum distance position can be determined in different ways.

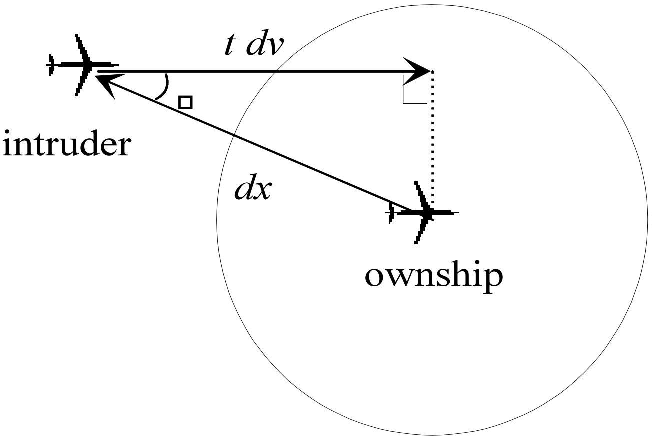

figure 5.7 Minimum distance position

From figure 5.7 it can be seen that by using two definitions for the angle β from the inproduct and the triangle, the formula for $t_{mindist}$ is easily found:

$$\cos\beta = \frac{(-\underline{dx})\cdot\underline{dv}}{\left|-\underline{dx}\right|\left|\underline{dv}\right|} = \frac{t\left|\underline{dv}\right|}{\left|\underline{dx}\right|}$$

$$t\left|\underline{dv}\right|\left|\underline{dx}\right|\left|\underline{dv}\right| \quad = \quad -\underline{dx}\cdot\underline{dv}\left|\underline{dx}\right|$$

$$t_{\min\, dist} = \frac{-\underline{dv}\cdot\underline{dx}}{\left|\underline{dv}\right|^{2}}$$

Since the horizontal conflict interval is already calculated, the minimum distance time can also be calculated using the average of $t_{in\ hor}$ and $t_{out\ hor}$, if these have not been limited in the process.

This minimum distance time is used in a call to the predictor module PREDPOS to basically evaluate the absolute equations of motion, yielding the position and velocities of both aircraft at the minimum distance point. These values are used by the resolution module.

In the traffic manager, the conflict detection process is called for all combinations of aircraft. Because of the symmetry of the conflict detection, there are potentially ½*n(n-1)* conflict polls required in case of a scenario with *n* aircraft.. To reduce computation power requirements several enhancements will make this process faster:

- Calculate every **sine and cosine only once** per aircraft Sines and cosines are in general calculated using Taylor-series that are relatively computing intensive.
- Before any calculation of distance or bearing, check whether the **vertical speed and altitude difference** allow the possibility for a conflict within the look-ahead time
- Estimate **the distance** (using a less computing intensive distance estimation routine) and verify whether the **magnitude of the speed** allows a conflict close to the look-ahead time
- **Skip** further calculation of the current pair of aircraft **at any stage** of the calculation when it is clear there is no conflict

These measures optimise the fast execution, especially important with a global off-line simulation of a scenario with a large number of aircraft.

When a conflict is detected using already filtered ADS-B data, it can still cause nuisance alerts. For example, when an aircraft is turning using the straight line will cause nuisance alerts. (Using the prediction based on turn rate would cause a similar effect.) To avoid these and similar nuisance alerts, conflicts detected are delayed via a conflict filter implemented in the module FILTCONF.

The conflict filter maintains a table that contains all starting times of a conflict per pair of call signs. Every time the conflict detection calculation has been performed, a new table is zero-ed and only the times of the current conflicts are copied. If a conflict is new, the current clock time is stored in the two cells of the table for this pair of aircraft.

Example of conflict filter table

	KL204	HV296	MP101	…..
KL204	-	12:22:45.03	0.0	…..
HV296	12:22:45.03	-	0.0	
MP101	0.0	0.0	-	….
				….
…..	…	…	….	….

This new table is then used to delete all conflicts, which are not 'on' long enough in relation to their time-to-conflict to be passed on the display, the alerting system and the resolution module. Currently there are two urgency levels defined (see also chapter 7 on the man-machine interface):

- Red: conflicts with a loss of separation within 3 minutes
- Amber: conflicts with a loss of separation between 3 to 5 minutes from now

For red conflicts a filter time of 4 seconds is used, for amber conflicts this is 10 seconds. These parameters are adjustable via scenario files or data files. The look-ahead time of the conflict detection module is increased with these values to ensure conflict will be shown when within the specified look-ahead time of 5 minutes.

When a conflict is not ‘on’ long enough yet, its starting time in the conflict filter table will be kept, but the actual conflict will be invalidated in the conflict database.

5.5 Conflict Resolution Module

The filtered conflict database is the input for the conflict resolution module. While the conflict detection module is a global module in the traffic manager, the resolution module is called separately for each aircraft (‘ownship’). The module can be divided in three parts:

1. Check for any conflict involving the ownship, within the look-ahead time, and order the conflicts chronologically
2. Calculate the horizontal and vertical resolution manoeuvres
3. Decide which manoeuvre to pass on to the pilot model (or flight management system)

Though in the software a part of the resolution module, the third part is functionally a part of the pilot model. It is dependent on the criteria specified by the user. Many variants are available:

- EBY - Initiate both manoeuvres (horizontal and vertical)
- EBYH – use only horizontal manoeuvre
- EBYV- use only vertical manoeuvre
- EBYHV – decide horizontal or vertical based on geometry and efficiency
- EBYHDG - change only heading (horizontal exlcusive speed changes)
- EBYDEC – decide horizontal or vertical just as EBYHV without speed control

Typing “RESONR <variantname>” in the traffic manager simulation will result in using one of the above mentioned variants. The calculation of the resolution manoeuvres will be described in this section.

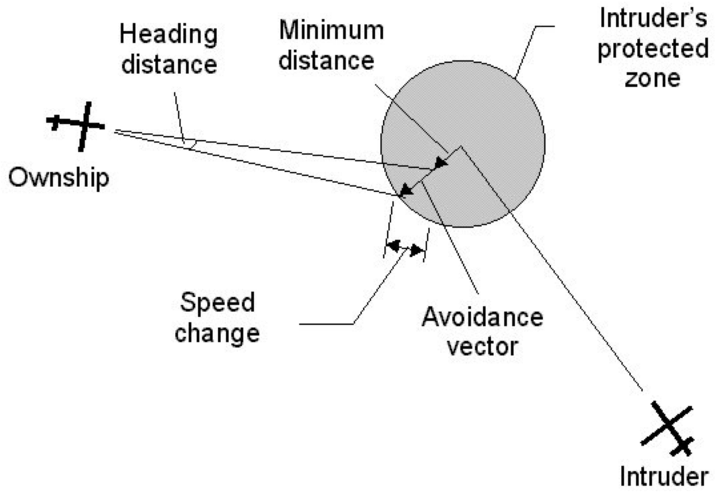

figure 5.8 Avoidance vector and resulting horizontal manoeuvre

The position of both aircraft at the minimum distance point (closest point of approach) are used to calculate the avoidance vector. This vector is translated into an avoidance manoeuvre $\underline{vavoid}$ by using the avoidance vector divied by the available manoeuvre time t_{manv}.

Variables from conflict database used by resolution module:

t_{confl}	clock time of minimum distance point
t_{intru}	clock time of moment of loss of separation
$latconfl_{own}$	latitude of ownship at minimum distance position
$lonconfl_{own}$	longitude of ownship at minimum distance position
$latconfl_{intruder}$	latitude of intruder at minimum distance position
$lonconfl_{intruder}$	longitude of intruder at minimum distance position
$altconfl_{ownship}$	altitude of ownship at minimum distance position
$altconfl_{intruder}$	altitude of intruder at minimum distance position

Ownship data:

V_{own}	Ground speed of ownship
crs_{own}	Track angle of ownship
vs_{own}	Vertical speed
t_{now}	Clock time

The calculation of the resolution manoeuvre is straightforward from figure 5.8:

Calculate bearing from intruder to ownship:

$$qdr(latconfl_{own}, lonconfl_{own}, latconfl_{intruder}, lonconfl_{intruder})$$

Calculate minimum distance: $dist(lat_{own}, lon_{own}, lat_{intruder}, lon_{intruder})$

In case of several conflicts, the horizontal avoidance vectors are summed. Vertically the maximum and minimum altitude are stored and used for the vertical resolution.

For this reason, the advised speed vector is initialised with the current speed vector. The co-ordinates of this vector are (r , χ , dh).

$$\begin{aligned} &sumavoid(1) = V_{own} \cos \gamma \\ &sumavoid(2) = crs_{own} \\ &sumavoid(3) = vs_{own} \end{aligned}$$

Calculate manoeuvre time for this conflict. This is the time to go to the minimum distance position:

$$t_{manv} = \max(30., tconfl_i - t_{now})$$

Using this manoeuvre time, calculate avoidance vector addition due to this conflict:

$$dalt = altconfl_{intruder} - altconfl_{own}$$

$$\begin{aligned} vavoid(1) &= \frac{\varepsilon \cdot R - dist}{t_{manv}} \\ vavoid(2) &= qdr \\ vavoid(3) &= \frac{DH - dalt}{t_{manv\ vertical}} \end{aligned}$$

In which ε is a factor that compensates for the small angle α between the line to the relative position of the intruder at CPA and the line to the position where the relative resolution speed vector touches the protected zone of the own ship (see figure below). This makes OX slightly longer than R.

Normally this factor is close to 1.0 , but when an aircraft is close (thus the relative speed is minimal) and the intrusion is large, it can become significant. In these cases, the margin that exists between the protected zone dimensions used in the resolution and the detection will not compensate for this factor.

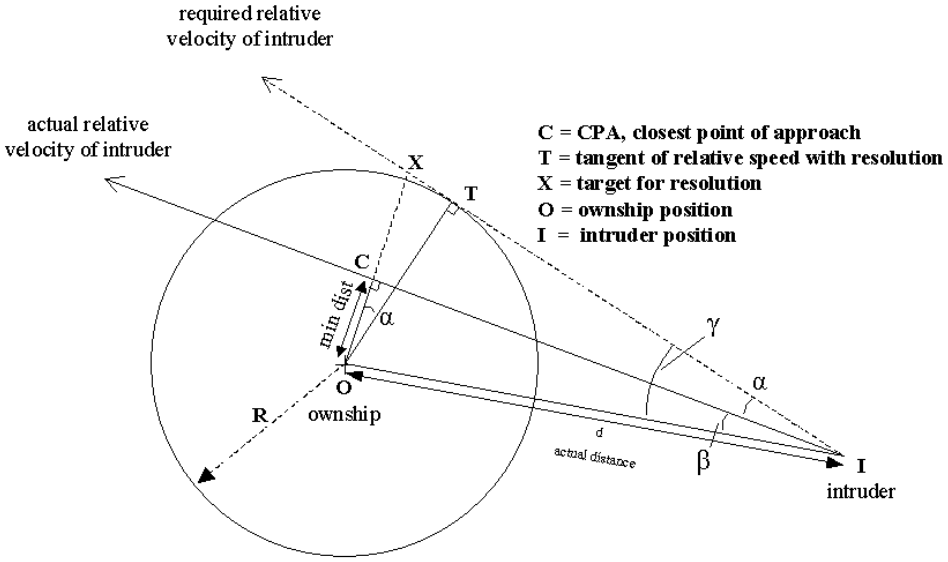

Figure 5.9 Geometry of CPA using ownship's protected zone and relative speed of intruder to show effect of factor of R

The correct length of the avoidance vector ε · R can be calculated as follows:

$$\alpha = \angle CIT = \angle COT \quad because \quad OC \perp IC \quad and \quad OT \perp IT$$
$$\beta = \angle OIC$$
$$\gamma = \angle OIX = \alpha + \beta$$
$$d = actual\,distance \quad dist = minimum\,distance$$

To calculate OX = ε R , we need α:

$$\Delta OIC : \sin\beta = \frac{OC}{OI} = \frac{dist}{d}$$
$$\Delta OIT : \sin\gamma = \frac{OT}{OI} = \frac{R}{d}$$
$$\alpha = \gamma - \beta = \arcsin(\frac{R}{d}) - \arcsin(\frac{dist}{d})$$
$$\Delta OTX : \varepsilon \cdot R = OX = \frac{OT}{|\cos\alpha|} = \frac{R}{\left|\cos(\ \arcsin(\frac{R}{d}) - \arcsin(\frac{dist}{d})\ )\right|}$$

It can be seen that if the actual distance *d* is much larger than R (which usually is the case) or if the minimum distance *dist* is close to *R* (hence a minimal intrusion), the cosine will be close to 1.0 and hence ε · R ~ R.

A typical situation where this factor makes an important difference, is a nearly parallel track with a severe intrusion.

The vertical manoeuvre time $t_{\text{manv vertical}}$ is calculated by comparing the geometry at the moment of loss of separation and at the CPA to determine the appropriate vertical speed.

This vector is then summed (vector-wise) to the *sumavoid* vector.

The third component of this vector is a vertical speed. Without extra measures, this resolution would advise to keep climbing. Therefore, by storing the altitude boundaries of the protected zones of (all) the intruder aircraft, the target altitude is set to avoid all conflicts detected.

The resulting output is:

- advised ground speed – to be converted to IAS for primary flight display (PFD)
- advised track – to be converted to magnetic track or heading for nav display
- advised vertical speed – to be displayed on the PFD
- advised altitude – to be used by pilot models

In the traffic manager, these data are output to the pilot and autopilot models in the traffic manager. The pilot models decide, depending on the logic that was selected, whether and how to execute the resolution manoeuvre. The traffic manager also performs the ASAS function for the simulator(s) connected to the traffic manager. This program sends a 'RESO' message containing the above data to display on the primary flight display and the navigation display. See chapter 7 for a description of the displays and alerting and the experiment descriptions in chapters 8 and 11 for a description of the experiment configurations.

5.6 Straight lines

One of the assumptions of the conflict detection and resolution algorithm described in this chapter is that aircraft fly in a straight line. This is obviously very often not the case as aircraft do:

- turn over **waypoints** (or avoid SUA, weather)
- **level off**
- initiate a **climb** or **descent**
- normally do **not** climb or descend with a **constant vertical speed**
- change from an **IAS to** a **Mach climb** and vice versa for a descent
- resolve other **conflicts** (!)

From this list, it seems ridiculous to assume the straight-line prediction.

There are several reasons why this simple approach still works. Some will be demonstrated later. The following considerations should be taken into account.

Waypoint, level off, climb and descent

It is true that by not knowing the intent of the other aircraft, without any extra measures a lot of very short term conflicts could occur. Instead of appearing at the look-ahead horizon of five minutes, a turn can initiate a conflict right away. The same goes for levelling off or starting a climb of descent, which can be regarded as a turn in the vertical plane. Decelerating and accelerating might also cause false alerts or missed conflicts.

In an upper airspace designated as Free Flight airspace, free routing will reduce the amount of turns significantly compared with today's situation of following airways. The straight line is more often an adequate prediction in a direct routing especially.

If instead of rounded number flight levels flying at any altitude is allowed, the step climbs will be replaced by a shallow cruise climb, which makes the flight path also nearly a straight line in the vertical plane. Only one top-of-climb and one top-of-descent will mean a 'turn' in the vertical path.

Causing short-term conflicts can be avoided by implementing a rule that inhibits any manoeuvre, which would result in a short-term conflict. Using the CDTI it is possible to see where other aircraft are flying. On top of that, an extra tool might be required to prevent this. In the NLR study, the predictive ASAS module shows on the primary flight display and on the navigation display bands on different scales. It shows 'no-go' zones in the track/heading scale, on the vertical speed scale and on the speed scale. The colours used for these bands, red and amber' correspond to the urgency level of the conflict that would result if a value was to be selected on the autopilot in these bands. Chapter 9 explains how predictive ASAS, sometimes referred to as PASAS or PREDASAS, works. The first man-in-the-loop experiment did not yet feature the predictive ASAS. This system was a result from recommendations from this experiment and has been evaluated in the second human-in-the-loop experiment.

No constant vertical speed or IAS/Mach climb transitions

The approximation of a climb or descent as a straight line is a simplification. During the climb or the descent, normally the thrust setting is fixed and the speed is fixed (either IAS or Mach). The vertical speed is a result from these settings and varies with altitude (air density). The resulting path is therefore a shallow curve instead of a straight line. It is possible to fly in vertical speed mode, in which one of the other variables are free. From registering the path of an aircraft and calculating (or actually estimating, since wind and atmosphere are not known) the Mach, IAS and vertical speed for that aircraft for some time it might be possible to guess what flight mode is used. This information could then be used to correct the prediction. In the NLR study this has not been implemented for several reasons. The added complexity and the limited benefit were the most important one. In addition, the reliability of the outcome of such an algorithm is not too high. Even if the correct mode is estimated, it may change from Mach to IAS climb making things worse.

The net quantitative effect of the climb or descend mode has been analysed in co-operation with two students, Bas Gijsbers and Mario Valenti Clair, and this is discussed in more detail in the next section. The conclusion is that the curve only slightly deviates from the straight line. The net effect on the conflict detection is something between these two extremes:

- the look-ahead time is reduced, but the intrusion is minimal
- the grazing of the protected zone is significant, but the look-ahead time is only reduced with a few seconds

Both extremes are also illustrated in the figure below.

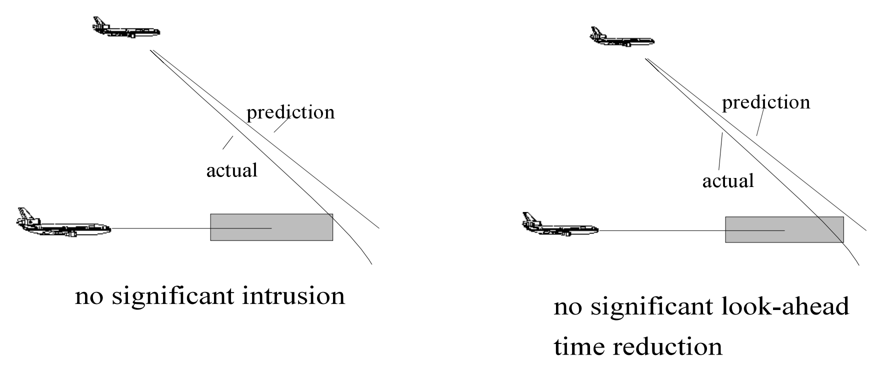

figure 5.10 Effect on conflict detection of curved descent

In other words, this effect slightly rounds off the corners of the protected zone, making it more the shape of a Gouda cheese instead of a pure cylinder with sharp edges.

Resolving conflicts results in new conflicts

This effect is rare but can occur. In this situation, it might take more than one manoeuvre to solve the conflict. For example instead of turning back to the original heading, a vertical manoeuvre could be more effective. One could argue that the conflict resolution module should never advise to turn into a new conflict. It might be beneficial sometimes to do this as is illustrated by the 'wall' scenario where a 'wall' of aircraft at minimum separation approaches one aircraft. The effect of sequentially running into a new conflict is the way this scenario is solved in an apparently intelligent way. See chapter 12 on complex conflict geometries.

The resolution module does take multi-aircraft conflict into account. Only new conflicts due to a resolution manoeuvre are not already included. Still, although the resolution module initially does not take new conflicts as a result of the manoeuvre into account, the pilot can. Especially using predictive ASAS, it is clear which manoeuvre will result in a new conflict and evasive action or a better selection of the manoeuvre is possible.

5.7 Effect of IAS/Mach climb or descent

The conflict detection module of the Traffic and Experiment Manager only uses a few input variables to predict a conflict. These variables include the aircraft's current position and altitude and the aircraft's trend vector (ground speed, track, and vertical speed). Hence, the aircraft's future positions are calculated by using the tangent of the flight path. However, when an aircraft performs a climb or descent, the aircraft's flight path is curved and does not equal a straight line. Due to the curved flight path, it is possible that the conflict detection module detects a potential conflict at a moment the time to intrusion is (far) less than the look-ahead time of five minutes. This chapter primarily describes the effects of a CAS/Mach climb and descent on the conflict detection module in a Free Flight environment. The first paragraph gives some general information about the calibrated airspeed and Mach number. Paragraph 5.7.2 mentions a steady climb with constant Mach while paragraph 5.7.3 describes the same climb being performed with a constant calibrated airspeed. Finally, paragraphs 5.7.4 and 5.7.5 mention two air traffic scenario's that have been investigated by using the Traffic and Experiment Manager.

5.7.1 Definition of CAS and Mach

The calibrated airspeed (CAS) is defined as the indicated airspeed of an aircraft, corrected for altitude and instrument error. Hence, the indicated airspeed is basically the same quantity as calibrated airspeed but includes the pressure error present in the pitot/static installation and the instrument errors present in a simple mechanical type of airspeed indicator instrument. The following formula can be used to compute the true airspeed (TAS) from the calibrated airspeed (CAS):

$$V_{TAS} = \left[\frac{2}{\mu} \frac{p(H)}{\rho(H)} \left\{ \left(1 + \frac{p_0}{p(H)} \left[\left(1 + \frac{\mu}{2} \frac{\rho_0}{p_0} V_{CAS}^2 \right)^{\frac{1}{\mu}} - 1 \right] \right)^{\mu} - 1 \right\} \right]^{1/2} \tag{5.1}$$

$$\mu = \frac{\gamma - 1}{\gamma} \quad and \quad \gamma = \frac{c_p}{c_v} \approx 1.40$$

The Mach number is defined as the ratio of the aircraft's true airspeed to the local speed of sound. The true airspeed (TAS) is defined as the speed of the aircraft relative to the surrounding air. Hence:

$$M = \frac{V_{TAS}}{a} \tag{5.2}$$

a = *speed of sound*

This section primarily describes the effects of a CAS/Mach climb and descent on the conflict detection in a Free Flight environment. Paragraph 5.7.2 mentions a steady climb with constant Mach while paragraph 5.7.3 describes the same climb being performed with a constant calibrated airspeed. Paragraphs 5.7.4 and 5.7.5 finally mention two air traffic scenario's that have been investigated by using the Traffic and Experiment Manager.

5.7.2 Climb with constant Mach

Consider an aircraft climbing with a constant commanded vertical speed and a constant Mach number (see figure 5.11).

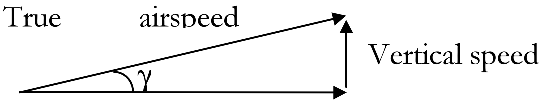

figure 5.11 Climb with constant Mach number and vertical speed

As stated earlier in the definition of Mach, the Mach number can be derived from the true airspeed (TAS) and the speed of sound (a). The speed of sound however reduces with increasing altitude as the temperature decreases until the tropopause height is reached. The variation of the speed of sound with temperature equals:

$$a = \sqrt{k \cdot R \cdot T} \tag{5.3}$$

$$k = 1.4$$

$$R = 287.0529$$

$$T = 288.15 - 0.0065 \cdot H$$

The variation of the speed of sound from sea level to FL400 is shown in figure 5.12.

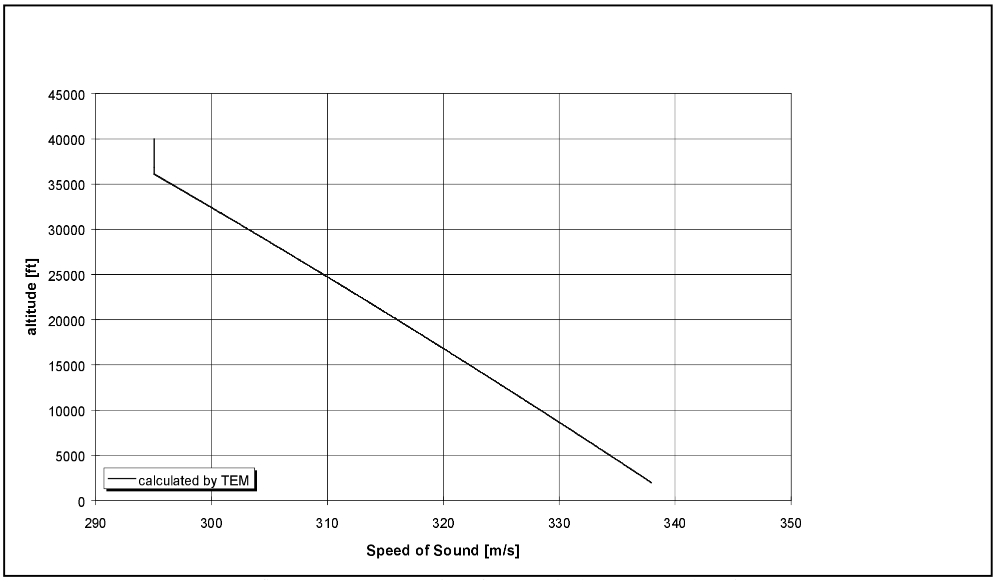

figure 5.12 Speed of sound in International Standard Atmosphere(ISA)

The equation for Mach yields:

$$V_{TAS} = Mach \cdot a \tag{5.4}$$

$$\frac{dV_{TAS}}{dH} = Mach \cdot \frac{da}{dH} \quad \left\{ \frac{da}{dH} < 0 \right\} \tag{5.5}$$

Hence, the true airspeed decreases with increasing altitude. When climbing with a constant vertical speed, the flight path angle (γ) increases with increasing flight level.

5.7.3 *Climb with constant calibrated airspeed*

Consider the aircraft mentioned in paragraph 5.7.2 climbing with a constant calibrated airspeed. The equation for CAS yields:

$$V_{TAS} = CAS \cdot \sqrt{\frac{\rho_0}{\rho}} \tag{5.6}$$

$$\frac{dV_{TAS}}{dH} = CAS \cdot -\frac{1}{2} \cdot \sqrt{\frac{\rho_0}{\rho^3}} \cdot \frac{d\rho}{dH} \quad \left\{ \frac{d\rho}{dH} < 0 \right\} \tag{5.7}$$

The relationship between the air density, ρ, and altitude, H, is shown in figure .3.

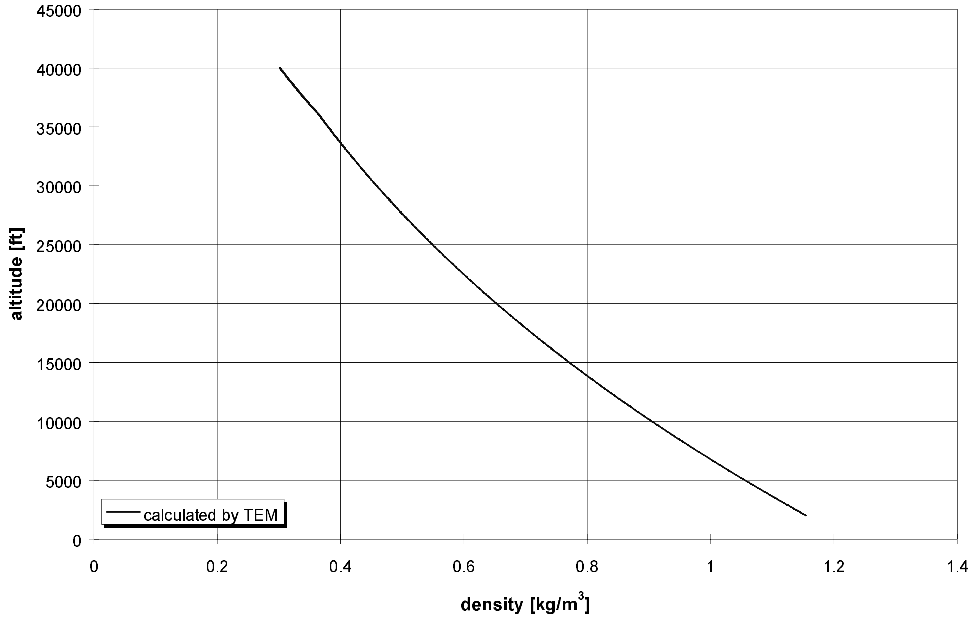

figure 5.13 Air density in ISA atmosphere

Hence, the true airspeed increases with increasing altitude. When climbing with a constant vertical speed, the flight path angle (γ) thus decreases with increasing altitude.

5.7.4 *Scenario (I) of CAS, Mach climb/descent*

Consider two aircraft numbered KL101 and MP747 as shown in figure 5.14. KL101 is flying at FL300 (Mach=0.80). MP747 starts a steady climb from FL250 to FL300 with a constant vertical speed of 1000 ft/min. The initial positions of both aircraft are such that the MP747 grazes the protected zone of KL101 at a flight time of approximately four minutes (see figure 5.15).

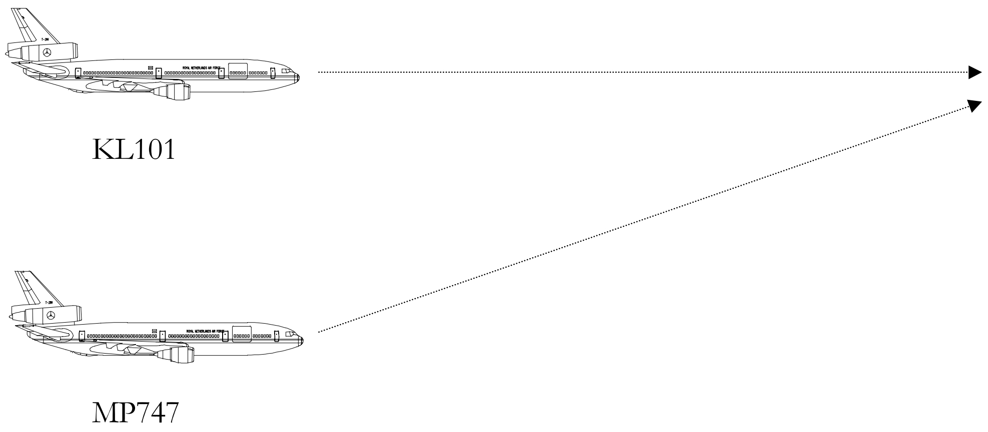

figure 5.14 Scenario I (number of aircraft = 2)

Using the Mach number equations yield for KL101:

$$T = 288.15 - 0.0065 \cdot 30000 \cdot 0.3048 = 228.7K$$

$$a = \sqrt{1.4 \cdot 287.0529 \cdot 228.7} = 303.2m/s$$

$$V_{TAS} = GS = M \cdot a = 0.80 \cdot 303.2 = 242.5m/s \cong 471kts$$

Assume a relative motion between the KL101 and MP747 as shown in figure 5.15. The ground speed of the MP747 thus equals:

$$GS = 242.5 - 5.08 = 237.42m/s$$

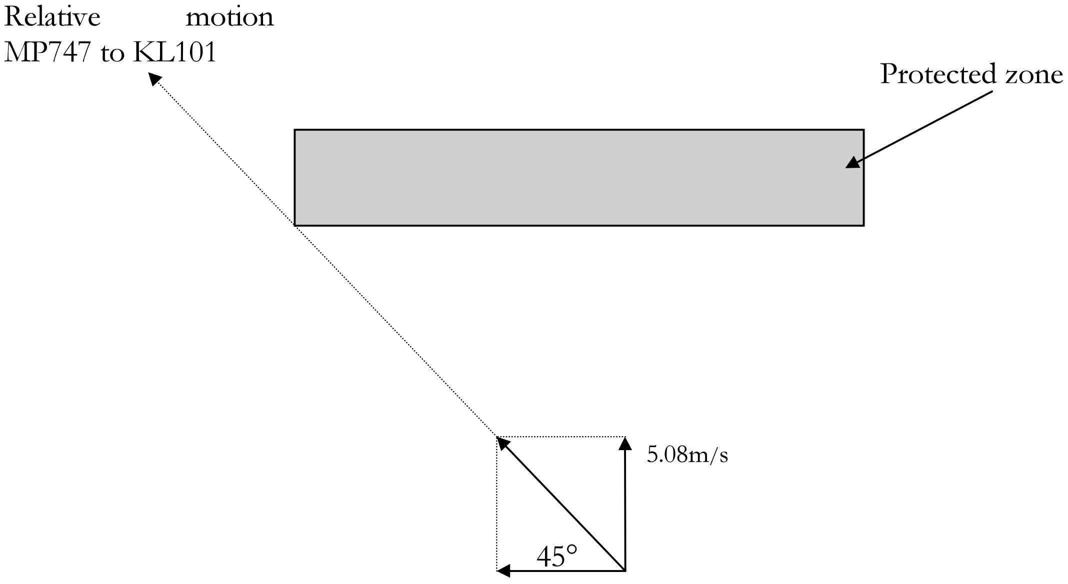

figure 5.15 Theoretical relative motion between KL101 and MP747

The following formulae are used to determine the Mach number of MP747:

Rate of Climb: $5.08 = V_{TAS} \cdot \sin\gamma$

Ground speed: $237.42 = V_{TAS} \cdot \cos\gamma$

Combining these equations yields:

$$5.08 = \frac{237.42}{\cos\gamma} \cdot \sin\gamma = 237.42 \cdot \tan\gamma$$

$$\gamma = 1.226^\circ$$

$$V_{TAS} = 237.47 m/s \cong 462 kts$$

Using the equations for Mach number yield for MP747:

$$T = 288.15 - 0.0065 \cdot 25000 \cdot 0.3048 = 238.6K$$

$$a = \sqrt{1.4 \cdot 287.0529 \cdot 238.6} = 309.7 m/s$$

$$M = \frac{V_{TAS}}{a} = \frac{237.47}{309.7} = 0.77$$

See figure 5.16 for the absolute flight path of both the KL101 and the MP747 being calculated by the Traffic and Experiment Manager.

Note from figure 5.16 that the flight path angle decreases when the MP747 performs a steady climb with a constant calibrated airspeed and that the flight path angle increases when the same climb is performed with a constant Mach number (see paragraphs 5.7.2 and 5.7.3).

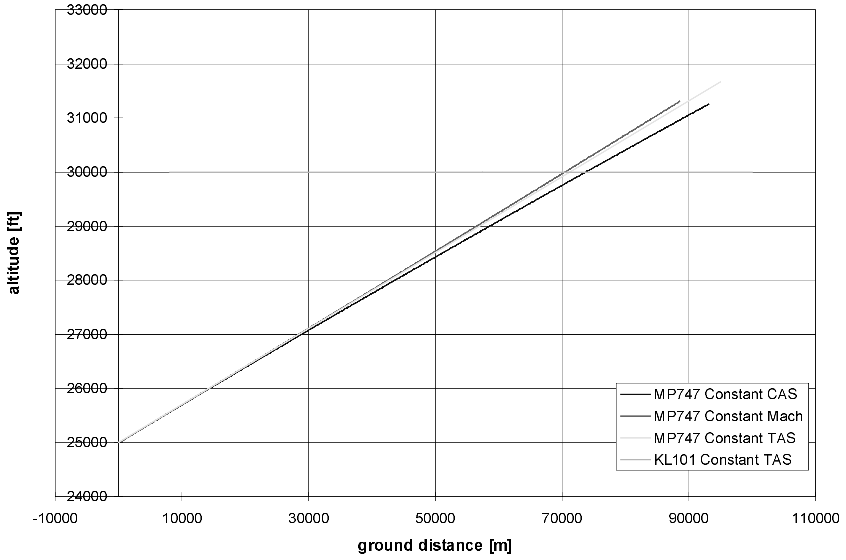

figure 5.16 Absolute Flight path KL101 and MP747

The relative motion between the MP747 and the KL101 is displayed in figure 5.17. Note that the theoretical relative motion (constant TAS) grazes the protected zone of the KL101 at a flight time of approximately four minutes (see also figure 5.15).

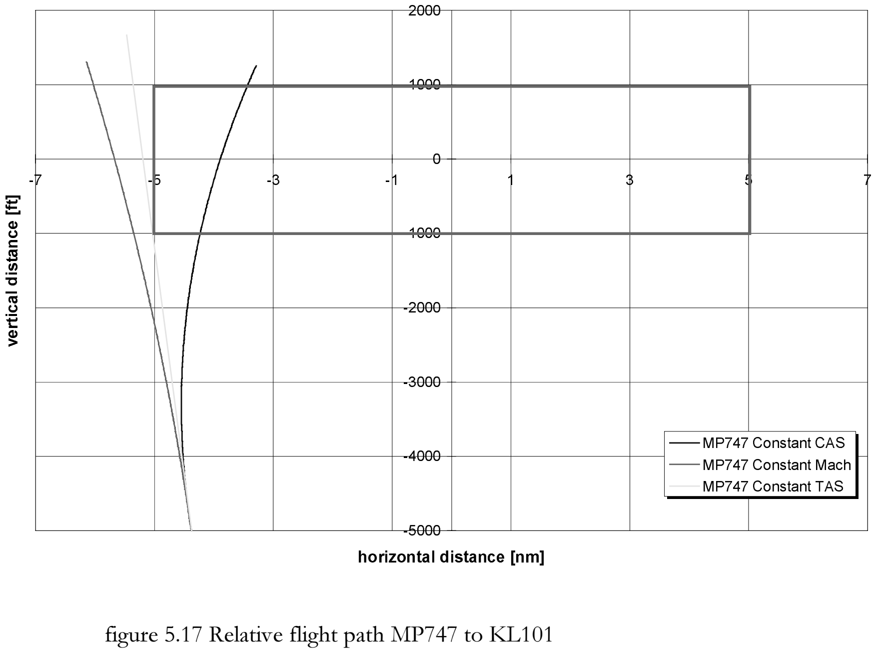

figure 5.17 Relative flight path MP747 to KL101

When the MP747 climbs with a constant Mach number, it slowly "moves" away from the protected zone of the KL101. Therefore, only one conflict is detected at the time the MP747 starts its climb. However, when the MP747 performs a climb with a constant calibrated air-speed, the range rate becomes negative as shown in figure 5.17. Note that the intrusion in the horizontal plane approximately equals one nautical mile at a flight time of five minutes when the MP747 climbs with a constant calibrated airspeed. When considering the theoretical relative motion between the two aircraft, the MP747 is located outside the protected zone of the KL101 at a flight time of five minutes.

5.7.5 Scenario (II) of CAS, Mach climb/descent

Consider the same two aircraft as mentioned in the paragraph 5.7.4. KL101 is flying at FL350 and starts a slow descent to FL250. MP747 is flying at FL250 and starts a steady climb to FL350 (see figure 5.18). Both aircraft use a vertical speed of 1000 ft/min to reach their desired flight level. The initial positions of both aircraft are such that the theoretical minimum distance approximately equals zero.

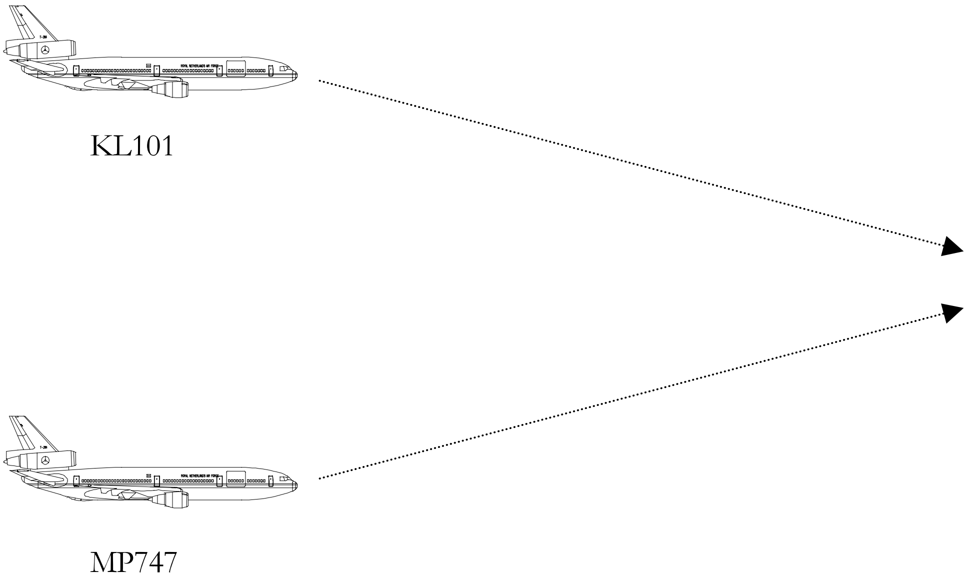

figure 5.18 Scenario II (number of aircraft = 2)

Using the atmospheric equations yield for KL101:

$$T = 288.15 - 0.0065 \cdot 35000 \cdot 0.3048 = 218.8K$$

$$a = \sqrt{1.4 \cdot 287.0529 \cdot 218.8} = 296.5m/s$$

$$V_{TAS} = M \cdot a = 0.80 \cdot 296.5 = 237.2m/s \cong 461kts$$

The calibrated airspeed of the KL101 at FL350 is calculated by the Traffic and Experiment Manager and approximately equals:

$$V_{CAS} = 139.9 m/s \cong 272 kts$$

The same calculations performed for the MP747 yield:

$$T = 288.15 - 0.0065 \cdot 25000 \cdot 0.3048 = 238.6 K$$

$$a = \sqrt{1.4 \cdot 287.0529 \cdot 238.6} = 309.7 m/s$$

Due to the fact, that the theoretical minimum distance equals zero, both the KL101 and the MP747 have to fly at the same true airspeed (TAS).

$$V_{TAS} = 237.2 = M \cdot 309.7$$

$$M = 0.77$$

The calibrated airspeed calculated by the Traffic and Experiment Manager equals:

$$V_{CAS} = 165.7 m/s \cong 322 kts$$

The graph in figure 5.19 displays a part of the absolute flight path of both the KL101 and the MP747.

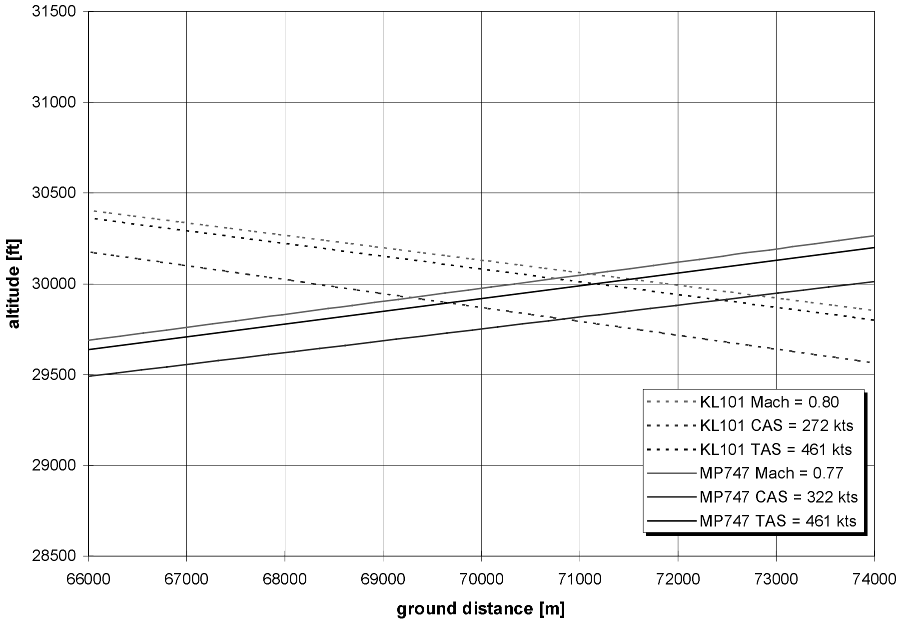

figure 5.19 Absolute Flight Path KL101 and MP747

Note from figure 5.19 that the maximum ground distance at FL300 occurs when both aircraft fly at a constant calibrated airspeed (CAS). In this case the flight path angle of the KL101 in-creases while the flight path angle of the MP747 decreases (see also figure 5.19). The ground distance at a flight time of five minutes approximately equals 3 nautical miles as can be seen from figure 5.20. In figure 5.20 the relative motion is shown between both aircraft when the KL101 flies at a constant calibrated airspeed.

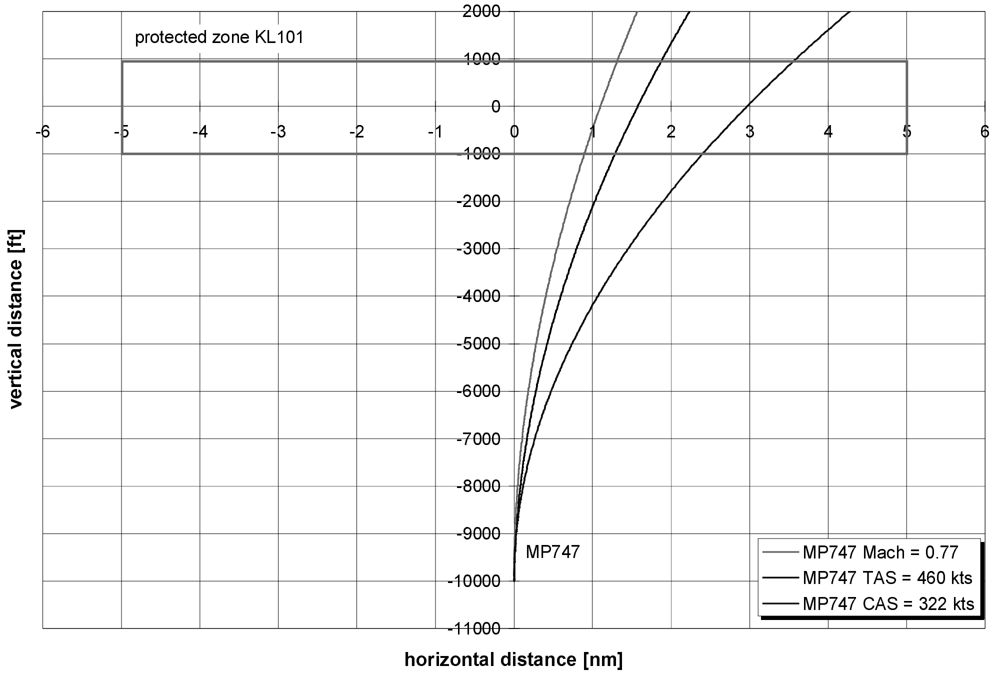

figure 5.20 Relative Flight Path MP747 to KL101
(flying at constant CAS)

These experiments with the Traffic and Experiment Manager proved that the CAS, Mach climb/descent has a considerable effect on the conflict detection and resolution module. The CAS, Mach climb/descent primarily initiates uncertainties of the predicted position of the intruder aircraft in the near future. The amount of uncertainty is dependent on the curvature of the aircraft's flight path. The curvature of the aircraft's flight path depends on the gradient of the true airspeed to the aircraft's altitude. The larger the absolute value of this gradient, the larger the amount of curvature of the aircraft's flight path. The experiments with the Traffic and Experiment Manager proved that the curvature of the flight path is largest when an aircraft performs a climb/descent with a constant calibrated airspeed instead of a climb/descent with a constant Mach number.

Critical air traffic situations are those in which the conflict detection module initially does not detect a potential conflict while, due to the curved flight path, there is an intrusion of the protected zone in the near future. The amount of intrusion depends on the curvature of the aircraft's flight path. Hence, the time to avoid a conflict is slightly less than the look-ahead time of five minutes and thus results in more immediate and costly manoeuvres of the aircraft.

The experiments with the Traffic and Experiment Manager proved, however, that all one-on-one conflicts resolve automatically and that no intrusions of the protected zone took place.

5.7.6 *Conclusion*

There are several solutions to improve the conflict detection and resolution during the climb and descent:

- estimate mode of other aircraft and correct prediction
- exchange mode or intent information
- add an extra comfort zone around protected zone

All these measures do have some disadvantages and may not be worth the added complexity and associated risks.

Although the prediction error, when using the straight-line flight path for aircraft descending and climbing with a constant CAS or Mach number can be significant, the net effect is less dramatic. With the maximum intrusion, the reduced look-ahead time is close to the originally specified look-ahead time. In the same way with the maximum reduction of the look-ahead time, the intrusion is minimal. See figure 5.21.

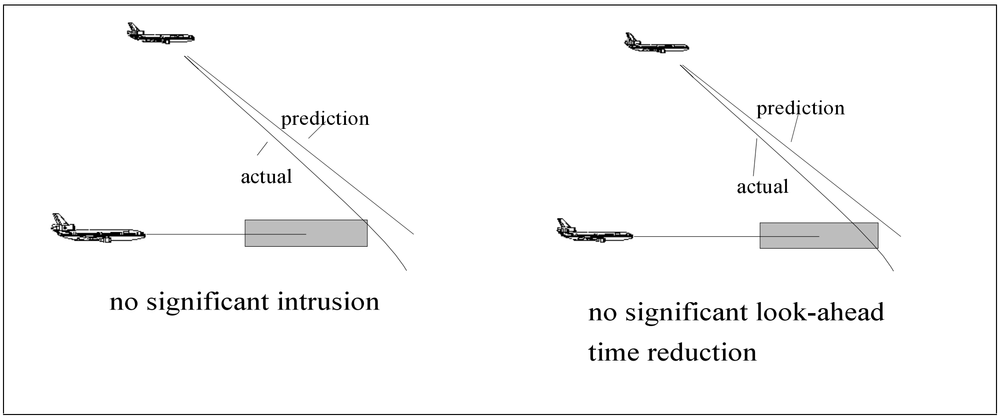

figure 5.21 Effect on conflict detection of curved descent

This limited operational effect probably is the reason, this has never proven to be a problem during the off-line and on-line experiments. No further action has been undertaken.

5.8 Effect of 2D CPA outside protected zone

The resolution module is mainly based on the two-dimensional picture of the conflict resolution geometry (see figure 5.2). The horizontal solution is based upon an avoidance vector that moves the closest point of approach outside the protected zone of the intruder to the edge of the zone. The minimum distance is then increased to the required separation minima. The conflict detection module registers the conflict geometry, so the resolution module can perform this calculation. However, there is a situation where this will not work. And this situation is not rare due to the extremely flat shape of the protected zone. In most figures the protected zone is drawn as a hockey puck shape. The actual dimensions make it look more like a large coin. The ratio height to width is about 1 to 30! Suppose an aircraft enters the zone via the top surface and leaves the protected zone via the lower surface with a considerable vertical speed. This means the actual conflict interval is rather small. Then there is a relatively high probability that the two dimensional closest point of approach is not located inside this conflict interval (just as the three-dimensional CPA, but that is irrelevant for the resolution module). This situation is shown in figure 5.22.

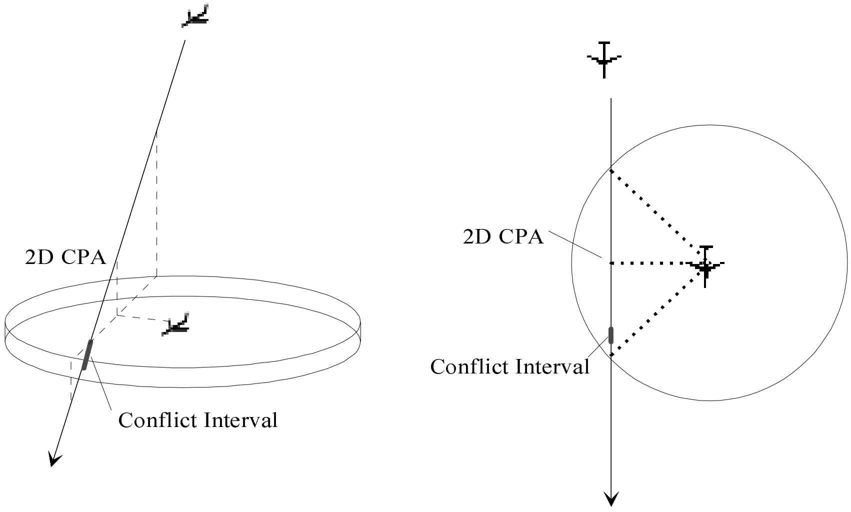

figure 5.22 In this situation the 2D CPA is outside the conflict interval

Only one minimum distance position (or CPA) should be used for both the horizontal and vertical resolution. This ensures one unambiguous speed resolution which is a part of both the horizontal and vertical resolution.

This ambiguity has been solved by changing the conflict position from the 2D CPA to a position close to the centre of the conflict interval on the time axis. The offset from the centre (5% percent of the conflict interval) ensures the conflict does not flip to the other side vertically, which would destroy the implicit co-ordination ensuring a co-operative manoeuvre vertically.

5.9 Effect of vertical direction of relative speed

There is another case where the standard resolution algorithm fails to resolve the conflict. This is just as the problem in the previous section caused by the vertical dimension of the protected zone. When the separation minima would have been specified as a sphere, the algorithm would have been more effective without the exception handlers that now are required to resolve all geometries. Assume an intruder flies 1 mile to the left and 4000 ft below the ownship. The intruder is climbing slowly and thereby causes a conflict several minutes ahead. The resolution algorithm will calculate a horizontal resolution based on the horizontal closest point of approach, even though the loss of separation will occur several minutes before that moment. Therefore by following this resolution, the intrude will not be at a horizontal distance of five nautical miles when he enters the protected zone via the lower surface. The resolution algorithm has therefore failed to solve this conflict horizontally because it has ignored the fact that the aircraft was already within the horizontal separation minimum of five nautical miles. This observation also indicated how this should be solved.

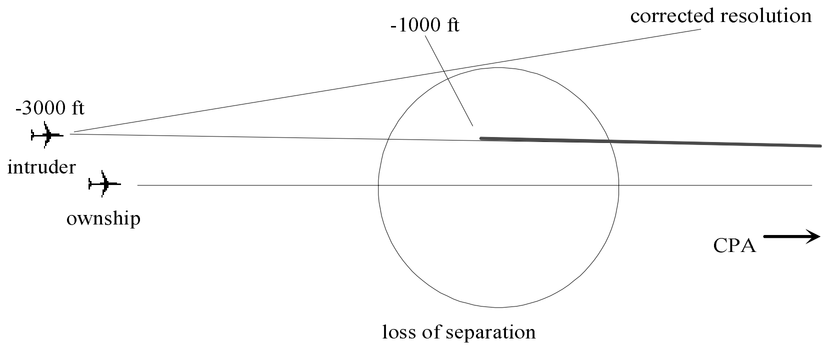

figure 5.23 Intruder is already within horizontal separation minimum => use intrusion point

The following logic has been added to the resolution algorithm to solve this:

> *If the intruder is already closer than 5 nm horizontally, use the time to loss of (combined) separation for the horizontal resolution calculation as manoeuvre time.*

When the intruder enters the zone via the lower surface but is still not within the horizontal separation minimum, the manoeuvre time can be calculated in the standard way (*use time to closest point of approach*).

5.10 Effect of singularities

During demonstrations of the resolution algorithm, the example of an exact head-on collision was often raised. The modified potential resolution algorithm is a geometrical method and like most geometrical methods, it has a singularity, or borderline case, which could potentially cause trouble. The direction of the already existing minimum distance vector determines the direction of the avoidance vector. See figure below.

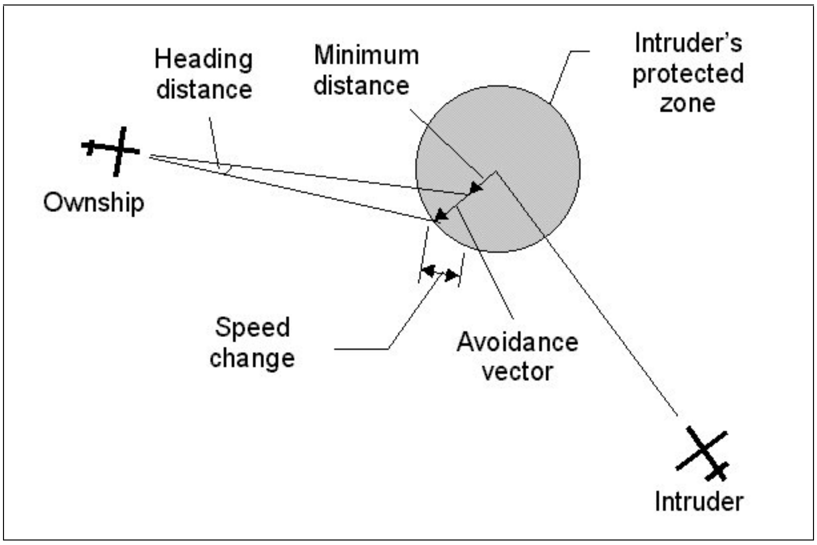

figure 5.24 Avoidance vector and resulting horizontal manoeuvre

If the minimum distance equals zero, like in the exact head-on collision, this cause a problem for the resolution algorithm. This distance is the outcome of a lat/lon calculation and a floating point value and not an integer (whole number). One will hardly ever see in a program a check for a floating point value being equal to zero or any other value. The probability for one floating point value being equal to another one, is extremely small, theoretically speaking. In this case, however it is still worth checking. This is caused by limited accuracy in which numbers are represented in the ADS-B message. Computers also have limited number of bits that are used to represent the numbers, which already increases the chance of the distance being equal to zero. In a lot of cases a distance close to zero will already cause overflows, but in this it is the lack of direction of the exact zero distance case that is causing the problems. In most computer programs, this problem can be handled by limiting the zero value to a lower or upper value (depending on the sign), effectively creating a dead band around zero.

In the ADS-B message the number of bits reserved for the position data is less than the number of bits generally used in computers to store floating point values. This increases the probability of creating singularities. Still, it will be rare, but not rare enough to ignore this problem.
An extra rule, or exception handler has been created to take care of all cases where the distance is zero or nearly zero. The nearly zero cases may have a direction, but are prone to flipping as a result of 'process noise' (for example caused by turbulence). The logic that has been added is:

If the minimum distance is predicted to be below a the treshold value then:

> *If the course difference is larger than or equal to 90 degrees (opposing traffic) both aircraft turn right else the higher aircraft turns right or in level cases (thus overtaking) the faster aircraft turns right.*

This exception handler logic in the resolution module will take care of all cases where the minimum distance is predicted to be close to zero. Because it is unambiguous it does not require any explicit resolution co-ordination or negotiation.

6 Preliminary safety analysis

6.1 Introduction

6.1.1 *Study objective*

In this chapter the results of a first TOPAZ safety assessment of the airborne separation assurance concept are presented. The safety assessment has been carried out in order to obtain a first insight into which safe separation is provided within a basic airborne separation assurance scenario and to identify possible weak spots with respect to safety.

The Free Flight concept is one of the promising candidates to provide the necessary increase in air traffic capacity, while maintaining the current (high) level of ATM safety. Two outstanding features of the Free Flight concept are that the aircraft are free to determine their routes individually, of course within some restrictions, and that aircraft use state based airborne separation assurance. This freedom of action has far reaching consequences in the organisation of safety, with a considerably smaller role for ground based ATC and more responsibility for the pilots with respect to safety.

The approach in this sfaety analysis is to investigate the organisation of safe separation by an ADS-B based airborne separation assurance part of the Free Flight concept by evaluating the accident risk originating from collision between aircraft that are flying in two parallel traffic flows of opposite direction at the same flight level. The accident risk is evaluated for various spacings between the traffic flows for the following situation:

- Two parallel airways with opposite direction traffic are considered.
- The ground does not have a role.
- Aircraft resolve conflicts autonomously using the conflict detection and resolution algorithm described in chapter 5.

Since the same situation has already been evaluated for a comparable ground based concept study for Eurocontrol[19], this allows comparison on safety of the airborne and ground based concepts.

6.1.2 *Accident risk assessment methodology*

Most studies on ATM safety either focus on hazard analysis techniques or on collision risk analysis: studies with thorough hazard analysis results generally use simplified collision risk models, advanced studies on collision risk between aircraft usually do not take into account hazards or non-nominal events (except in adapted tails of probability density functions). It appears that most established techniques fall short in integrating hazard analysis techniques with advanced collision risk analysis techniques. In order to support the advancement of ATM,

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[19] M.H.C. Everdij, G.J. Bakker, H.A.P. Blom and P.J.G. Blanker, Demonstration report in preparation to designing EATMS inherently safe, TOSCA-II WP4 Phase 1 report, NLR report CR 97419 L, 1997

NLR developed a risk assessment methodology[20] that combines established hazard analysis techniques with advanced stochastic modelling and analysis, such as Generalised Reich collision risk models[21], Stochastic differential equation evolution in hybrid state space[22] and Dynamically Coloured Petri Net modelling[23] to evaluate ATM safety. To support the construction and the numerical evaluation of these ATM models, a complementary toolset was developed in parallel. In a former study[24] it is shown that for ATM the use of these state of the art modelling techniques has some major advantages over established hazard analysis and safety assessment techniques. For example, the explicit modelling of time allows to appropriately handle delays in safety critical actions, to take into account dependent events correctly, to incorporate recoverable events, to include time related dependencies, and to combine frequency analysis, consequence analysis and collision risk models in a mathematically sound way. In order to handle the complexity of this stochastic modelling approach, a systematic and staged way of working has been used. The diagram in figure 6.3 gives an impression of these stages.

6.2 Encounter scenario and ATM concepts

The accident risk assessment is performed for a simple scenario of two en-route traffic streams of RNP1 equipped traffic, flying in opposite direction, all at one single flight level. This rather hypothetical scenario has been developed by Eurocontrol with the aim to learn understanding how ATC influences accident risk, and how far the nominal separation S between opposite RNP1 traffic streams can safely be reduced. The specific details of this scenario are:

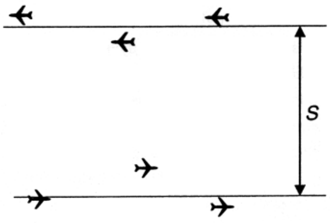

figure 6.1 Opposite direction traffic in a dual lane route

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[20] H.A.P. Blom, G.J. Bakker, P.J.G. Blanker, J. Daams, M.H.C. Everdij and M.B. Klompstra, Accident risk assessment for advanced ATM, Proceedings 2nd USA/Europe ATM R&D Sem-inar, Orlando, FAA/Eurocontrol, Dec. 1998

[21] G.J. Bakker and H.A.P. Blom, Air Traffic Collision risk modelling, Proc. 32nd IEEE Conference on Decision and Control, pp. 1464-1469, December 1993.

[22] H.A.P. Blom, Bayesian estimation for decision-directed stochastic control, Ph.D. thesis, Delft University of Technology, 1990.

[23] M.H.C. Everdij, H.A.P. Blom and M.B. Klompstra, Dynamically Coloured Petri Nets for Air Traffic Management Safety purposes, In: Proceedings 8th IFAC Symposium on Transportation Systems, pp 184-189, 1997b.

[24] M.H.C. Everdij, M.B. Klompstra and H.A.P. Blom, Development of mathematical techniques for ATM safety analysis, MUFTIS Safety study Final Report Part II, European Union DGVII, NLR report TR 96197 L, 1996

- Straight route, with two traffic lanes (figure 6.1),
- Flight plans contain no lane changes
- Parameter S denotes distance between the two lanes,
- Opposite traffic flows along each lane,
- Aircraft fly at one flight level only
- Traffic flow per lane is 3.6 aircraft/hour,
- All aircraft nominally perform RNP1,
- None of the aircraft are TCAS equipped,
- Target level of safety is 5 10^{-9} accidents/flight hour.

This simple scenario is considered for the following three ATM concepts:

I. Procedural separation only. In this case there is no ATC surveillance system. This is the type of situation encountered with traffic over the North Atlantic.

II. STCA-only based ATC. In this case there is R/T communication, but it is assumed that ATC is doing nothing unless its STCA system issues an alert; thus assuming no monitoring by the ATCo. It should be noticed that this differs significantly from conventional ATC, where an executive controller autonomously monitors and issues corrective actions, while STCA is a safety net only.

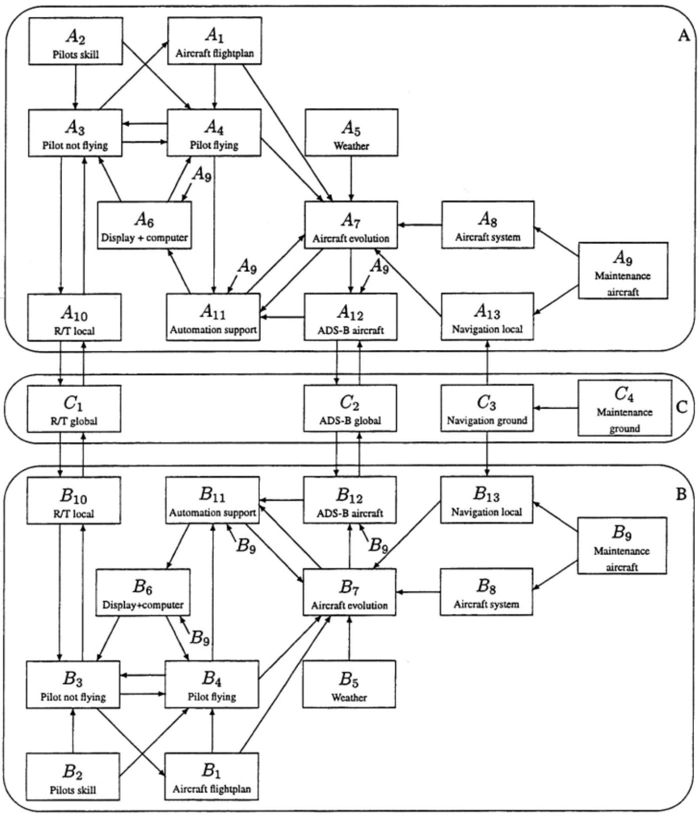
III. Basic airborne separation assurance. In this case there is ADS-B surveillance and R/T between aircraft, but there is no ATC. For this concept it is assumed that aircraft behave co-operatively, in the sense that when an aircraft's CDR (Conflict Detection and Resolution) system detects a conflict with another aircraft, then its pilot will try to make an avoidance manoeuvre. Thus, in most cases both pilots will try to make an avoidance manoeuvre.

For each of these three ATM concepts there are various traffic navigation and encounter scenarios that deserve an accident risk evaluation. We believe, however, that it is most effective to learn understanding the safe separation issues for a simple traffic navigation and encounter scenario first, before considering other and more complicated scenarios.

Given this simple scenario, for each ATM concept operational experts have been involved to define under normal working conditions, the human responsibilities, the operational procedures that are used and the functioning of the technical systems that are part of the ATM scenario within the operational boundaries and time horizon. In support of this concept definition phase a functional representation of the ATM concept is also being made. This representation consists of modules and the information flow between those modules and depicts the ATM environment through sub-systems or sub-processes. For the basic airborne separation assurance concept III the functional representation is given in ..

Next the non-nominal events and working conditions are identified through making use of NLR's existing hazard database, and the established structured brainstorming approach with various operational experts, pilots and controllers.

The hazards newly identified for concept III are given in Table 6.1. From this point on the risk assessment activities continue with the quantitative part through stochastic modelling, Monte Carlo simulation and collision risk evaluation. The various steps of this approach are depicted in figure 6.3.



A_1, B_1: Aircraft flight plan
A_2, B_2: Pilots level of skill
A_3, B_3: Pilot not flying, level of performance
A_4, B_4: Pilot flying, level of performance
A_5, B_5: Type of weather
A_6, B_6: Display+computer
A_7, B_7: Aircraft evolution
A_8, B_8: Aircraft system
A_9, B_9: Level of maintenance, aircraft
A_{10}, B_{10}: R/T, local
A_{11}, B_{11}: Automation support
A_{12}, B_{12}: ADS-B aircraft
A_{13}, B_{13}: Navigation support, local
C_1: R/T, global
C_2: ADS-B, global
C_3: Navigation support, ground
C_4: Maintenance ground

figure 6.2 Functional representation of ATM modules and their interrelations for the basic airborne separation assurance concept III. The modules named A- and B refer to specific aircraft functons while C refers to functions common for all aircraft..

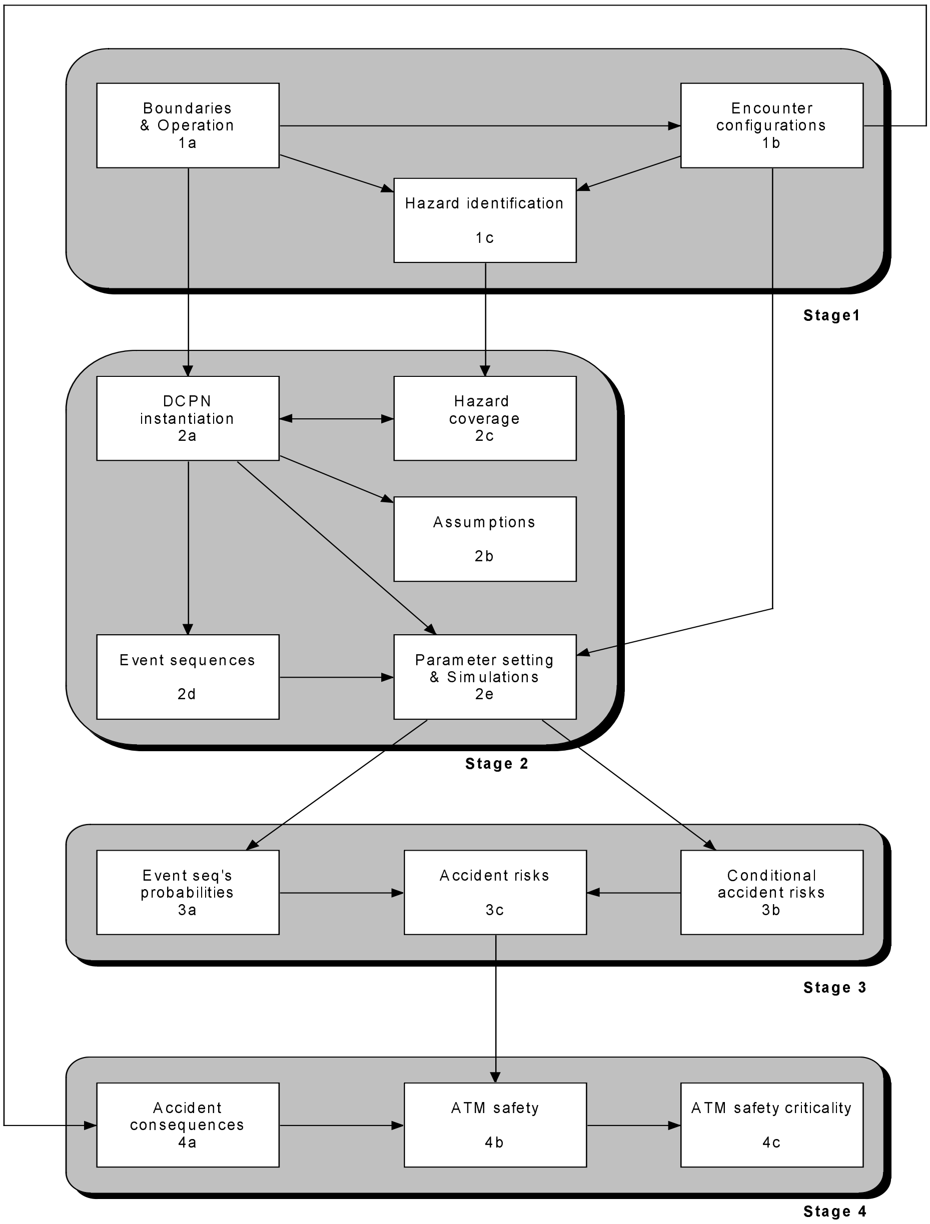


figure 6.3 Overview of TOPAZ methodology

Table 6.1 New hazards of concept III: free flight

#	**Non-nominal event**	***Comment***
1	ADS-B receiver malfunction	
2	ADS-B transmitter malfunction	
3	Misidentification signal/aircraft	
4	False conflict alert	
5	Secondary conflicts	*Caused by evasive manoeuvre*
6	Mountains	*Possible problem for evasion*
7	Software errors	
8	Avoiding bad weather: more conflicts	*Higher local traffic density: aircraft fly around bad weather*
9	Restricted airspace	*Higher local traffic density: aircraft fly around restricted airspace*
10	Weather influence on airborne systems	
11	Avoiding bad weather: increase crew workload	
12	Bad weather: shift pilot attention	
13	Identification non-existent conflict	*Intruding aircraft does not exist*
14	Military aircraft	
15	Influence competition airlines	*See 16, 17, 18*
16	Breaching rules	*Crew overrules resolution*
17	"Push" other aircraft out of the way	*Let other aircraft evade*
18	Formations of same airline	
19	Increased traffic density	*Leads to more conflicts*
20	Airport closures	*Leads to local increased traffic density*
21	Fuel shortage	*Due to many evasive manoeuvres*
22	(Unidentified) emergency flight	*Is expected to follow the rules but cannot*
23	Single-man crew	*Other crew members unavailable*
24	Aircraft manoeuvre off limits	*Aircraft can not perform resolution*
25	Transponder breakdown	
26	ADS-B performance level wrong	*ADS-B is not fully developed yet*
27	Anticipation on conflict resolution	*Aircraft enter conflict such that resolution is to their favour*
28	Wrong navigational input	
29	Wrong navigational output	
30	Transmission without FMS	*ADS-B transmission should contain FMS data*
31	Confusion FMS/heading info.	
32	Lack of pilot situational awareness	*Conflict resolution is too automated*
33	Pilot does not acknowledge conflict res.	
34	Pilot reaction too late	
35	Aircraft in wrong mode for conflict res.	*Conflict resolution in FMS mode only*
36	Multiple conflicts without resolution	*Situation not covered by resolution generator*
37	Domino effect conflicts (stable)	*Each conflict causes one or less than one new conflicts (on average)*
38	Snowball effect conflicts (explodes)	*Each conflict causes one or more than one new conflicts (on average)*
39	Visual contact interference	*Causes pilots to improve upon proposed resolution*
40	Danger of conflict underestimated	
41	Border protected zone: "never mind" effect	*Conflict is ignored*
42	Communication between crews	*Crews negotiate other resolution*
43	Pilot "improves" upon advisory	
44	Pilot reaction time	
45	Display failures	
46	Noise in aircraft speed vectors (turbulence)	*Alert switches on/off*
47	Total electronic failure	
48	Navigational error: own position	
49	Speed differences too large for look ahead time	*Conflict occurred before detection*
50	GPS failure/breakdown	
51	Wrong altitude measurement setting	
52	Autopilot failure	
53	TCAS alert	*Increase crew workload*
54	Weather forecast wrong	*Aircraft unnecessarily avoid bad weather*
55	Up date weather forecast	*Aircraft adjust their plans at the same time*
56	Crew disagreement	
57	Crew overload	

#	Non-nominal event	*Comment*
58	Priority flights	*Possibly not noticed*
59	TCAS advisory different from Free Flight resolution	
60	Flight path different from FMS	*Wrong intent information is sent*

6.3 Accident risk assessment results obtained

For each of the three ATM concepts an assessment of accident risk has been performed for the above scenario, as a function of the spacing parameter S. The resulting accident risk curves are presented in figure 6.4. Since all three curves are based on conservative modelling assumptions for the ATM situations considered, they provide an upper bound for the true accident risk.

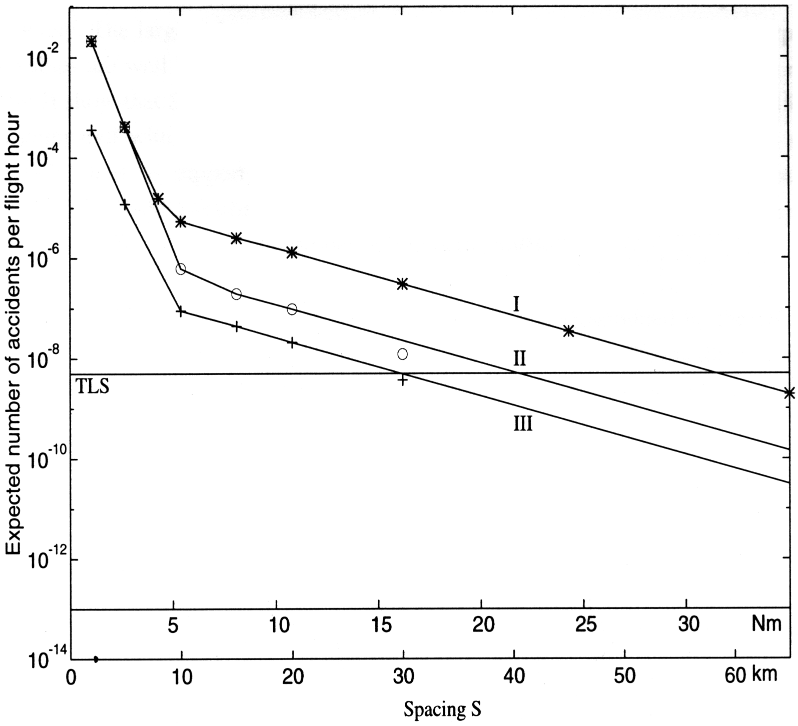


figure 6.4 Accident risk for the opposite traffic scenario, as a function of spacing parameter S, for the three ATM concepts considered: I) Procedural separation, II) STCA-based ATC, III) Basic airborne separation assurance

These results are obtained during two subsequent studies. The first en-route study was conducted for Eurocontrol, and covered ATM concepts I and II. The assessment of concept I was rather straightforward, and could also have been done following ICAO's approach[25]. For the assessment of the other two concepts, however, full use has been made of the advanced risk assessment methodology. Concept II has been assessed during an initial study for Eurocontrol. Concept III has been developed and assessed during studies within the Free Flight research programme. The safety assessment results from concepts I, II and III have subsequently been fed back to NLR's Free Flight design team to support the further development of Airborne Separation assurance concepts.

The risk curves in figure 6.4 show that for RNP1 performing aircraft, the ATM concept may have quite an impact on the selection of the spacing parameter S within a straight dual lane route structure. For the three ATM concepts considered it has been shown that the spacing S can safely be reduced to 31 NM, 22 NM and 16 NM for ATM concepts I, II and III respectively. The large value of 31 NM for concept I does not come as a real surprise, such large values are well known for procedural traffic situations over the ocean. The results for concept II show that STCA really is a safety net which provides at least a factor 15 in safety when compared with concept I for sufficiently large spacing S. Apparently, this STCA safety net alone falls short to support the kind of spacings necessary for busy fixed route traffic situations. This finding confirms the prior expectation that concept II is not representative for conventional ATC, in which a controller monitors the traffic.

It appeared that for all three concepts, the safe spacing was determined by the effects of the exponential tails of large deviations due to non-nominal situations. This is illustrated in figure 6.5 for concept III. Thus the weakness of all these concepts is that the non-nominal effects stay above the TLS and this determines the safe spacing.

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[25] ICAO, Methodology for the Derivation of Separation Minima Applied to the Spacing between Parallel Tracks in ATS Route Structures, Circular 120-AN/89, 1974.

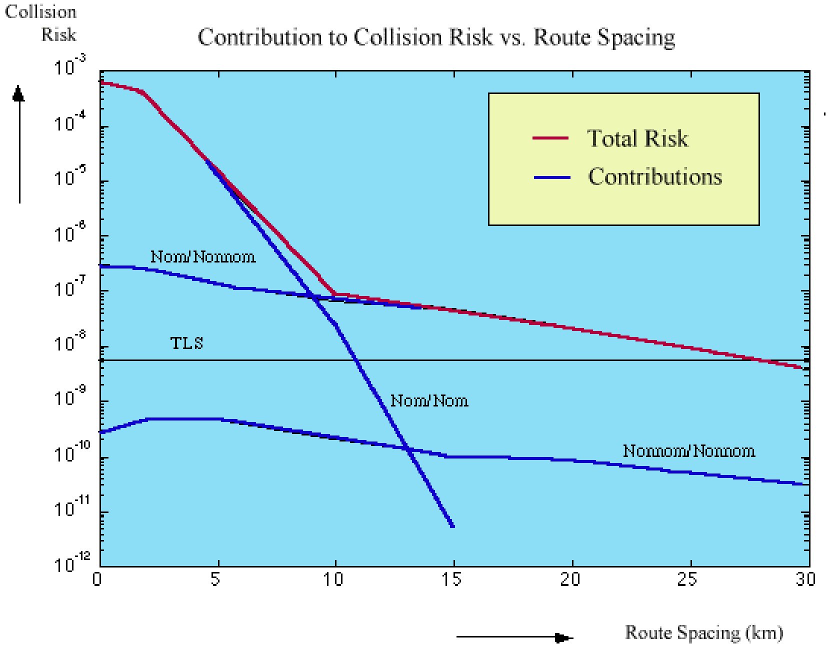

figure 6.5 Concept III, contribution to risk of a/c evolution values (upper bounds). Explanation of graphs. From top to bottom: nominal/nominal, nominal/non-nominal, non-nominal/non-nominal.

At that time rather unexpectedly, the co-operative basic airborne separation concept III appears to perform better than concept II. The reason appeared to be that with the ground-based concept II there is one single monitoring and decision-making loop (surveillance-STCA-ATCo-R/T-pilot-a/c), while for the co-operative airborne-based concept III each of the two encountering aircraft has a monitoring and decision-making loop (surveillance-CDR-pilot-a/c) which are partly independent. As a result, the safety net of concept III leads to a factor 5 lower risk than concept II for the same spacing, or allows to safely reduce S from 22 NM to 16 NM. Obviously, such improved safety net still falls short to support the kind of spacings necessary for busy fixed route traffic situations. Thus in view of their safe spacing values of 22 NM and 16 NM, concepts II and III do not support spacings that are required for busy fixed route situations over the continent.

6.4 Concluding remarks

Summarising, the results obtained show:

- The basic airborne separation assurance concept has lower risk than a comparable ground based concept as evaluated in an earlier study, especially for spacings below 5 Nm. The target level of safety, however, is met for spacings of about 16 Nm. For these spacings the collision risk improvement is about a factor 5.
- The graph of the risk versus the route spacing shows a decrease of slope at a route spacing of approximately 5 Nm. This effect occurs for both the airborne and ground based concepts. The underlying reason for the decrease of slope is that for route spacings beyond 5 Nm situations where one aircraft

has non-nominal evolution are the main contributor to collision risk. Non-nominal evolution includes events like failures of navigation systems (both air and ground), aircraft having a flight plan that does not correspond to the parallel route and failures of aircraft airborne systems in general. The decrease of collision risk with increasing route spacing is considerably less for aircraft that have non-nominal evolution than for aircraft with nominal evolution.

- The increase in capacity is significant: the sufficient separation value of 22 Nm for the ground based concept goes down to about 16 Nm for the basic airborne separation assurance concept
- Situations where two conflicting aircraft both refrain from performing a timely evasive manoeuvre are not the main contributors to collision risk. This is due to the fact that the capability of an aircraft to perform an evasive manoeuvre is almost independent from the capability of other aircraft being able to perform an evasive manoeuvre. Hence the probability that none of two aircraft timely realizes an evasive manoeuvre is relatively low.

It should be stressed that these findings form an initial safe separation comparison of airborne separation assurance concept (III) versus ground based concepts (I and II) only. For this comparison several hypothetical assumptions have been adopted. Under those hypothetical assumptions, the evaluated Airborne separation Assurance concept appears to induce a lower accident risk than the evaluated ground based concepts. A change from concept II to concept III in particular shows the impact of three effects:

1. The Basic Airborne separation Assurance concept (III) avoids the extra delay incurred with the involvement of an air traffic controller,
2. The Basic Airborne separation Assurance concept (III) avoids the need for R/T communication,
3. The Basic Airborne separation Assurance concept (III) implies that nominally both aircraft execute an avoidance manoeuvre, and not just one aircraft such as with “ground based separation ”.

These findings provide basic insight into ATM conceptual design, as long as the hypothetical nature of the assessments is kept in mind.

It is clear that these initial risk assessment results are not intended to answer the general question if Airborne based Separation is better than ground based separation. Many important aspects are simply not covered, such as:

- Conventional ATC commonly implies that the tactical controller applies radar monitoring based control, rather than reacting on STCA only.
- With Airborne separation assurance concepts normally the pilot-not-flying monitors the traffic.
- Airborne separation assurance concepts are aimed at aircraft to fly outside fixed route structures and without a procedural clearance.
- The result is only valid within this operational concept
- Encounters, e.g., with climbing, descending or manoeuvring traffic should also be assessed.
- Possible presence of TCAS has been ignored

Reasonably, these aspects have to be understood before one could make any safety comparison between conventional ATM and Free Flight. This asks for additional risk assessment studies. As such our following risk assessment evaluations are directed to gaining insight into aspects of monitoring and communication. This step-by-step approach is the only way to learn answering the possibilities and limitations of airborne separation assurance and ground based concepts.

7 Human Machine Interface

7.1 Task analysis

To perform airborne separation, it is required to have adequate information on the surrounding traffic. This is not available in today's cockpit. Therefore changes in cockpit avionics are required. To determine the requirements for the human machine interface, the separation assurance is divided in the following subtasks:

1. Traffic monitoring
2. Conflict detection
3. Conflict resolution
4. Recovery
5. Inter-Traffic radiotelephony

7.1.1 Traffic Monitoring

Monitoring the traffic has several goals:

1) build up situational awareness
2) check conflict detection
3) strategic traffic flow

To be able to see the dynamic traffic patterns on the display, allows the crew to see the 'history' of several flights to the vicinity. This will provide the crew with the 3-D (4-D) mental model of the position and speeds of the relevant aircraft. This may seem a daunting task. During experiments however it has been shown that airline crews, without any extra means but the radiotelephony, were able to draw a sketch with the positions of up to four aircraft[26]. These aircraft were selected for relevancy for the flight. Since airline pilots already possess this skill, there apparently is a need to do this. Indeed, over areas without radar coverage, this backup of ATC has often proven to be essential.

The resulting mental traffic picture also aids the crew in the decision how to resolve a conflict. An idea of where space is available or which maneuver will result in a bottleneck further away, is helpful in the selection of the conflict resolution maneuver.

The situational awareness might also be enhanced by observing maneuvers of other aircraft, indicating a weather situation like thunderstorms, turbulence or favorable winds.

Another goal of monitoring the traffic is to check the conflict detection module. Although detecting a conflict several minutes ahead is a calculation better suited to computers, humans can still be a last-minute backup. If there is a total failure of the conflict detection module, a traffic display might provide a way to at least

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[26] Result from NLR trials investigating party line effect in basic R/T compared to Controller-Pilot Data Link

avoid a near-miss. The lookahead time will probably be decreased and the achieved separation may be less than required, but it is still a useful backup.

The third in the list of goals of monitoring the traffic is the strategic aspect. To be able to see the history of traffic pattern, especially in a known route environment, might provide the crew with information enabling them to adjust the route to avoid delays or 'clouds' of traffic further away than the lookahead time of the conflict detection module.

7.1.2 Conflicts Detection

Detecting the conflict consists of several subtasks:

1) predicting the ownship's trajectory for the look ahead time horizon
2) selecting potential intruders for the look ahead time horizon
3) predicting the intruder's trajectory
4) estimating the minimum distance at the closest point of approach (CPA)
5) comparing minimum distance with required separation

In this study the conflict detection task has been allocated to the automation as opposed to showing the traffic information on the display and leave the detection of conflicts up to the crew.

The reasons for this allocation are:

1) humans are not good at monitoring tasks, so one shouldn't rely on them monitoring traffic for conflict detection
2) there is a clear computational aspect to all five identified subtasks. Similar to ICAO guidelines[27] it is the belief of the project team that computation is one task which should be left to the automation. These calculations, which can be regarded as data processing or conversion, should provide the crew with enough information for the conflict resolution decision. Decision making is a task which should be performed by the human operator. This ensures the human is in the loop.
3) Scheduling advantage: a computer can run a computation continuously (that is: when new data are available), while the crew has several other tasks and is also not able to continuously check for conflicts during the remaining time for several hours.

Therefore in this study the five subtasks are performed by the conflict detection module inside the ASAS (Airborne Separation Assurance System).

As soon as a potential conflict has been detected within the look ahead time, the crew should be alerted and all the information regarding the nature of conflict should be shown in a way that enables the crew to understand the conflict detection process resulting in this alert (thus providing transparency).

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[27] ICAO circular 249-AN/149 guidelines

7.1.3 Conflict Resolution

After the conflict has been detected and the crew is aware of the fact that there is a conflict, the conflict resolution process starts. The conflict resolution task consists of the following steps:

1) assessing conflict situation
2) generating options to solve the conflict
3) deciding how to solve the conflict
4) executing resolution maneuver
5) monitor until the conflict has been solved
6) adjust maneuver when necessary to most optimal conflict-free direction

The first step is to assess the conflict situation focused on the next step: generating options to solve the conflict. After several options have been generated, a decision has to be made, and in case of a two man crew, agreed-upon, which conflict resolution maneuver is going to be used. The next step is actually dialing in the resolution maneuver into the mode control panel or keying it into the flight management system (FMS).

When the maneuver is being performed by the aircraft, the crew monitors not just the flight state, but also the effect on the detected conflict to determine the effectiveness of the maneuver. Sometimes it might be necessary to go back to step 2 of the process, though this should be avoided in the design of the systems and procedures as much as possible, since time is precious when a conflict has been detected.

In case of a co-operative maneuver, the conflict might already be solved halfway the conflict resolution maneuver. In that case there is a sixth step: adjusting the conflict resolution maneuver. It might consist of for example selecting Heading Hold halfway a Heading Select maneuver, that initially did not assume any horizontal maneuvering of the intruder aircraft.

The automation might provide help in the first two steps, since this involves computations without any decision making. The decision for the resolution maneuver should be left up the crew, since they might be aware of relevant factors unknown to the ASAS system.

7.1.4 Recovery Maneuver

A conflict resolution maneuver is in general a deviation from the optimal route. Though in case of direct routing there is no need to return to the original route (see figure 7.1), it is still desirable to fly to the destination (or next fix outside the free flight airspace) in the most optimal way as soon as possible. In general this is possible after passing the intruder aircraft.

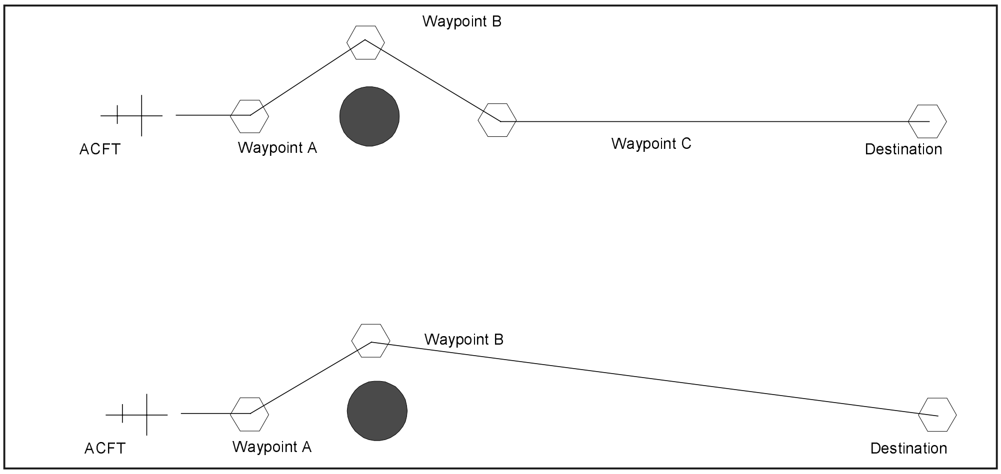


figure 7.1 The effect of a route deviation compared to a deviation in a direct route environment

From both the flight dynamics (pitching is quicker than turning) as economical point of view, vertical resolutions are optimal. The economic advantage is caused by two effects: the magnitude of a vertical maneuver is best due to the flat shape of the protected zone (the required vertical speed is in the order of 100 feet per minute) and the exchange of potential and kinetic energy can be reversed in the recovery maneuver, minimizing the effect on the efficiency of the flight.

7.1.5 Inter Traffic Radiotelephony

Apart from the radiotelephony between the ground based air traffic controller and the crew in the aircraft, there is often inter-traffic radiotelephony, especially in sectors without radar coverage and without a large amount of the controller interference like over the oceans. The nature of this communication varies: often it is to warn following aircraft for turbulence at certain altitudes, sometimes the feasibility of a request to change altitude is verified before requesting it to ATC.

7.2 Cockpit Display of Traffic information

What are the requirements for the human machine interface resulting from the task analysis in section 7.1? The subtasks, as identified in the previous section, are listed below together with the resulting requirements.

Traffic Monitoring:
TM1 – position of traffic: latitude/longitude or bearing/distance and altitude
TM2 – speeds of traffic: ground speed, track, vertical speed
TM3 – traffic information should be in same reference frame as the navigation information

Conflict Detection:
CD1 – provide alert when a conflict has been detected, that is also effective when the crew is not monitoring a specific display (thus aural)

CD2 – provide symbology with conflict information: when, where, who and geometry of closest point of approach (nature of conflict)
CD3 – provide transparency as to why the system predicts this conflict

Conflict Resolution:
CR1 – compute several options
CR2 – show options on display as advisories
CR3 – assists crew in execution of resolution maneuver
CR4 – provide insight into vertical situation because vertical maneuvers are generally preferable

Recovery Maneuver:
RM1 – enable crew to determine moment of recovery

Inter Traffic Radiotelephony:
IR1 – provide call sign on the traffic information display to enable the crew to call the aircraft via the radio (call sign is also useful for crew coordination)

General requirements used in the design:
1) minimize impact on cockpit
2) minimize clutter
3) provide crew with means to configure display
4) minimize training by avoiding cryptic symbology
5) minimize crew actions

7.3 Cockpit Display of Traffic information

7.3.1 Predecessor: TCAS display

The task of the Cockpit Display of Traffic Information (CDTI) is to inform the crew of the traffic around the aircraft. It is similar to the radar screen of the air traffic controller but from the perspective of one aircraft. There is already some traffic information available in today's aircraft fitted with TCAS and a navigation display. This traffic information is shown integrated on the navigation display with the symbology as shown in figure 7.2.

figure 7.2 Example of a TCAS displays (Honeywell TCAS 2000 display)

This Honeywell TCAS 2000 display shows the aircraft's own position by an aircraft symbol surrounded by a ring of dots representing a range of 2 nm. Four standard TCAS symbols, in increasing order of threat, indicate the status of traffic:

- an outline diamond (other traffic)
- a filled-in diamond (proximate traffic)
- an amber circle (TA – Traffic Advisory)
- and a red square (RA – Resolution Advisory)

An intruder's relative altitude, in hundreds of feet, is shown by a "+" or "-" sign followed by two digits. Altitude data are displayed above the symbol for "aircraft above" and displayed below for "aircraft below." An arrow after the altitude indicates whether the intruder is climbing or descending more than 500 feet per minute. The maximum range of traffic generating TCAS alerts is about 20 nm. Aircraft fitted with mode-S (the same medium that can be used to exchange ADS-B) are detected up to 100 nm with position information from the message

The TCAS symbology also formed the basis for the traffic symbology on the CDTI. There are also some differences. The way TCAS senses the position of other aircraft results in the following data:

- Bearing
- Altitude and vertical speed (derived from altitude)
- Range and range rate (derived from range)

The ADS-B position and velocity message results in larger and more accurate data set:

- Call sign
- Latitude
- Longitude
- Altitude
- Ground speed
- Track angle ('heading')
- Vertical speed

The TCAS symbology, using diamonds, circles and squares, does not show the call sign, the ground speed and the track. For maximum TCAS compatibility adding extra text labels and a line to indicate track is an option. The disadvantage of this is the resulting clutter of especially the track lines in high traffic density situations. An example of a CDTI based on TCAS symbology is shown in the figure below.

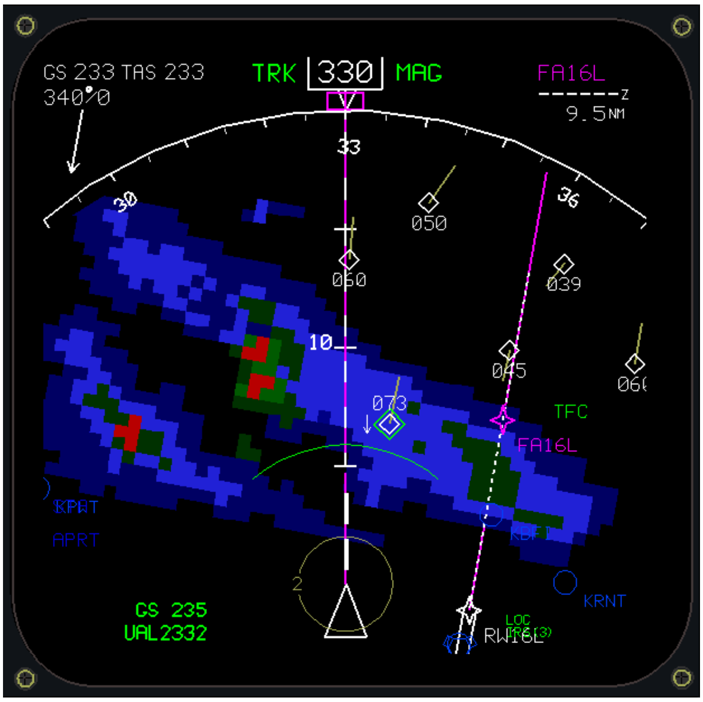


figure 7.3 CDTI based on TCAS symbology with track line (source: MITRE)

7.4 NLR Traffic Display

7.4.1 Display Layout

Both to avoid a major impact on the cockpit and to minimize crew actions, the traffic information is shown on the navigation display in the map mode, instead of a dedicated traffic display or a separate mode. Showing the traffic symbols integrated on the navigation display also ensures the same reference frame is used for traffic information and the navigation information [requirement TM3].

To stress the vertical aspect [CR4], a vertical display has been added, resulting in the following configuration:

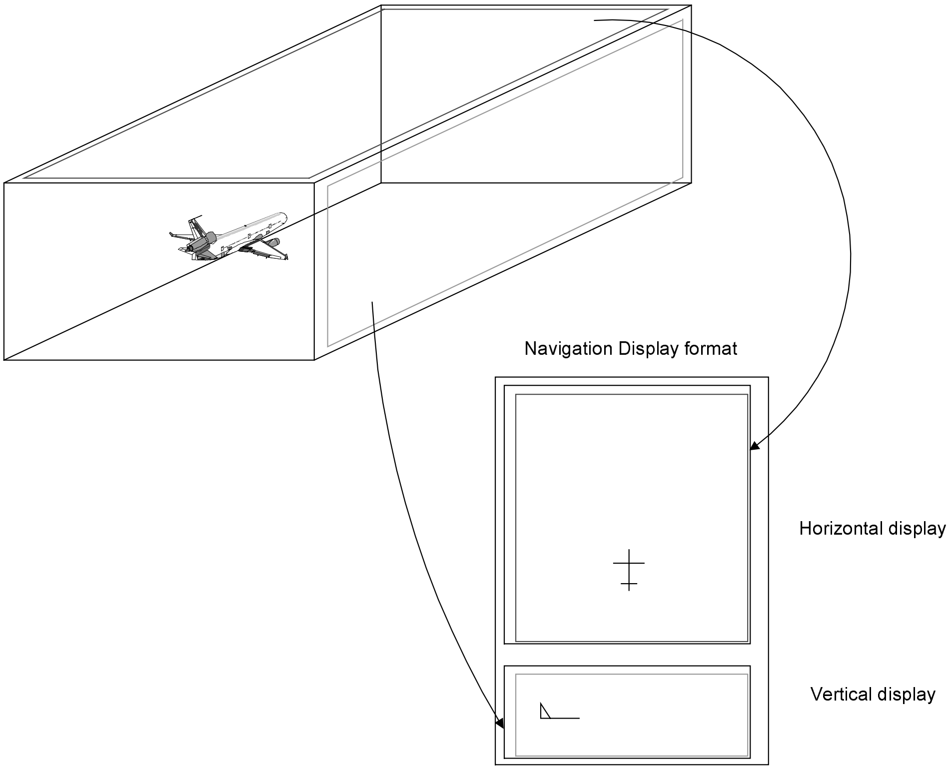


figure 7.4 Projection method of biplanar (co-planar) traffic display

The horizontal display shows the top view and the vertical display shows the side view of the block of air selected by the horizontal and vertical range. Aircraft outside the vertical range are not shown on the horizontal display and vice versa. In this way, the horizontal display can be decluttered by decreasing the vertical range.

An alternative to the side view is the view from behind the aircraft. Using this projection has been considered for the vertical display. It facilitates the correlation with the traffic symbols on the horizontal display. The reason for not using this projection for the display is the fact that the ground speed vector is perpendicular to this plane. When the ground speed lies in the plane, it provides a useful time axis for the conflict information.

A study performed by Merwin, O'Brien and Wickens[28] have compared different projection methods for several tasks among which traffic monitoring. From these studies it was concluded that the co-planar projection was optimal for showing traffic information. Therefore this projection method was chosen for this study. Still, alternative display formats like a perspective display are being investigated and developed at NLR.

7.4.2 *Traffic Information*

The traffic symbol used in the NLR display is different from the diamonds as used by TCAS. By using a directional symbol, it is possible to show the track without cluttering the display with extra lines. To display the traffic position and speed [TM1, TM2], the following symbol was chosen for the NLR display:

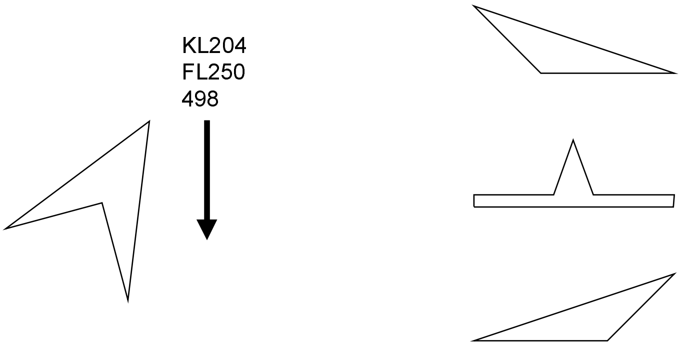


figure 7.5 Traffic symbol on horizontal display (left) and vertical display (right). The vertical symbols indicate an aircraft flying in the same direction (top), within 30 deg perpendicular to our track (center) or opposite traffic (bottom)

7.4.3 *Conflict Symbology*

The conflict symbology should be shown in the same reference frame as the navigation information [TM3]. Therefore the absolute position of the conflict is shown on the display instead of the relative position (see figure 7.6).

---

[28] Merwin, D., O'Brien J. V., & Wickens, C. D. (1997). Perspective and coplanar representation of air traffic: Implications for conflict and weather avoidance. Proceedings of the 9th International Symposium on Aviation Psychology. Columbus, OH: Dept. of Aerospace Engineering, Applied Mechanics, and Aviation, Ohio State University.

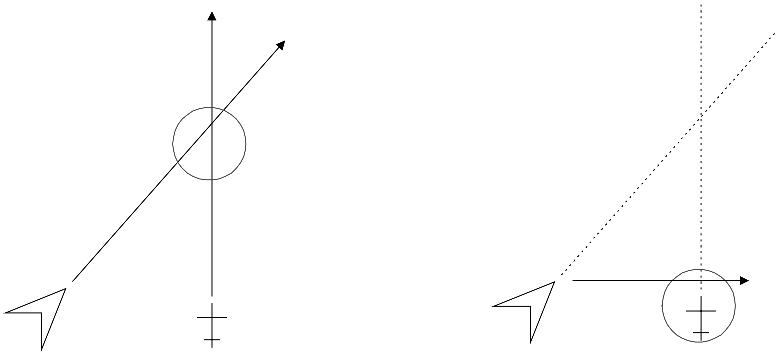


figure 7.6 Absolute (left) and relative (right) indication of conflict location

The geometry of the conflict, or more precisely the closest point of approach (CPA), is important for the conflict resolution. Therefore this geometry is shown by drawing the protected zone of the intruder aircraft at this position. The resolution maneuver should aim to avoid crossing this zone. Then the minimum distance will be equal to the required separation and hence the conflict will be resolved.

The conflict symbology is shown in the figure below. It is in fact that same figure as used to explain the resolution algorithm in section 5.5 providing transparency [requirement CD3]. Connecting the CPA with the intruder aircraft yields the intruder's trackline and connects the conflict symbology with the problem aircraft (indicating the 'who' from requirement CD2). In the traffic symbols of the intruder aircraft an extra text field pops up when there is a conflict. This field indicates the time to loss of separation ('when' from requirement CD2). This time can be substantially earlier than the time of CPA if the closure rate is low. The time to loss of separation is also used for determining the urgency level:

- red symbology indicates a loss of separation within 3 minutes
- amber symbology indicates a loss of separation between 3 and 5 minutes ahead

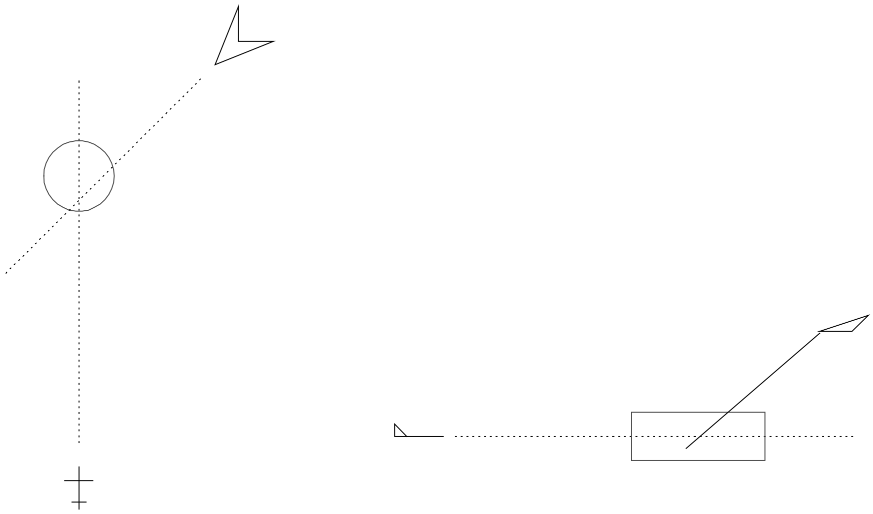


figure 7.7 Conflict symbology for horizontal (left) and vertical display (right)

7.4.4 Resolution Symbology

Though the conflict symbology already indicates what the geometry and thus the advised resolution maneuver will be, there is some additional, magenta resolution symbology to assist the crew in executing the resolution maneuver [CR3]. The resolution advisory consists of an advised heading (or track), speed and vertical speed. The precise values of this advisory are indicated by a dashed track line, a bug on the heading scale, a dashed vertical path line and bugs on the speed and vertical speed scale. The symbology allows the crew to choose between the horizontal and the vertical maneuver as well as to exchange a speed change with some extra heading change.

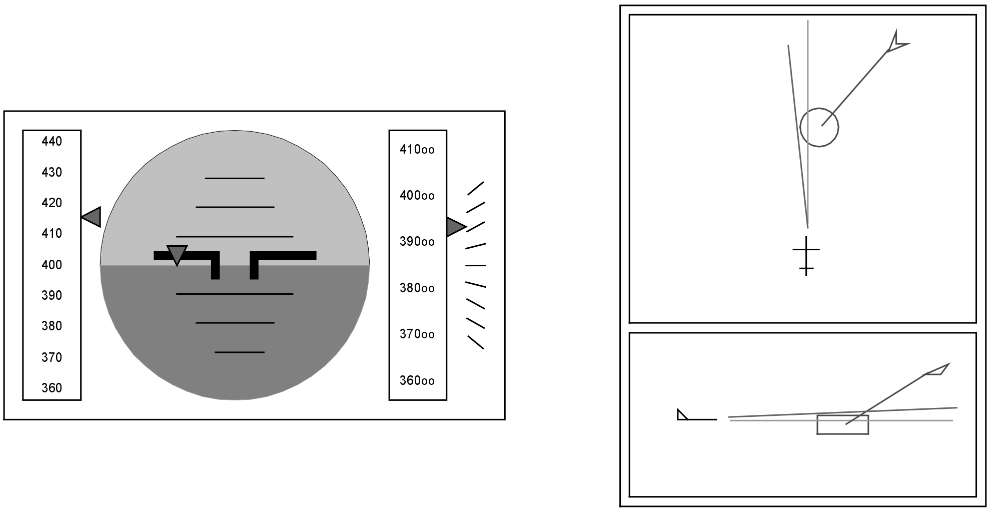


figure 7.8 Resolution symbology (in magenta) on primary flight display and navigation display

7.4.5 Additional Features

If the other aircraft maneuvers in the same plane as the ownship, the conflict symbology will disappear halfway to maneuver. At that moment the conflict is solved and the crew can select for example the Heading Hold mode to maintain the direction of the current speed vector, until the intruder aircraft has passed [RM1].

When a conflict consists of only a minor intrusion, the conflict symbology may appear for only a short moment. The conflict symbology can also disappear because the intruder aircraft responds quickly to a minor conflict. In these situations a crew might hear the aural alert but miss the conflict symbology. To inform the crew which aircraft caused the alert, the traffic symbol of that aircraft will remain red or amber for little while (on average about 10 seconds). It also increases situational awareness [TM1] in general by indicating the aircraft for which the conflict has been solved.

Conflict alerts due to turning aircraft are suppressed by the filters in the conflict detection module.

The horizontal display can be decluttered by decreasing the vertical range. Though the vertical display is also affected by an adjustment of the horizontal range, it does not sufficiently declutter the display. This is due to the fact that the horizontal range is in the plane of the vertical display. To provide a declutter option for the vertical display, horizontal clipping lines have been added. By adjusting the position of these lines with the display control panel, a smaller part of the horizontal display can be selected for the side view in the vertical display (see figure 7.9)

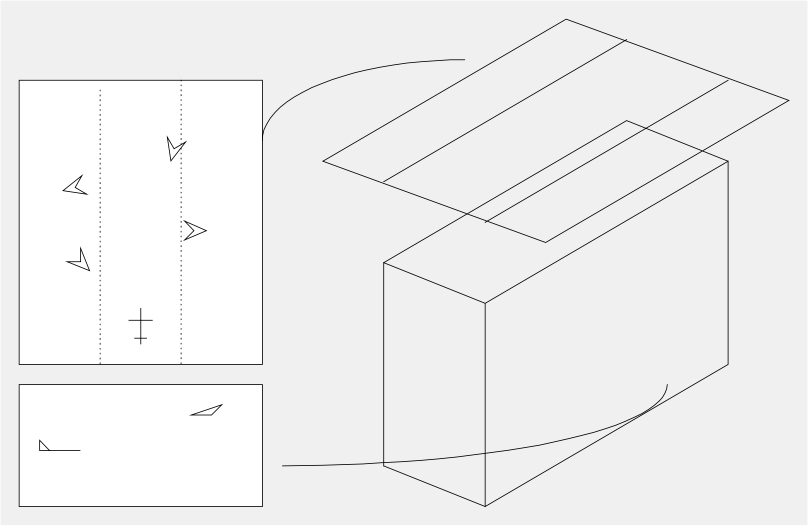


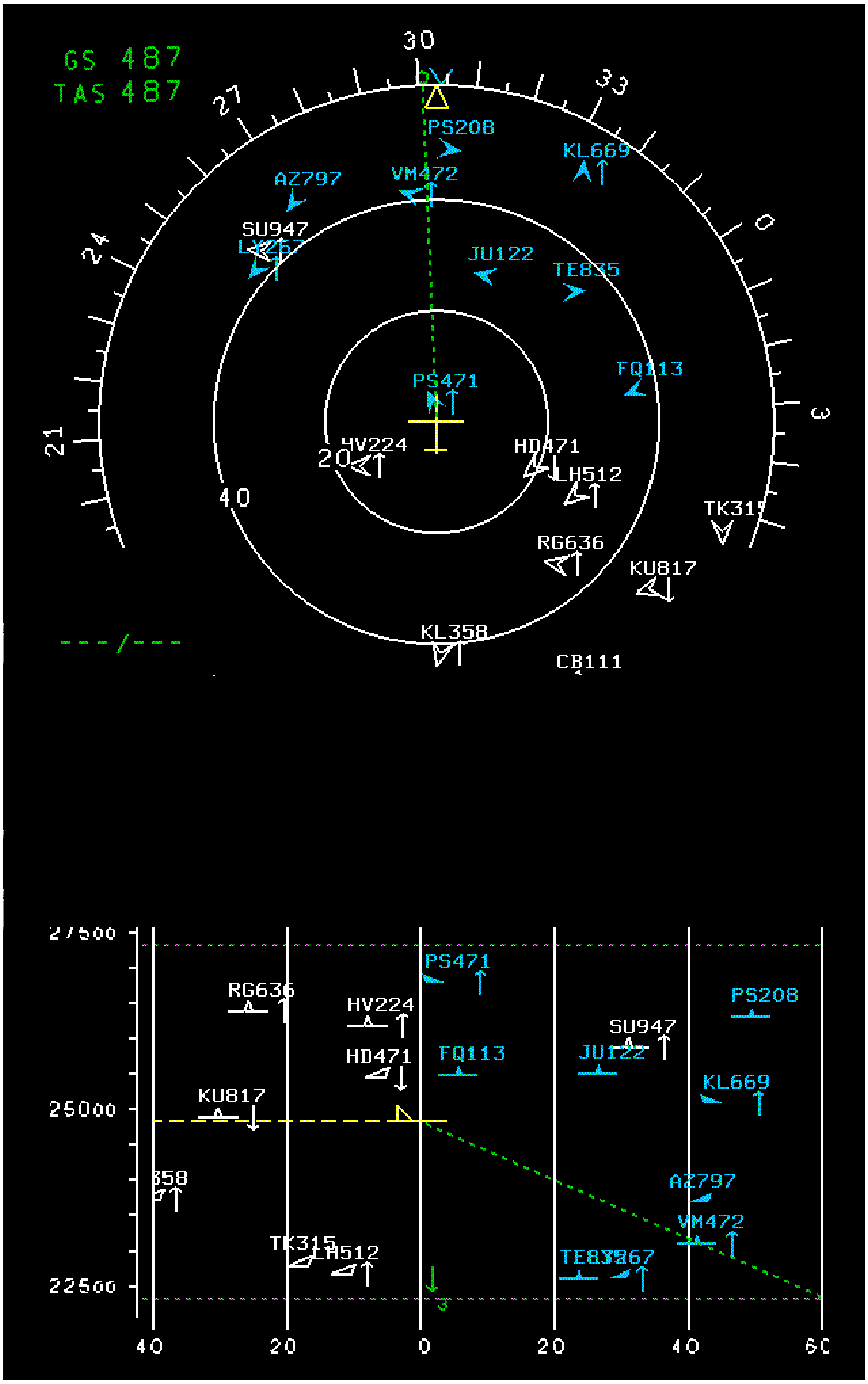
figure 7.9 Effect of horizontal clipping lines on vertical display

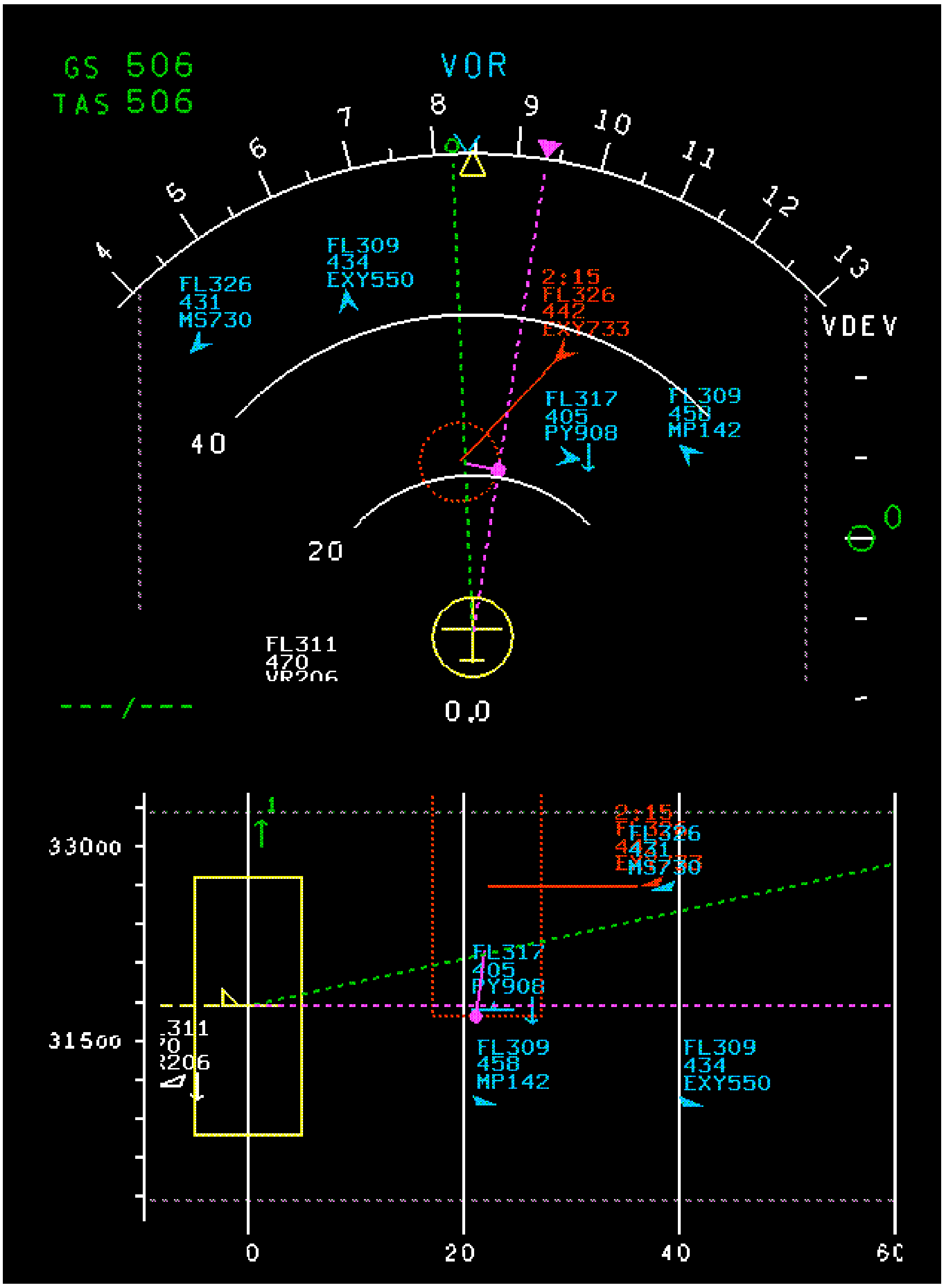
It provides the crew with a tool to look at a smaller cross-section straight a-head.

When an aircraft is outside the selected display range, the ASAS will still detect the conflict and it will also be shown despite the current range settings. If both the horizontal and vertical range are set too low, the lines as well as the protected zone of the ownship will show up on the display, indicating there is a conflict and indicating the azimuth and elevation angles of the CPA.

7.4.6 Snapshots of CDTI

The resulting navigation display with traffic and conflict information shown in the figures on the following pages. For the color of the traffic symbol two different conventions have been used in the study: in the first experiment blue indicated with a decreasing distance (negative range rate), white traffic had an increasing distance (positive range rate). In the mixed equipage runs in the second pahse trials the colour was used to indicate equipage level: white traffic was equipped, blue was not ASAS-equipped. The snapshots show the convention where color was determined by range rate.


GS 487
TAS 487
30
33
27
24
21
0
3
PS208
KL669
AZ797
VM472
SU947
LX267
JU122
TE835
FQ113
PS471
HV224
20
40
HD471
LH512
TK315
RG636
KU817
KL358
CB111
---/---
27500
25000
22500
40
20
0
20
40
60
PS471
RG636
HV224
PS208
SU947
HD471
FQ113
JU122
KL669
KU817
358
AZ797
VM472
TK315
LH512
TE835
LX267
3


GS 506
TAS 506
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FL326
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MS730
FL309
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EXY550
2:15
FL326
442
EXY733
VDEV
FL317
405
PY908
FL309
458
MP142
40
20
0
FL311
470
VR206
---/---
0.0
33000
31500
2:15
FL326
4431
MS730
FL317
405
PY908
FL309
458
MP142
FL309
434
EXY550
0
20
40
60

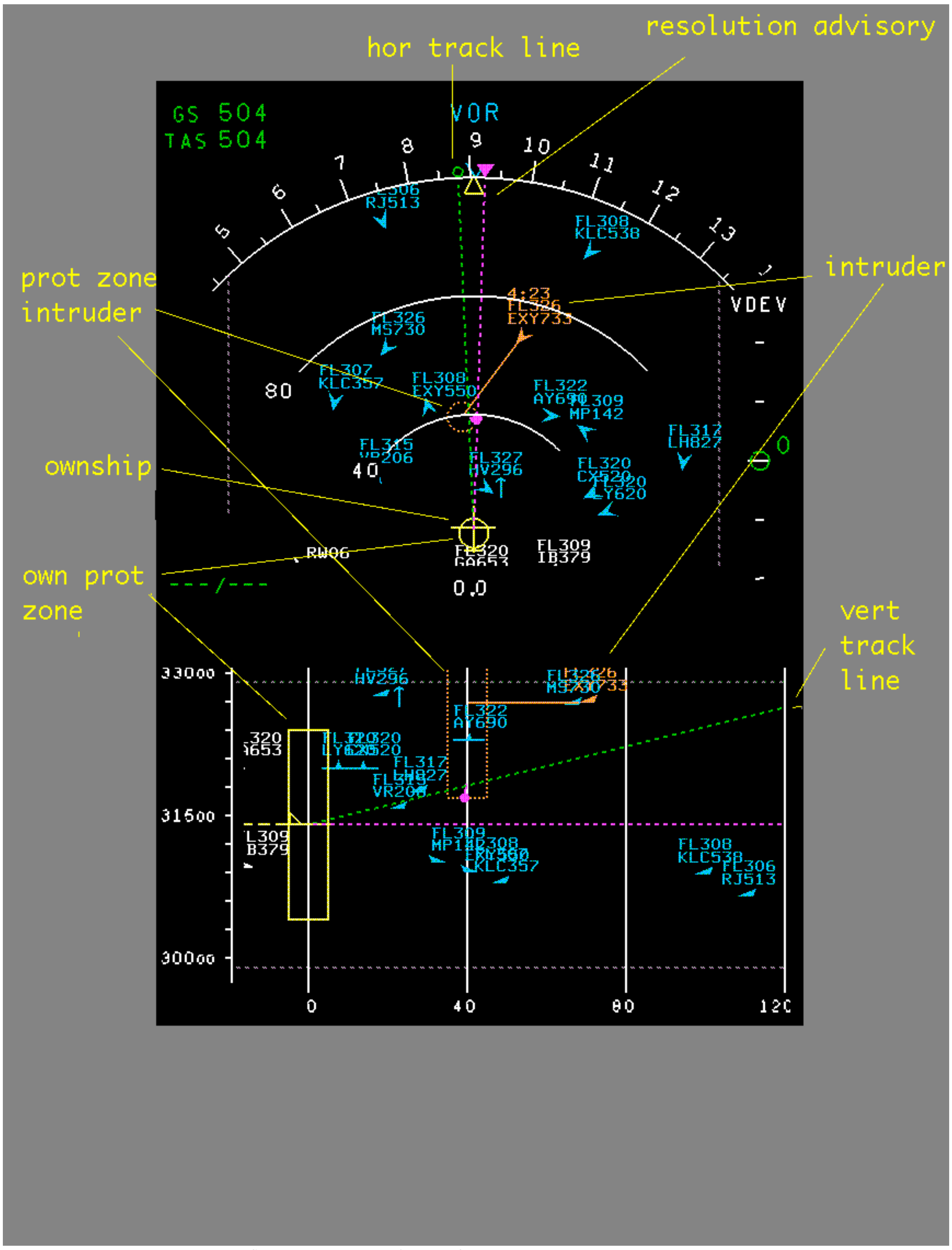


figure 7.10 Snapshots of NLR CDTI

7.5 Aural Alerts

To provide an alert when the crew is not monitoring the traffic display, an alerting sound has been added to the user interface. The goal of this aural alert is to be distinctive, indicate the urgency and prompt the crew to look at the traffic display.

Two urgency levels have already been defined in by the conflict symbology color:

- red conflict symbology indicating a conflict within 3 minutes
- amber conflict symbology indicating a conflict within 3 to 5 minutes

For these two levels a different sound has been chosen. For the amber (lower) urgency signal a beep-sound is used. The same sound indicates a threatening radar lock in the F-18 Hornet. It consists of two high-pitched beeps with a low repetition rate. For the red (higher) urgency level a sound indicating a missile launch in the F-18 has been used. This sound consists of continuously repeating this same beep with a high repetition rate.

7.6 Predictive ASAS

After the first simulation trials an additional system called predictive ASAS has been developed. The user interface was also expanded with symbology for the system. This symbology is described in a separate chapter describing the predictive ASAS system. The user interface as described in this chapter is the system that was used in the phase 1 simulator trials.

7.7 Autopilot Resolution Modes

To investigate the usefulness of autopilot modes assisting the crew in solving the conflict, two variants of new autopilot modes have been developed:

- separate: two buttons to select the horizontal (heading and speed) or the vertical (speed and vertical speed) maneuver.
- combined: one button to select a combined horizontal and vertical maneuver (heading, speed and vertical speed)

These modes were optional and manually solving the conflicts by dialling in a heading, speed or vertical speed is referred to as ‘manually’ solving the conflict, even though the autopilot controls the aircraft.

8 Phase I Flight Simulator Trials

8.1 Goal of the Trials

After the development of the conflict detection and resolution algorithm and the design of the human machine interface, the next step was to perform the human-in-the-loop trials. At this stage the conflict detection and resolution algorithm have been verified using several scenarios with a high traffic density. The data gathered in human-in-the-loop trials was required to validate the principle of airborne separation before doing more off-line simulations to investigate for instance critical geometries.

Investigating the human factors of airborne separation was the main goal in the first year of the study. The study was still in an exploratory phase. There was no intention to develop a mature ASAS system or free flight concept. The idea was to create human factors problems by using a straightforward, basic ASAS system and high traffic densities. Investigating the human factors problems would give insight into the issues of performing airborne separation.

For this reason the following choices were made:

- no active ATC
- no exchange of intent information
- look at cruise phase first
- high traffic densities up to three times the average Western European traffic density
- high conflict rates: nine times the average Western European conflict rate

8.2 Research Questions

The basic question of the first phase experiment was:

“What happens when pilots have to perform their own separation assurance?”

This question can be refined as follows:

“Will they be able to ensure separation?”
“What happens to the workload?”
“Is airborne separation acceptable to pilots? Do they feel safe?”

On top of this, several other issues were also explored:
“What should the role of ATC be?”
“Where is the exchange of intent information required?”
“What happens in non-nominal situations like emergencies or failures?”

8.3 Experimental Design

The experiment matrix has two independent variables:
1) Traffic Density: single, double, triple
2) Level of autopilot assistance: manual, execute, automatic

Traffic Density

The average Western European traffic density of 1996 was used as reference. This so-called "single" traffic density corresponds to 12 aircraft per area of 100 x 100 nautical mile in the airspace of of 10 000 feet. During peaks the traffic density can be twice the average density on certain times of the day in the holiday season. The conflict rate for this density in a direct routing, cruise climbing scenario is about one conflicts per hour per aircraft (this was found with off-line traffic simulations based on references for the traffic density).

Since the simulator runs only lasted 20 minutes and the goal of the experiment was to induce human factors problems, a higher conflict rate was used. For a single density scenario there was one conflict in the run of 20 minutes, for the double density two conflicts and for triple density three conflicts were prepared. This effectively means a tripling of the conflict rate. Therefore in the worst scenario of the experiment the conflict rate was nine times the average normal conflict rates.

Level of Automation

Originally three levels of automation were planned:
"manual" – manual selection of autopilot modes (no automatic resolution modes)
"execute" – activation of a resolution mode
"automatic" – automatic selection and execution of the resolution after a brief period allowing an override by the pilots

The fully automatic mode proved to be ineffective during the tryouts for several reasons:

- the human is out-of-the-loop
- the outside world effectively controls the aircraft
- no knowledge of terrain, weather and SUA in the system can lead to undesirable actions

Therefore the levels of automation were redefined as follows:

"manual" – pilot selects a heading, vertical speed, altitude and/or speed on the mode control panel to solve the conflict using the advisories on the display.

"execute separate" – pilot selects a "horizontal resolution mode" or a "vertical resolution mode", which causes the autopilot to select the advised resolution values until the conflict is solved. Then the corresponding "HOLD" mode can be selected by the pilots to freeze to speed vector. This "HOLD" selection prevents overreacting to conflicts that should be solved cooperatively.

"automatic/execute combined" – This features one combined conflict resolution mode, which will use all advisories (horizontal and vertical) simultaneously to solve the conflict

The resulting experiment matrix has 3 x 3 = 9 cells. These 9 cells are flown twice per crew, once in the nominal situation and once in a non-nominal situation. Kept the total experiment matrix is then: 2 x 3 x 3 = 18 experimental runs per crew. Nine crews were planned in total. Nine events were placed in all nine cells by varying the place of an event in the matrix between crews.

From the safety analysis, the following events were planned and identified with a code ranging from 21 to 29 (for software reasons):

Non nominal behavior of other aircraft
21 = other aircraft starts an emergency descent
22 = other aircraft starts an inverse resolution maneuver
23 = other aircraft does not maneuver to solve the conflict

Failures
24 = ADS-B overload: unreliable, flickering and disappearing traffic symbols
25 = conflict detection failure (no aural alerts or conflict symbology)
26 = conflict resolution failure (no advisories on display)

Events to induce delays
27 = captains navigation display fails after distracting company call for co-pilot
28 = conflict detection delayed until three minutes before intrusion
29 = resolution advisory delayed until three minutes before intrusion

These events were introduced to explore the effects of the airborne separation task. For other purposes only the data of the nominal runs were used. The total experiment matrix is given below. The distribution of events over the experimental conditions per crew is shown in the second table.

First character:: m = manual
e = execute(separate modes)
a = automatic (combined mode)

Second character:: s = single
d = double
t = triple traffic density

Third/Fourth character:: n = nominal
nn = non-nominal

		CREW								
		1	2	3	4	5	6	7	8	9
RUN	1	msn	esn	asn	mtn	etn	atn	msn	esn	asn
	2	msnn	esnn	asnn	mtnn	etnn	atnn	mdnn	ednn	adnn
	3	mtnn	etnn	atnn	mdnn	ednn	adnn	mdn	edn	adn
	4	mdn	edn	adn	msn	esn	asn	mtn	etn	atn
	5	mtn	etn	atn	mdn	edn	adn	mtnn	etnn	atnn
	6	mdnn	ednn	adnn	msnn	esnn	asnn	msnn	esnn	asnn
	7	etn	atn	mtn	esn	asn	msn	esn	asn	msn
	8	etnn	atnn	mtnn	ednn	adnn	mdnn	esnn	asnn	msnn
	9	edn	adn	mdn	edn	adn	mdn	etn	atn	mtn
	10	esn	asn	msn	etn	atn	mtn	edn	adn	mdn
	11	ednn	adnn	mdnn	etnn	atnn	mtnn	etnn	atnn	mtnn
	12	esnn	asnn	msnn	esnn	asnn	msnn	ednn	adnn	mdnn
	13	asnn	msnn	esnn	asnn	msnn	esnn	atnn	mtnn	etnn
	14	adn	mdn	edn	asn	msn	esn	atn	mtn	etn
	15	adnn	mdnn	ednn	atnn	mtnn	etnn	adnn	mdnn	ednn
	16	atn	mtn	etn	adn	mdn	edn	asn	msn	esn
	17	atnn	mtnn	etnn	adnn	mdnn	ednn	asnn	msnn	esnn
	18	asn	msn	esn	atn	mtn	etn	adn	mdn	edn

		CREW								
		1	2	3	4	5	6	7	8	9
SCENARIO	msnn	21	29	28	27	26	25	24	23	22
	esnn	22	21	29	28	27	26	25	24	23
	asnn	23	22	21	29	28	27	26	25	24
	mtnn	24	23	22	21	29	28	27	26	25
	etnn	25	24	23	22	21	29	28	27	26
	atnn	26	25	24	23	22	21	29	28	27
	mdnn	27	26	25	24	23	22	21	29	28
	ednn	28	27	26	25	24	23	22	21	29
	adnn	29	28	27	26	25	24	23	22	21

The subjects were commercial airline pilots. In general they are only available for two consecutive days. The following schedule was used:

Day 1:
Morning: Briefing, Training runs
Afternoon: The first session of six experiment runs

Day 2:
Morning: Second session of six experiment runs
Afternoon: Third session of six experiment runs

In the experiment matrix it can be seen that the runs were grouped for level of automation. Every session started with a training run for this mode of operation. Changing the mode of operation for every run would be too confusing for the crews.

8.4 Experiment scenarios

For every experiment run, the crew in the Research Flight Simulator (RFS) would fly a 20 minute en-route segment starting east of England, overflying Belgium until close to Germany.
To simulate the background traffic for this flight with high traffic density requires a high number of flights to be simulated.

As a first attempt to generate the scenarios, original real-life ATC data was converted to the scenario file format of the Traffic manager. Using a tool that could sum scenario files, a double and triple density scenario could be created. Using real data would ensure a realistic scenario. The problem with this approach was that the resulting traffic patterns did not reflect a direct route environment: all aircraft flew on airways and rounded numbered flight levels. Using a relocation function based on position origin and destination, placed a lot of aircraft out of the experiment area. Due to the limited size of the sampled data, the additional aircraft which should be relocated inside the area were unknown. Another way of creating scenarios was required.

The traffic manager allows manual creation of traffic. To develop 18 scenarios this way was not do-able. The volume of airspace that can be viewed during a 20 minute flight with cruise speed is quite large. This is reflected by the size (and shape) of the experimental area in figure 8.1:

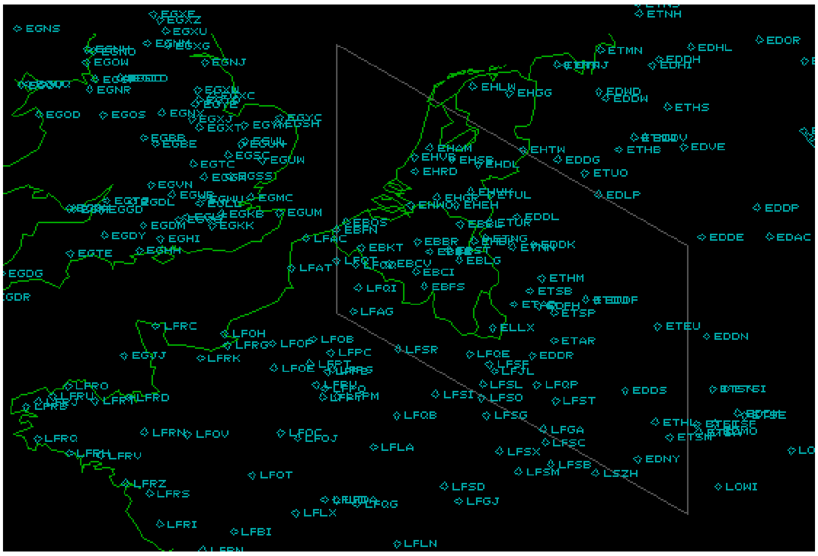


figure 8.1 Experiment area based on a 200 nautical mile ADS-B range

Since the experiment area covers 75000 nm^2, in a single density scenario, on average 90 aircraft should be present in this area, thus for the triple density 270 aircraft should be flying inside the experimental area. Clearly, manual creation of aircraft for all scenario files is too labour intensive.

Using the multiple create ("MCRE") command creates traffic with random values for altitude, speed, heading etc. This does not simulate a realistic route environment because it is too random.

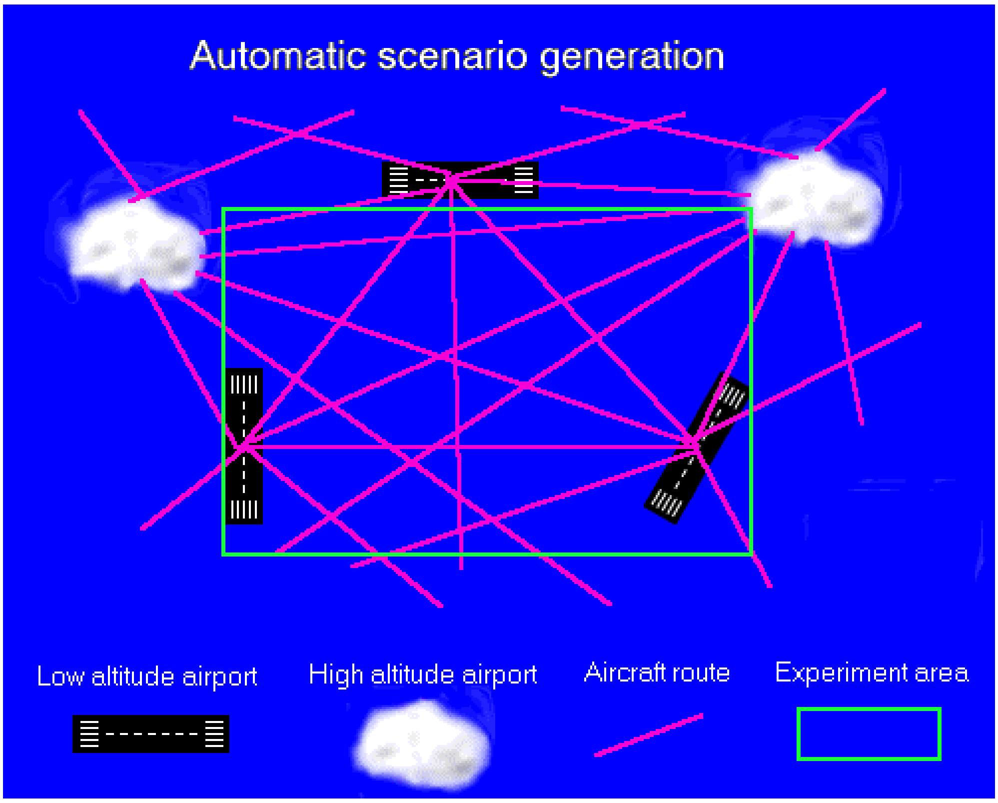


figure 8.2 Scenarios were generated by defining traffic sources on the ground (airports) and int he air (outside the experiment area)

Therefore a scenario generation function has been developed. By defining airports and en-route entry points ("high altitude airports") around and inside the experiment area, a realistic route environment is created in a pseudo random way. These scenarios have recorded from the moment traffic density was constant. Using the measured traffic density with the references, the traffic density could be adjusted by adding airports and modifying take-off interval times (which are random within margins)

The recorded scenario files were used as background traffic environment. During the experiment only the recorded scenario files were used to ensure repeatability. Specific aircraft on a course conflicting with the RFS route were added. Aircraft types and companies were limited to a selection from files. Every airport and en-route point was defined in so-called "autoscen" files (extension.asc).
These files were activated using the "autoscen <filename>" command.

An example of an airport definition in this file is:

```
####################### ORIGIN ###############################

autoap   = 'LFPG'            ;Airport
swfx10   = F                 ;Switch FX10 special aircraft
eqpfrac  = 1                 ;Equippage (0 %  => frac = 0, tot = 1)
eqptot   = 4                 ;          (75 % => frac = 3, tot = 4)

# Number of runways:
# nautorw = 1 => random generated altitudes with autoaltd
# nautorw > 1 => cyclic generated altitudes with 2000 ft separation

nautorw  = 1                 ;Number of runways at airport

# Takeoff/start data: interval, altitude, speed, heading

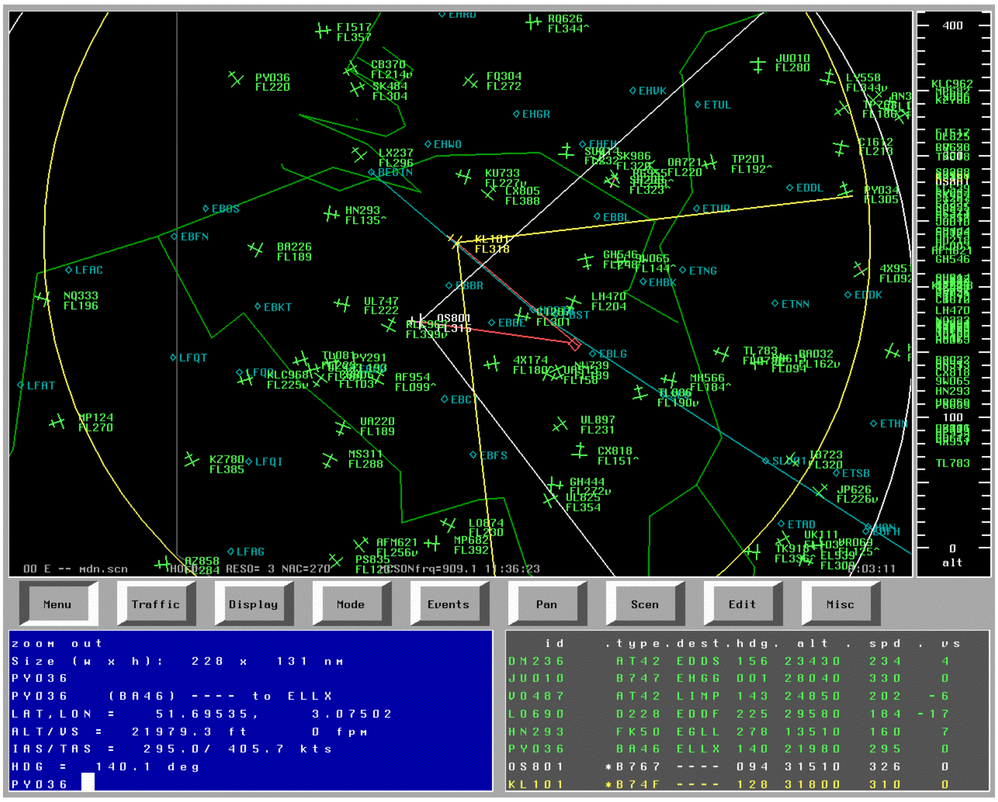
autoint  = 120.0      [s]    ;Takeoff interval (per runway)
autointd = 20.0       [s]    ;Takeoff interval delta (per runway)
autoalt  = 60.0       [FL]   ;Takeoff altitude (lower minimum if cyclic)
autoaltd = 10.0       [FL]   ;Takeoff altitude delta
autospd  = 220.0      [kts]  ;Takeoff speed
autospdd = 40.0       [kts]  ;Takeoff speed delta
autohdg  = 240        [deg]  ;Takeoff heading (not used at low)
autohdgd = 20.0       [kts]  ;Takeoff heading delta (not used at low)

# Destination:

autodest = T      ;Automatic destination(otherwise continue on hdg)
ndestlst = 5
destlst  = 'EHAM'
destlst  = 'EKBI'
destlst  = 'ENFB'
destlst  = 'EHGG'
destlst  = 'EDDH'
```

During the experiment an aircraft could be controlled via the traffic manager to make sure that all planned conflicts would occur despite earlier unexpected crew actions. To ensure such corrective actions would not be noted by the crew, aircraft tracks were only corrected when still outside the scanning volume of the RFS crew. For this purpose the scanning volume of the RFS was shown on the traffic manager screen.

Another way to control an aircraft was to hand it over to the AIRSIM desktop flight simulation program by issuing a “GIVE <acid>”command. This was used to simulate for example abnormal behaviour of conflicting aircraft during non-nominal runs.
In figure 8.3 a snapshot of the traffic manager’s map window is shown. The yellow aircraft symbol (called sign KL101) is the RFS which is in conflict with an aircraft controlled via the AIRSIM flight simulation (white symbol OS801). The yellow and white circles correspond to the navigation display range settings.



```
zoom out
Size (w x h):  228 x  131 nm
PY036
PY036   (BA46) ---- to ELLX
LAT,LON =    51.69535,     3.07502
ALT/VS =  21979.3 ft       0 fpm
IAS/TAS =  295.0/ 405.7 kts
HDG =  140.1 deg
PY036
```

```
     id    .type.dest.hdg.  alt  .  spd  .  vs
DM236      AT42 EDDS 156 23430   234     4
JU010      B747 EHGG 001 28040   330     0
V0487      AT42 LIMP 143 24850   202    -6
L0690      D228 EDDF 225 29580   184   -17
HN293      FK50 EGLL 278 13510   160     7
PY036      BA46 ELLX 140 21980   295     0
OS801     *B767 ---- 094 31510   326     0
KL101     *B74F ---- 128 31800   310     0
```

figure 8.3 Snapshot of Traffic manager map window during man-in-the-loop experiment.

8.5 Experiment Configuration

For the first phase experiments a configuration of three main components was used:

1. Research Flight Simulator
2. AIRIM Desktop Flight Simulation
3. Traffic manager

The traffic manager was the central component in the configuration. It performed the following functions:

- Experiment manager station (monitoring & controlling)
- Traffic simulation
- ASAS for traffic, RFS and AIRSIM
- Data logging (conflicts, intrusions, etc.)
- Events generation

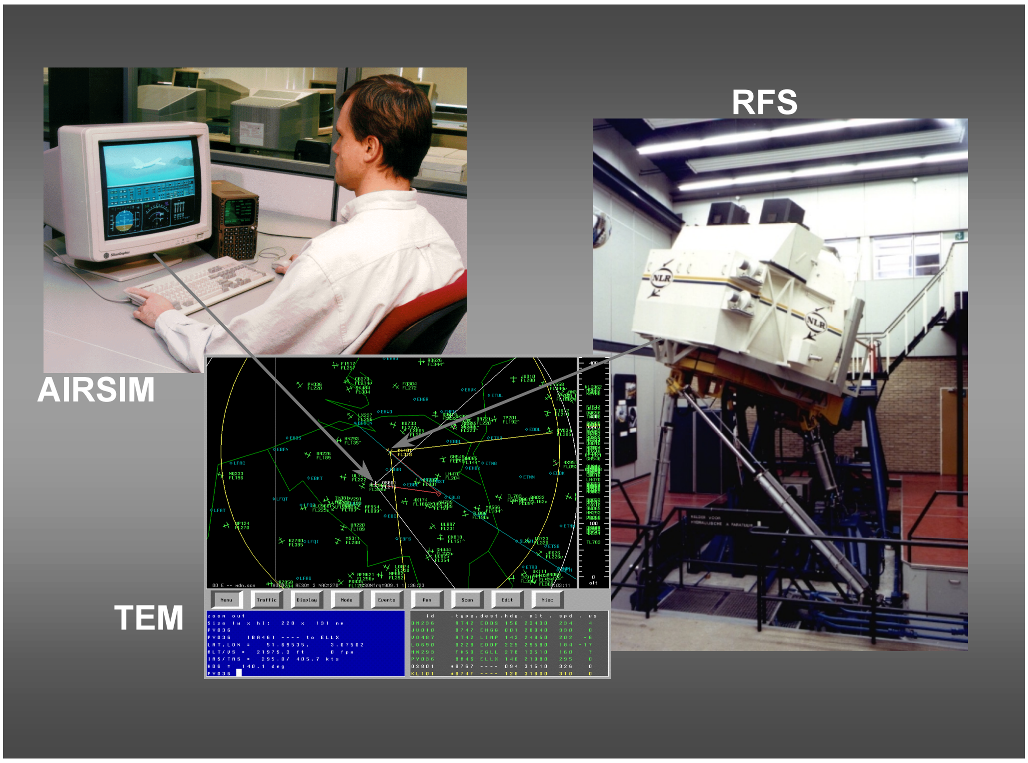


figure 8.4 Man-in-the-loop simulation configuration

The next figure shows an overview of the configuration and the communications.

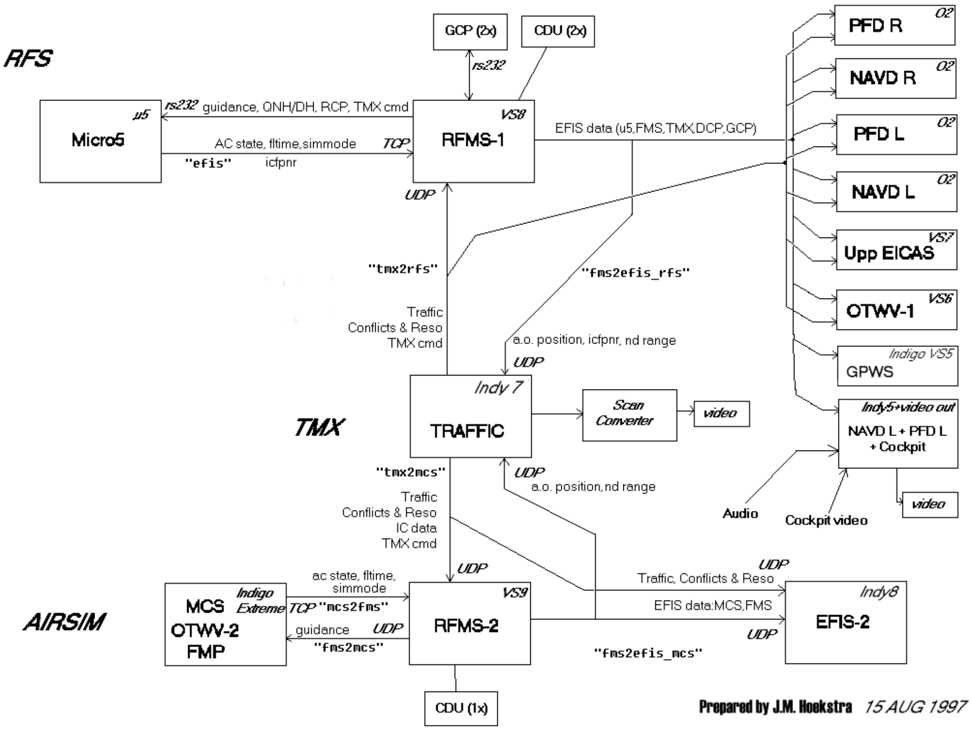


figure 8.5 Diagram as used during the development of simulation configuration, showing the computers and the communications

In the RFS, eye-tracking was used to investigate scanning patterns and head-down time. Physiological data on pupil diameter, respiration rate and heart-rate variability was collected to correlate it to workload ratings. Video recordings of both the cockpit and the traffic manager were made. All data was synchronized using a time server. All mode-control panel actions as well as flight data of the RFS has been collected. Several questionaires were used during the experiments.

8.6 Subjective questionnaires

Most of the results are divided by the type of the session. The following divisions are made:

- Related to traffic density:
  single, **double** and **triple** i.e. once, twice and three times the "normal" density in Western-European airspace

- Nominal versus non-nominal:
  Nominal (no events) sessions versus **non-nominal** (with events) sessions

- Related to the active autopilot resolution mode:
  Manual, **Execute combined**, **Execute separately**

- Divided per set of runs:
  set 1 means the first 6 sessions of 18 (first day afternoon)
  set 2 means the second 6 sessions of 18 (second day morning)
  set 3 means the third 6 sessions of 18 (second day afternoon)

8.6.1 Acceptability of free flight concept

After each session the pilots had to rate the acceptability of their last flight. The distribution of responses as a function of the three densities used during the experiment across all sessions and across all subject pilots is shown in figure 8.6.

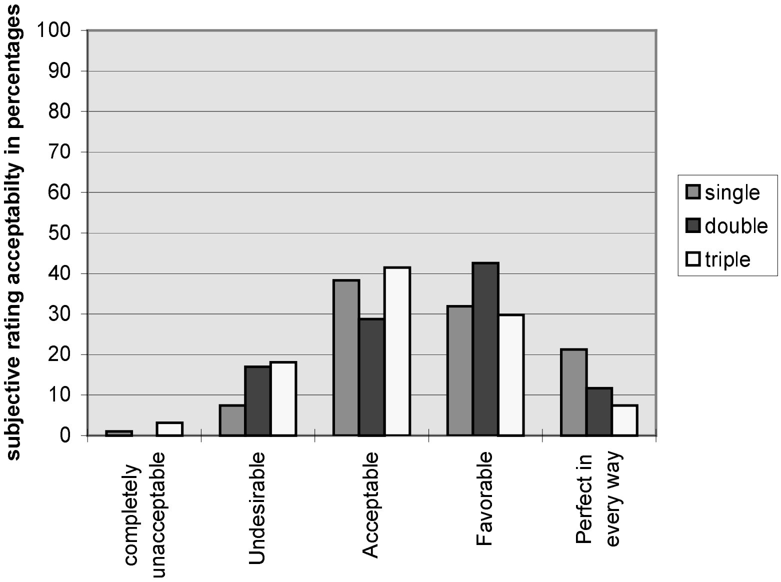


figure 8.6 Acceptability of free flight as a function of the traffic density

The percentages of ratings at a level of acceptable or higher as a function of the three densities used during the experiment across all flights and across all subject pilots are shown in figure 8.7. The percentage of subject pilots rating the session as acceptable or higher during single density was 91.5, during double density was 83.0 and during triple density was 78.7.

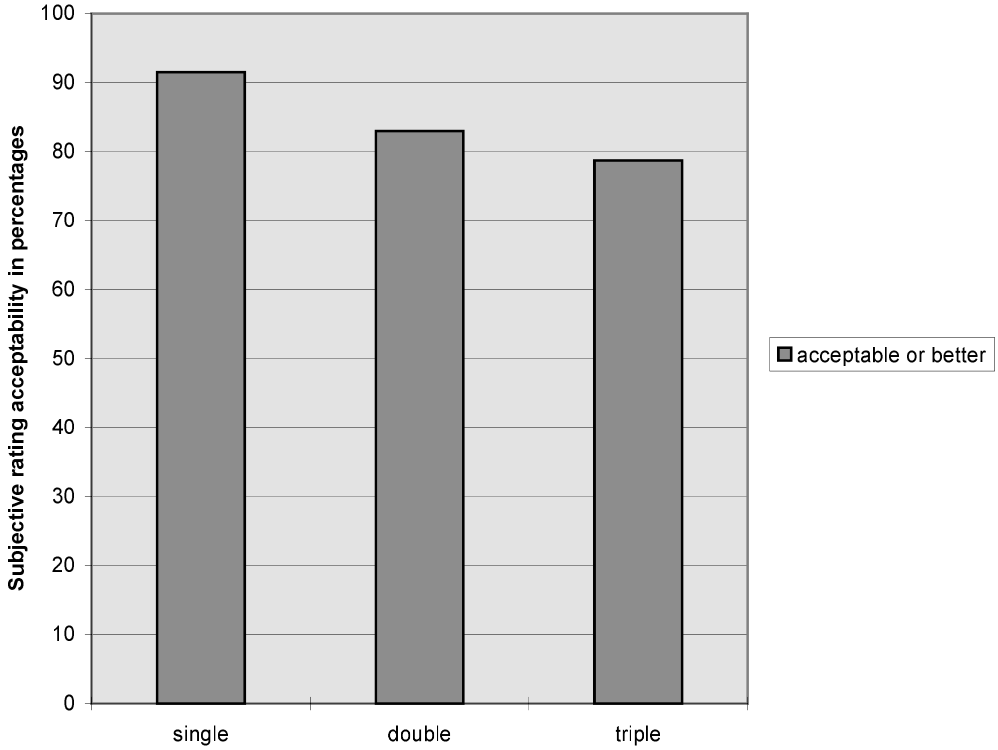


figure 8.7 Acceptability of free flight concept rated as acceptable or higher, as a function of the traffic density

The distribution of responses as a function of nominal conditions versus non-nominal conditions used during the experiment across all sessions and across all subject pilots is shown in figure 8.8.

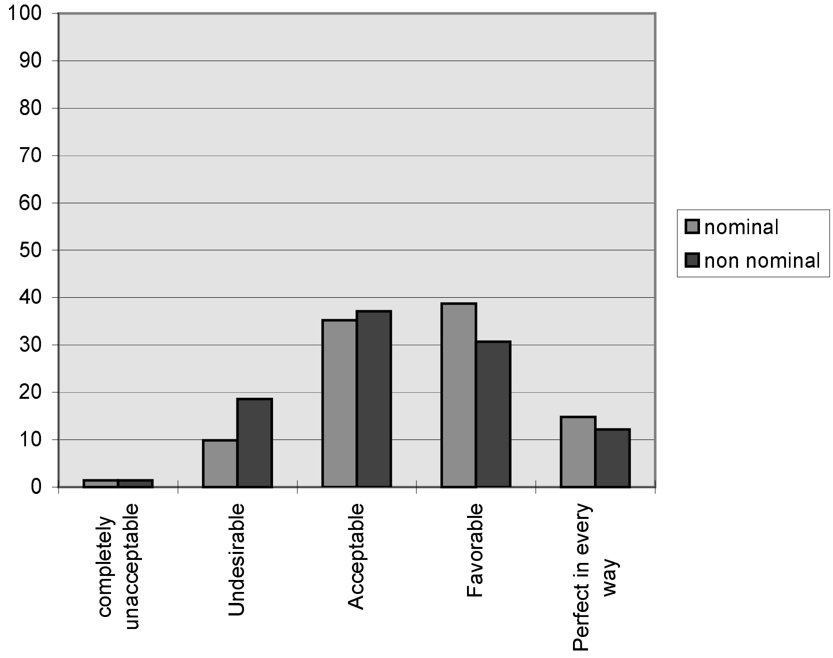


figure 8.8 Acceptability of free flight concept nominal conditions versus non-nominal conditions.

The percentages of ratings at a level of acceptable or higher as a function of nominal conditions versus non-nominal conditions used during the experiment across all flights and across all subject pilots are shown in figure 8.9. The percentage of subject pilots rating the session as acceptable or higher during nominal conditions was 88.7,during non-nominal conditions was 80.

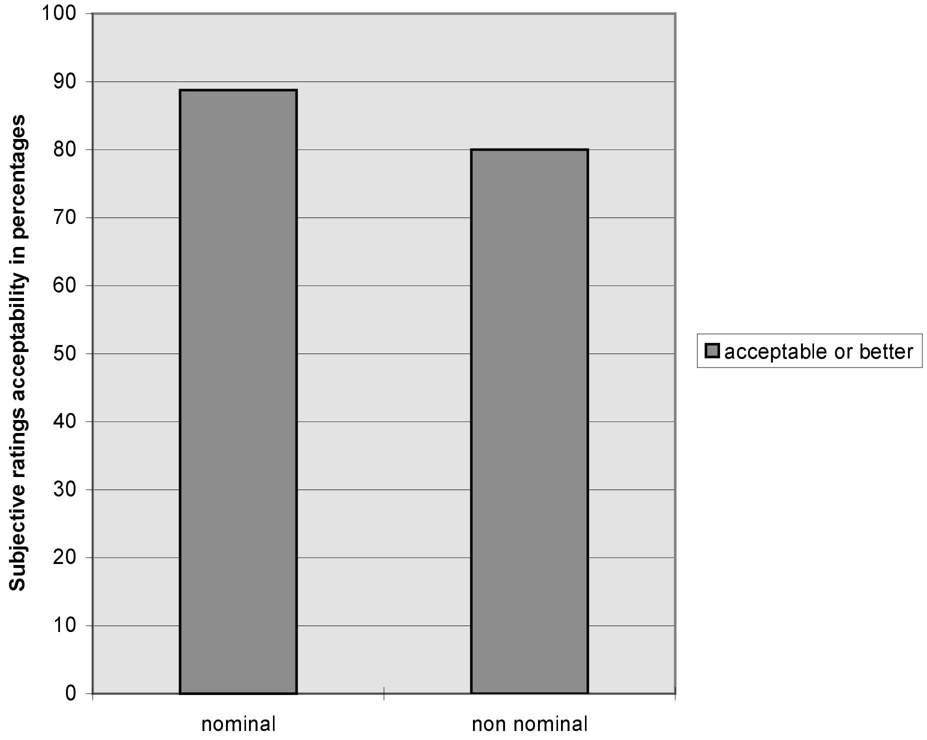


figure 8.9 Acceptability of free flight concept rated as acceptable or higher, nominal conditions versus non-nominal conditions

The distribution of responses as a function of the three different modes used during the experiment across all sessions and across all subject pilots is shown in figure 8.10.

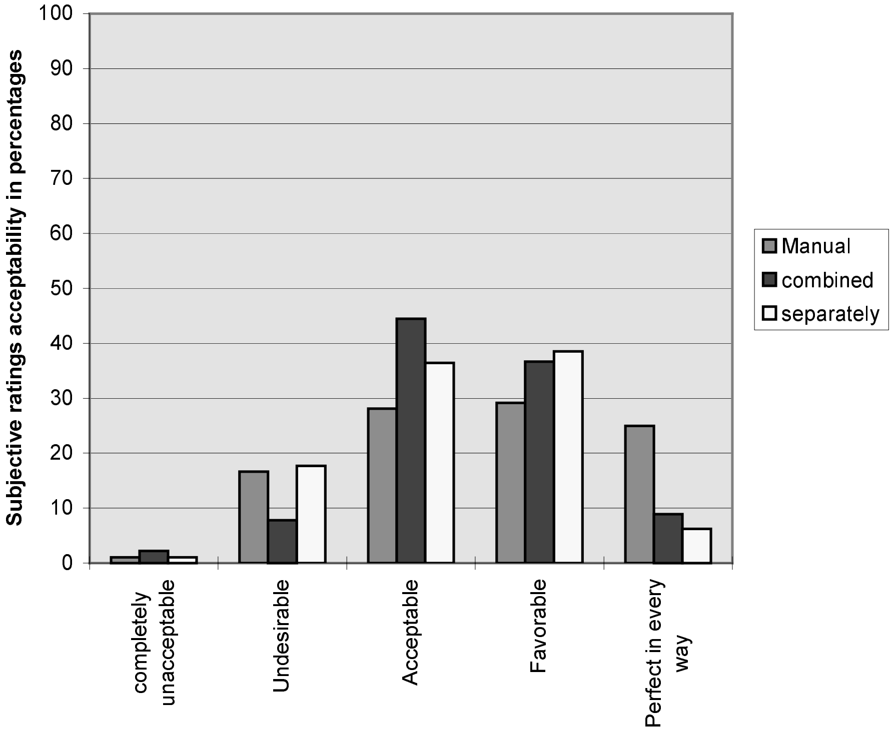


figure 8.10 Acceptability of free flight concept as a function of the three different modes

The percentage of ratings at a level of acceptable or higher as a function of the three different modes used during the experiment across all flights and across all subject pilots are shown in figure 8.11. The percentage of subject pilots rating the session as acceptable or higher during manual mode was 82.3, during Execute combined mode was 90 and during execute separately mode was 81.3

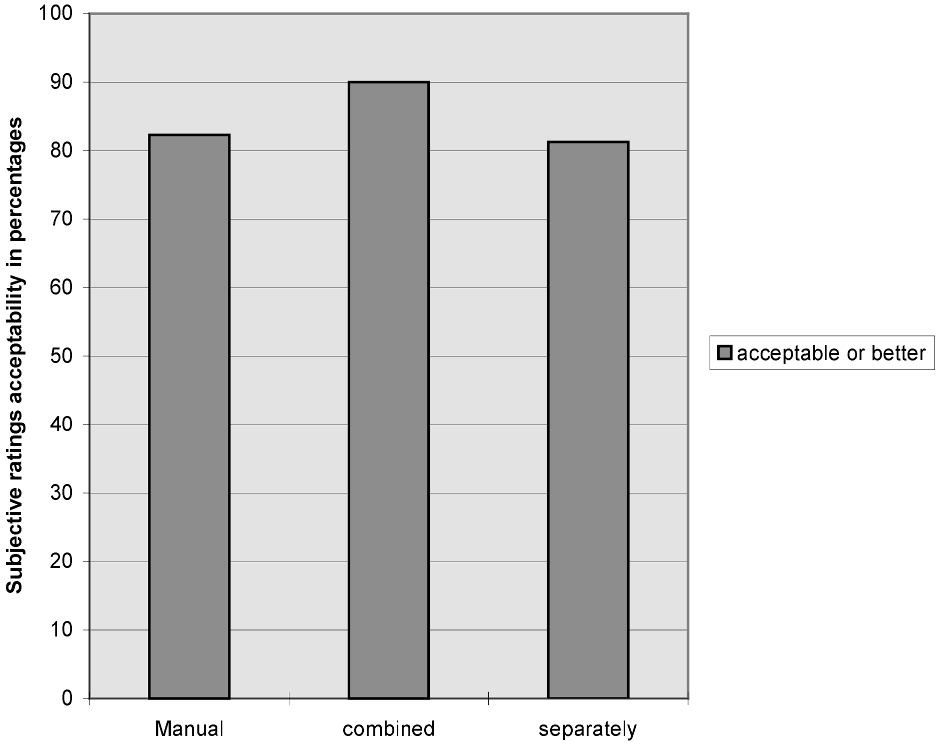


figure 8.11 Acceptability of free flight concept rated as acceptable or higher, as a function of the three different modes

The distribution of responses as a function of the three following sets of 6 sessions during the experiment across all sessions and across all subject pilots is shown in figure 8.12.

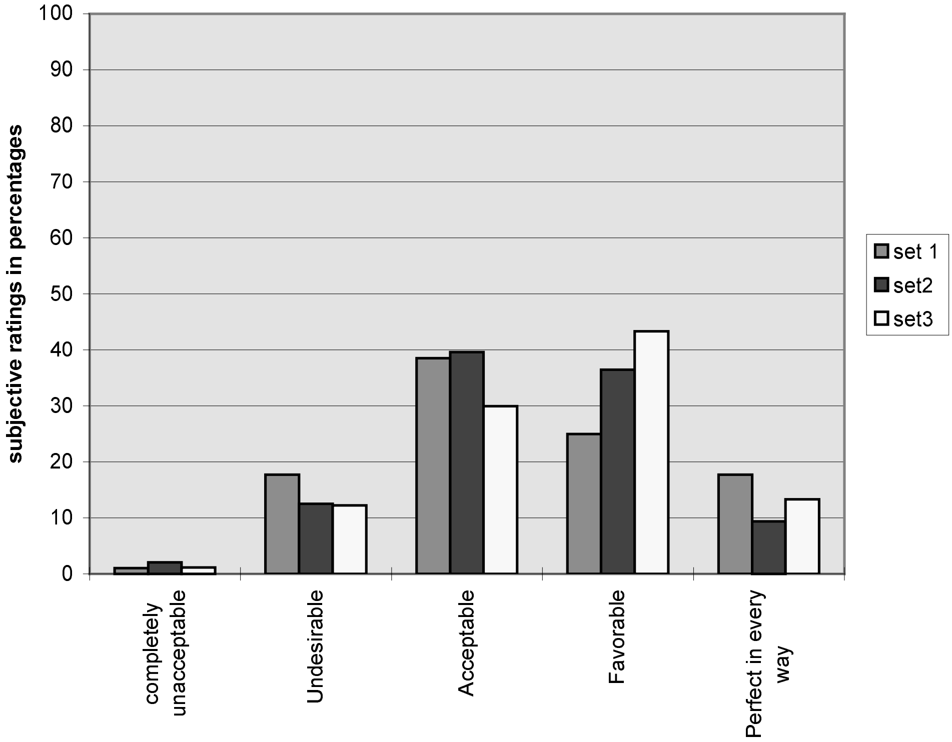


figure 8.12 Acceptability of free flight concept as a function of the three following sets

The percentages of ratings at a level of acceptable or higher as a function of the three following sets during the experiment across all flights and across all subject pilots are shown in figure 8.13. The percentage of subject pilots rating the session as acceptable or higher during set 1 was 81.3, during set 2 was 85.4 and during set 3 was 86.6.

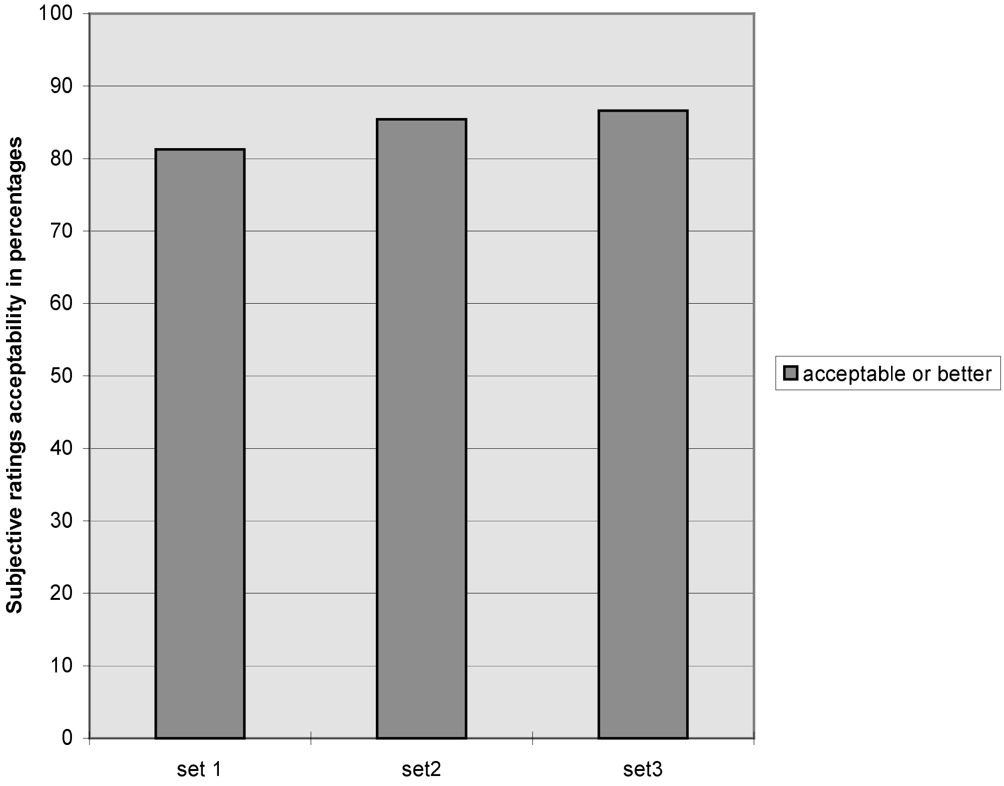


figure 8.13 Acceptability of free flight concept rated as acceptable or higher, as a function of the three following sets

8.6.2 Subjective safety compared to ATC

After each session the pilots had to rate the safety of their last flight compared to modern present day ATC operations. The distribution of responses as a function of the three densities used during the experiment across all subject pilots is shown in figure 8.14.

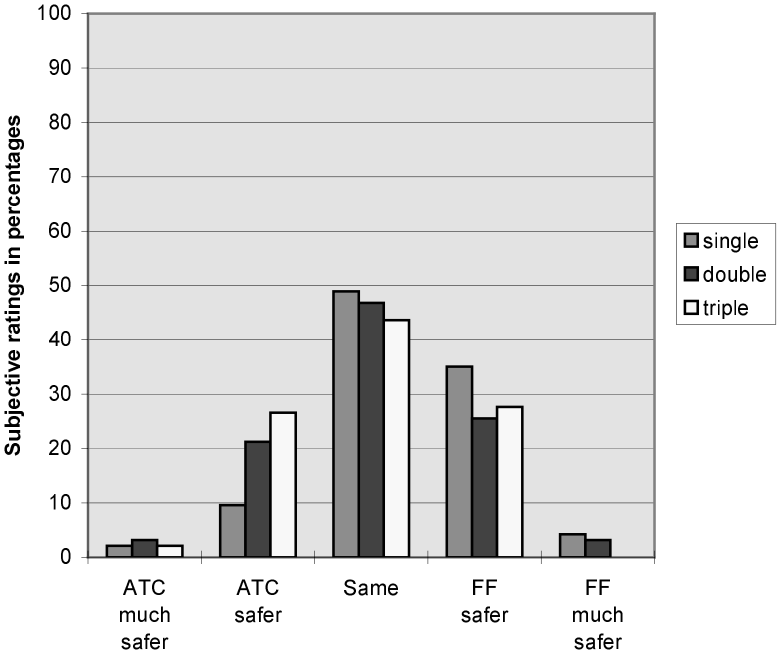


figure 8.14 Safety of free flight concept as a function of the traffic density

The percentages of ratings at a level of same safety as present day ATC or higher as a function of the three densities used during the experiment across all flights and across all subject pilots are shown in figure 8.15. The percentage of subject pilots rating the safety of the session as the same to present day ATC or higher during single density was 88.3, during double density was 75.5 and during triple density was 71.3.

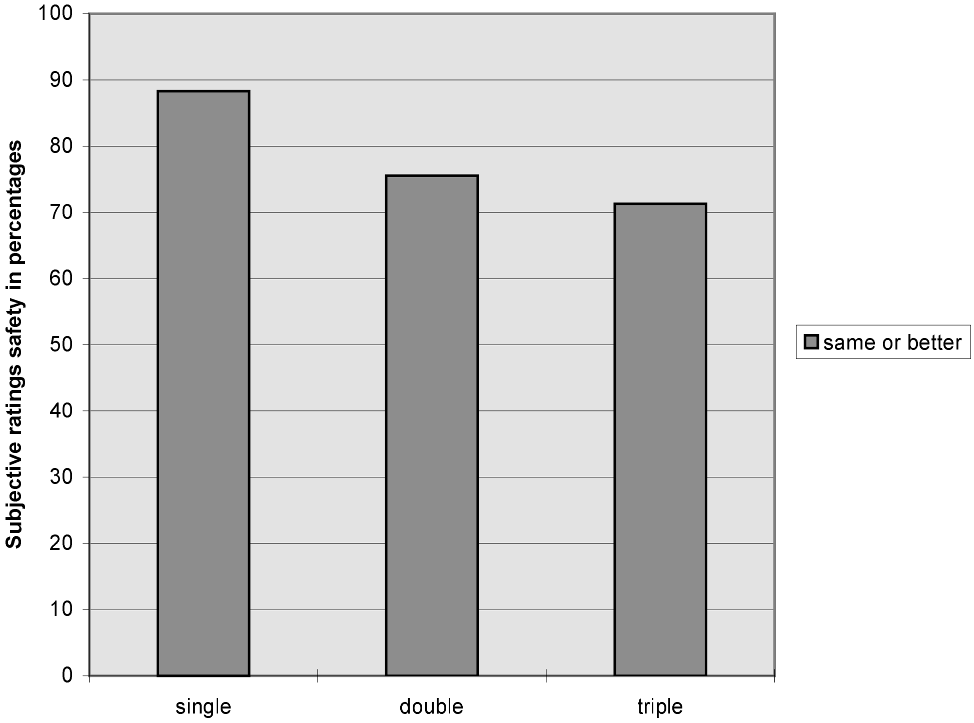


figure 8.15 Safety of free flight concept compared to present day ATC rated same or higher, as a function of traffic density

The distribution of responses as a function of nominal conditions versus non-nominal conditions used during the experiment across all sessions and across all subject pilots is shown in figure 8.16.

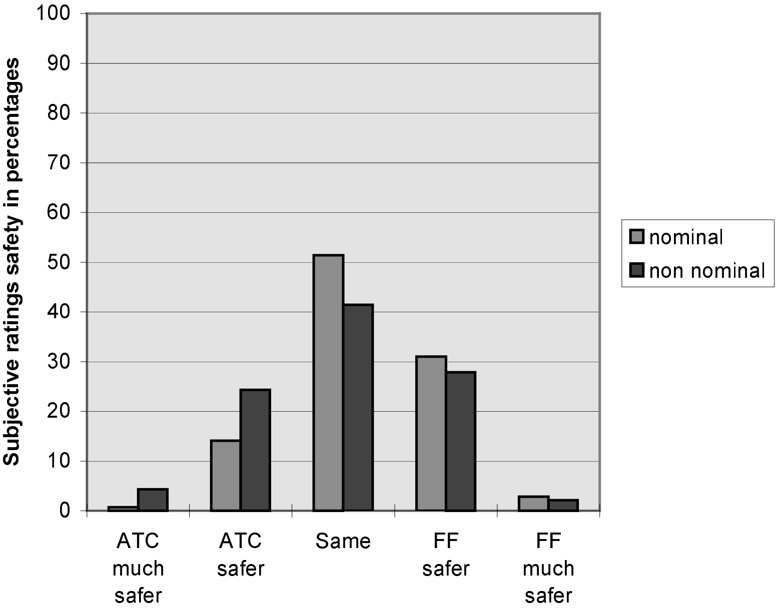


figure 8.16 Safety of free flight concept compared to present day ATC as a function of nominal versus non-nominal conditions

The percentages of ratings of an equal or higher level of safety relative to present day ATC as a function of nominal conditions versus non-nominal used during the experiment across all flights and across all subject pilots are shown in figure 8.17. The percentage of subject pilots rating the safety of the session as the same to present day ATC or higher during nominal conditions was 85.2, during non-nominal conditions was 71.4.

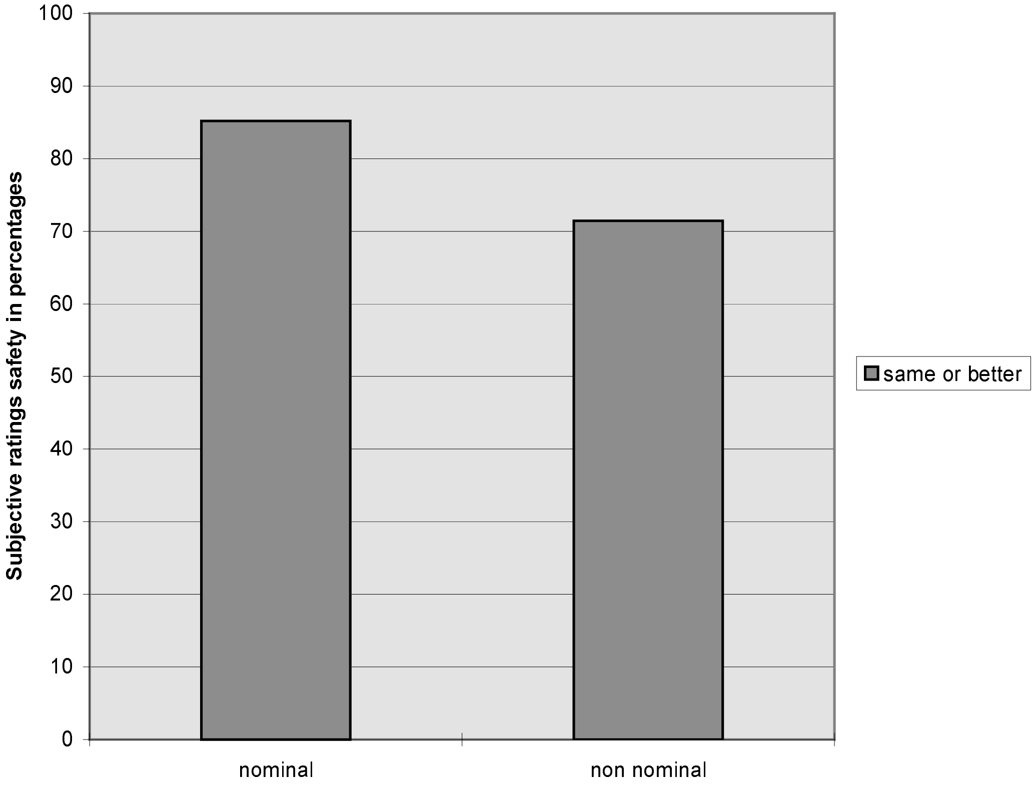


figure 8.17 Safety of free flight concept compared to present day ATC rated same or higher, as a function of nominal conditions versus non-nominal conditions

The distribution of responses as a function of the three different modes used during the experiment across all sessions and across all subject pilots is shown in figure 8.18.

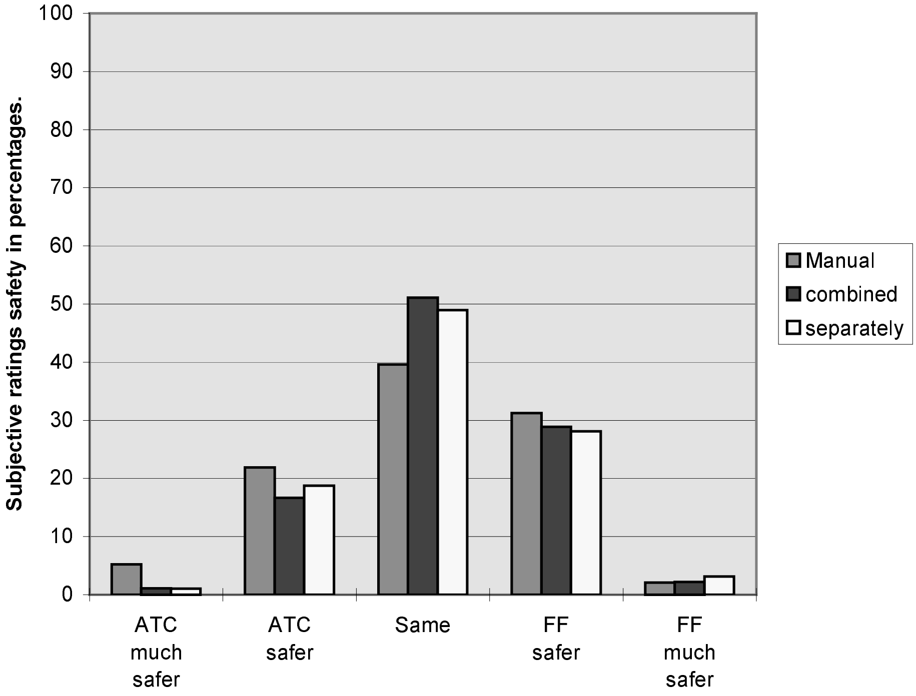


figure 8.18 Safety of free flight concept compared to present day ATC as a function of the three different modes

The percentages of ratings at a level of same safety as present day ATC or higher as a function of the three different modes used during the experiment across all flights and across all subject pilots are shown in figure 8.19. The percentage of subject pilots rating the safety of the session as the same to present day ATC or higher during manual mode was 72.9, during Execute combined mode was 82.2 and during execute separately was 80.2.

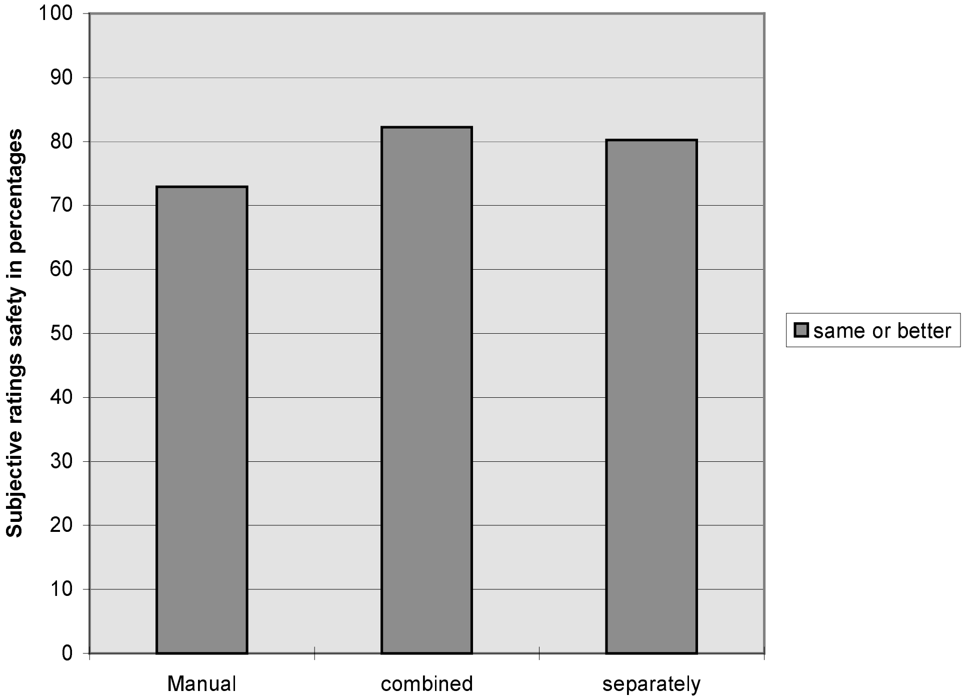


figure 8.19 Safety of the free flight concept compared to present day ATC rated same or higher, as a function of the three different modes

The distribution of responses as a function of the three following sets of 6 sessions during the experiment across all sessions and across all subject pilots is shown in figure 8.20.

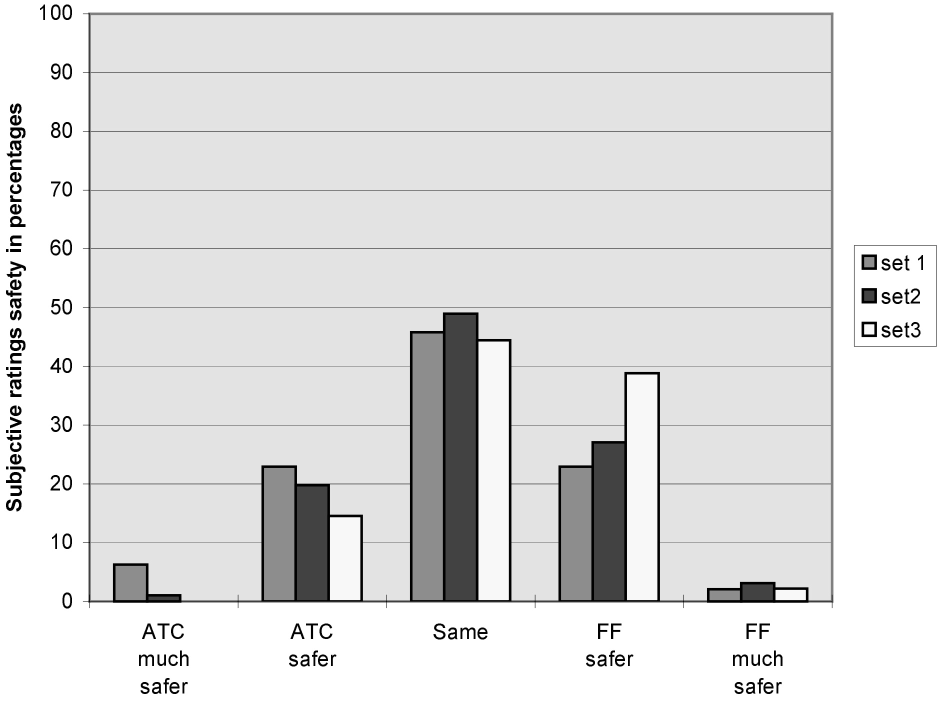


figure 8.20 Safety of free flight concept compared to present day ATC as a function of the three following sets

The percentages of ratings at a level of same safety as present day ATC or higher as function of the three following sets during the experiment across all flights and across all subject pilots are shown in figure 8.21. The percentage of subject pilots rating the safety of the session as the same to present day ATC or higher during set 1 was 70.8, during set 2 was 79.1, during set 3 was 85.5.

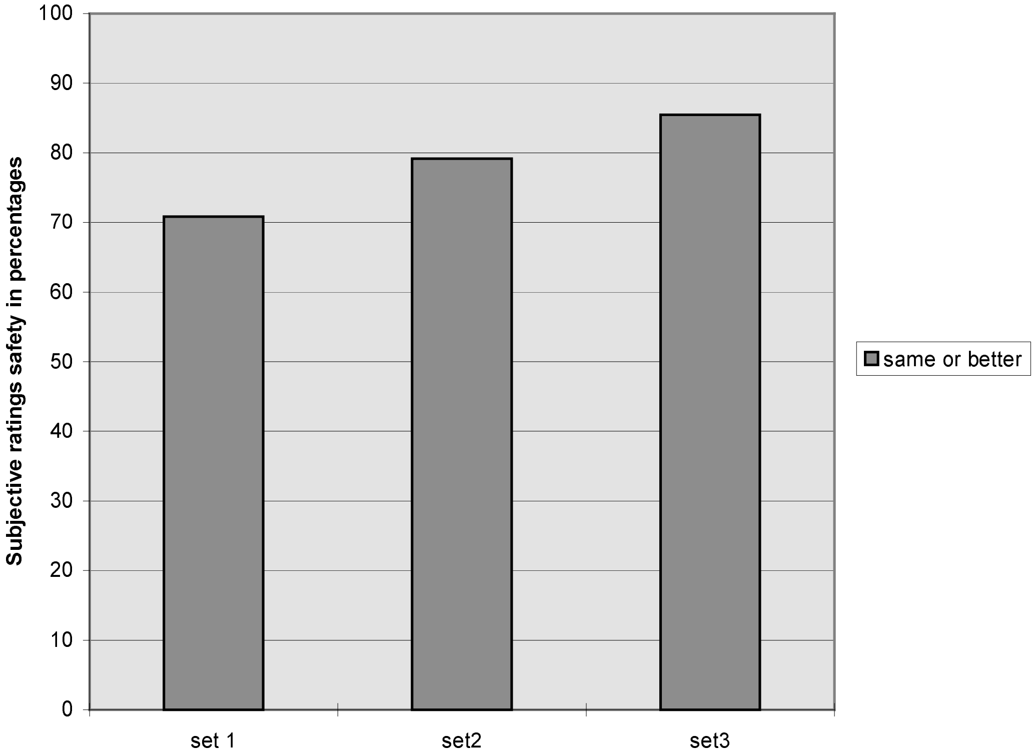


figure 8.21 Safety of free flight concept compared to present day ATC rated same or higher, as a function of the three following sets

8.6.3 Subjective mental workload

After each session the pilots had to rate the subjective workload of their last session on a scale from 0-150 on a RSME (Rating Scale Mental Effort). The average ratings during the experiment across all sessions and all subject pilots as a function of traffic density are shown in figure 8.22. The average rating during single traffic density was 30.3, during double traffic density was 35.0 and during triple density was 39.0.

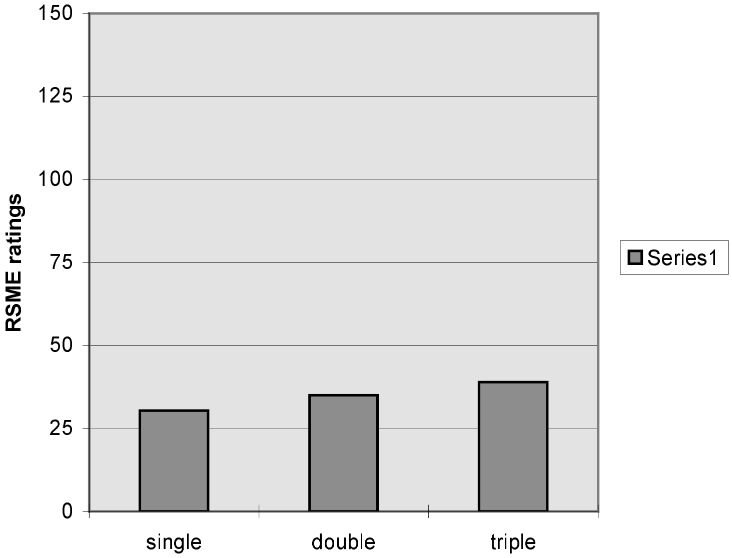


figure 8.22 Average ratings Subjective mental workload as a function of traffic density

The average subjective workload ratings during the experiment across all sessions and all subject pilots as a function of nominal conditions versus non-nominal conditions are shown in figure 8.23. The average rating during nominal conditions was 32.6, during non-nominal conditions was 36.9.

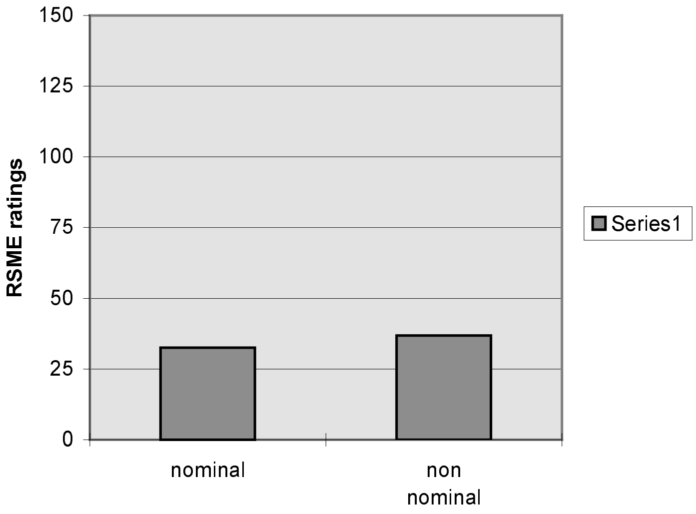


figure 8.23 Average ratings Subjective mental workload as a function of nominal conditions versus non-nominal conditions

The average subjective workload ratings during the experiment across all sessions and all subject pilots as a function of the three different modes are shown in figure 8.24. The average rating during Manual mode was 36.7, during execute combined mode was 36.0, during execute separately mode was 31.8.

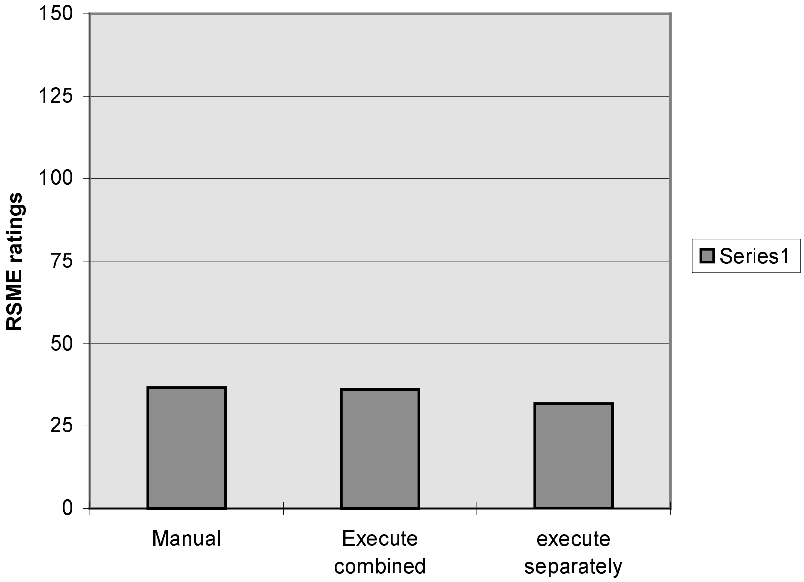


figure 8.24 Average ratings Subjective mental workload as a function of the three different modes

The average subjective workload ratings during the experiment across all sessions and all subject pilots as a function of the three following sets are shown in figure 8.25. The average rating during set 1 was 39.2, during set 2 was 36.0, during set 3 was 29.0.

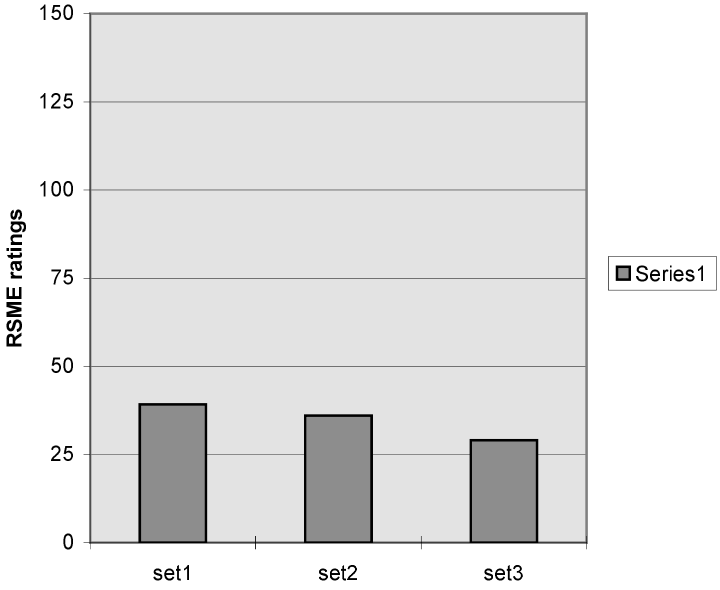


figure 8.25 Average ratings Subjective mental workload as a function of the three following sets

8.6.4 True/False questions

After each session the subject pilots had to answer a few questions with True of False.

These were the following questions:

1a: I think I could safely guarantee the airborne separation with the set-up just flown.
1b: I manoeuvred more than normally
1c: I exceeded passenger comfort levels
1d: I need more explicit rules of the road to guarantee the safety
1e: I need more explicit on board procedures to guarantee the safety
1f: I need more training to guarantee the safety.

The percentages of the subject pilots who answered the questions with true as a function of the traffic density across all sessions and all subject pilots are shown in figure 8.26.

The exact results are shown in the table below.

	Single	Double	Triple
Question 1a	89.4	81.0	79.9
Question 1b	17.2	35.1	43.8
Question 1c	7.9	14.7	16.1
Question 1d	18.0	24.0	21.6
Question 1e	18.0	20.2	23.4
Question 1f	23.5	26.8	32.0

Table 1 Percentage of True/False questions answered with true as a function of traffic density.

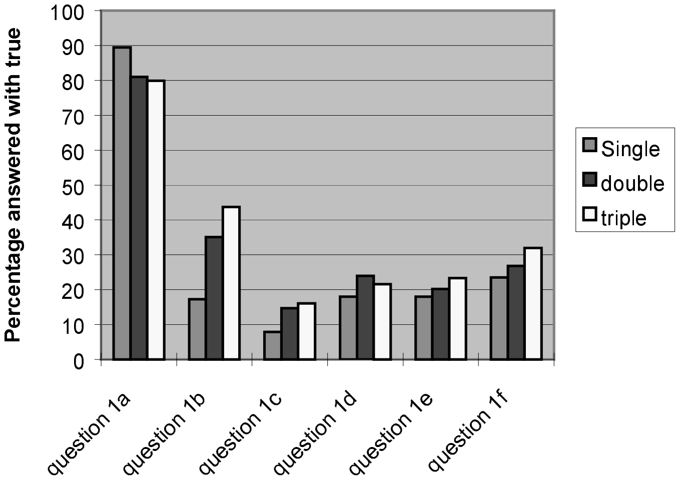


figure 8.26 Percentage of True/False questions answered with true as a function of traffic density

The percentages of the subject pilots who answered the questions with true as a function of nominal conditions versus non-nominal conditions across all sessions and all subject pilots are shown in figure 8.27.

The exact results are shown in the table below.

	Nominal	Non-nominal
Question 1a	85.9	80.7
Question 1b	33.8	30
Question 1c	15.5	10
Question 1d	14.8	27.1
Question 1e	16.9	24.3
Question 1f	26.1	28.6

Table 2 Percentage of True/False questions answered with true as a function of nominal conditions versus non-nominal conditions.

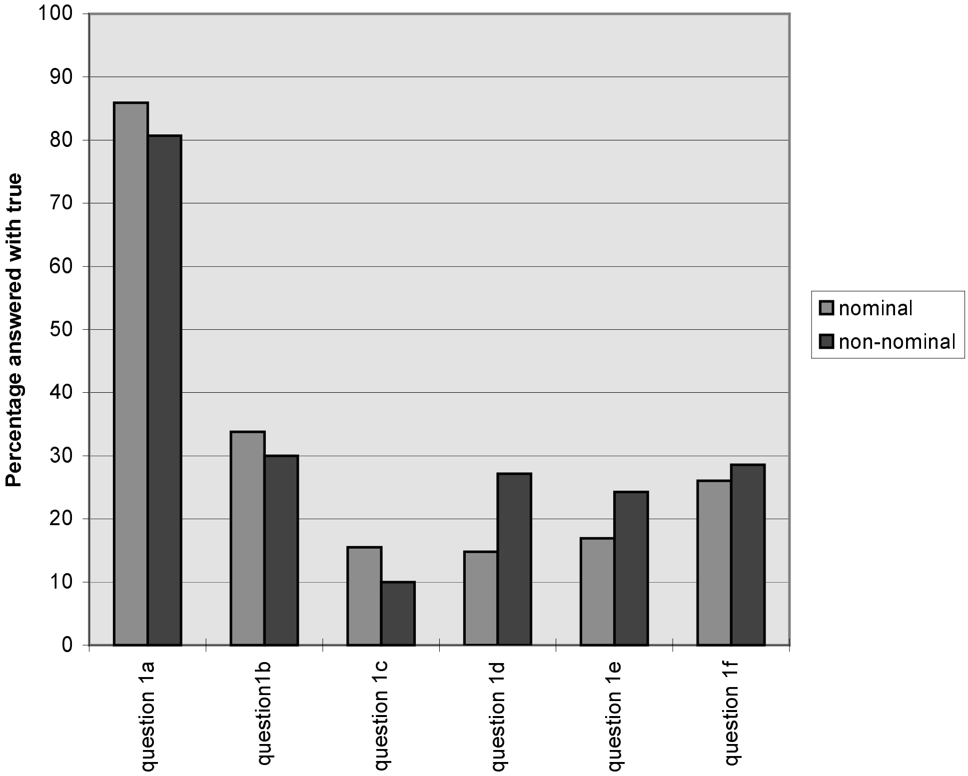


figure 8.27 Percentage of True/False questions answered with true as a function of nominal conditions versus non-nominal conditions

The percentages of the subject pilots who answered the questions with true as a function of the three different modes across all sessions and all subject pilots are shown in figure 8.28. The exact results are shown in table 3

	Manual	Execute combined	Execute separately
Question 1a	79.2	88.9	82.3
Question 1b	22.9	42.0	31.3
Question 1c	7.3	20.9	10.4
Question 1d	19.8	22.5	20.8
Question 1e	24.0	15.7	21.8
Question 1f	28.1	30.0	24.0

Table 3 Percentage of True/False questions answered with true as a function of the three different modes.

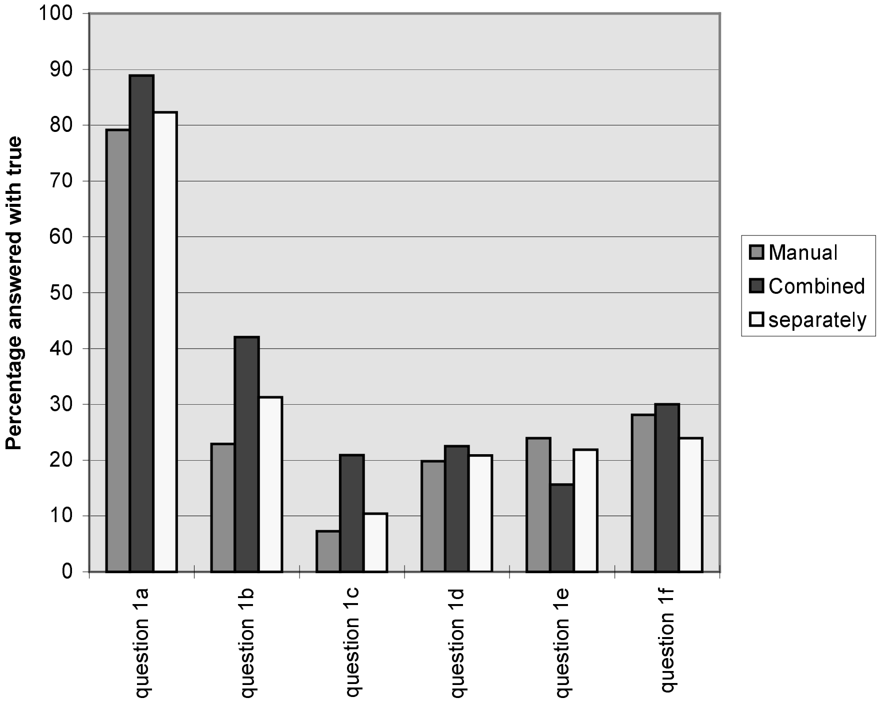


figure 8.28 Percentage of True/False questions answered with true as a function of the three different modes

The percentages of the subject pilot who answered the questions with true as a function of the three following sets across all sessions and all subject pilots are shown in figure 8.29. The exact results are shown in table 4.

	Set 1	Set 2	Set 3
Question 1a	71.4	82.7	89.2
Question 1b	32.3	32.3	34.9
Question 1c	11.5	10.4	18.75
Question 1d	25.	19.8	16.7
Question 1e	25.	17.7	17.7
Question 1f	39.6	22.9	17.7

table 4 Percentage of True/False questions answered with true as a function of the three following sets.

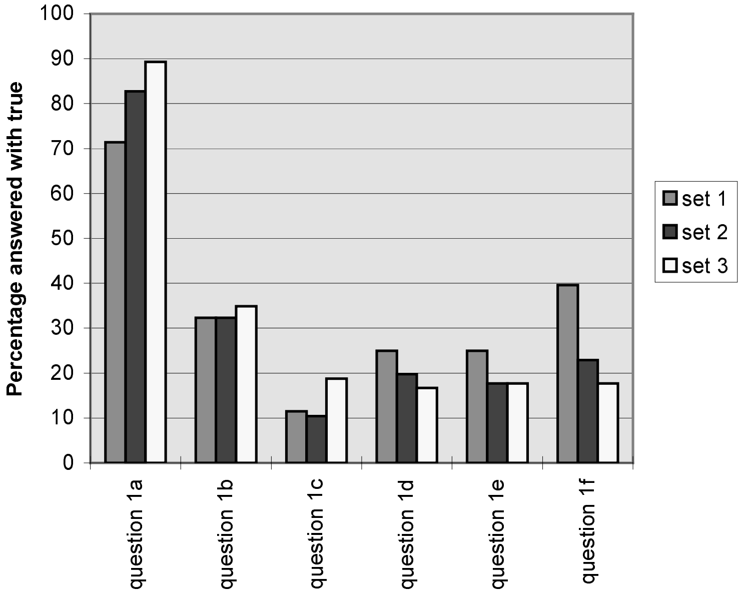


figure 8.29 Percentage of True/False questions answered with true as a function of the three following sets

8.6.5 Post trial questionnaires

After each set of 6 sessions the subject pilots has to fill in a Post trial questionnaire. The most relevant two questions are shown. The distribution of the responses across all sets and subject pilots on the question "rate the acceptability of the aspect: no ATC present" is shown in figure 8.30. The percentage of the subject pilots answering the question with completely unacceptable in set 1, set 2 and set 3 is 12.5, with undesirable in set 1 is 62.5, in set and set 3 is 25, with acceptable in set 1 is 12.5, in set 2 and set 3 is 50, with favourable in set 1, set 2 and set 3 is 12.5, with perfect in every way in all sets is 0.

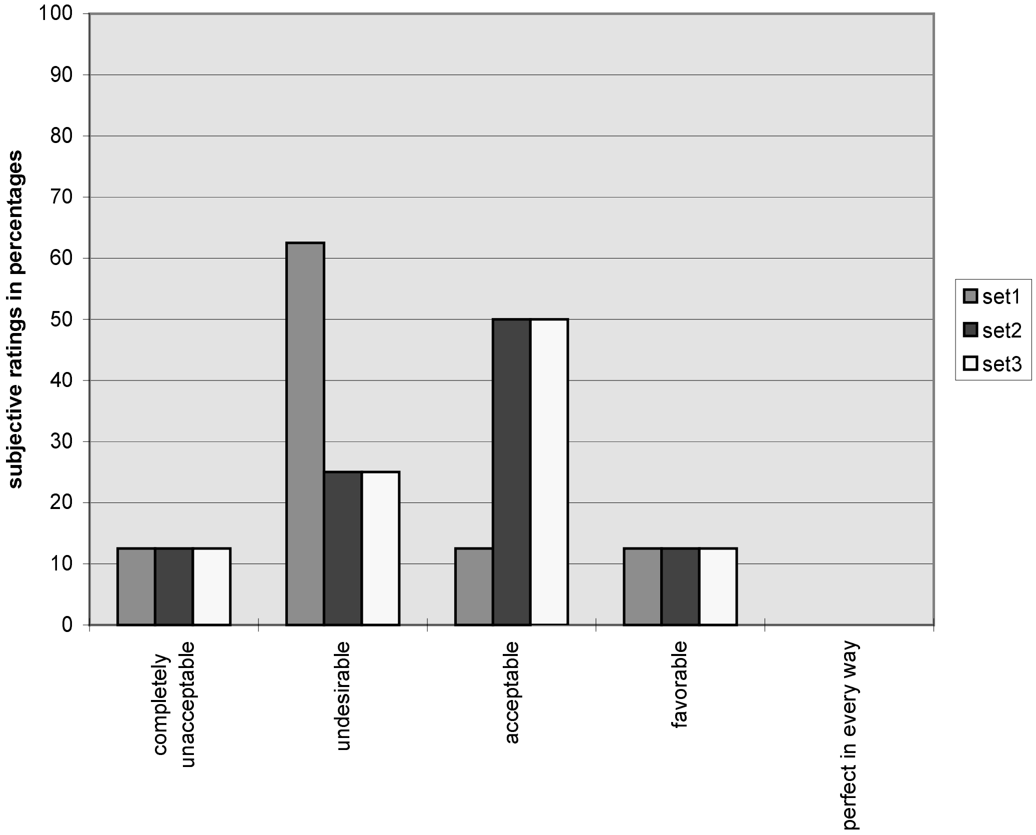


figure 8.30 Acceptability on the aspect that there was no ATC present

The distribution of the responses across all sets and all subjects on the question "rate the acceptability on the aspect that there are no priority rules" is shown in figure 8.. The percentage of the subject pilots answering the questions with completely unacceptable in set 1 is 6.25, in set 2 and set 3 is 0, with undesirable in set 1 is 37.5, in set 2 is 43.75, in set 3 is 31.25, with acceptable in set 1 is 18.75, in set 2 and set 3 is 25, with favourable in set 1 is 37.5, in set 2 is 31.25, in set 3 is 43.75, with perfect in every way is 0.

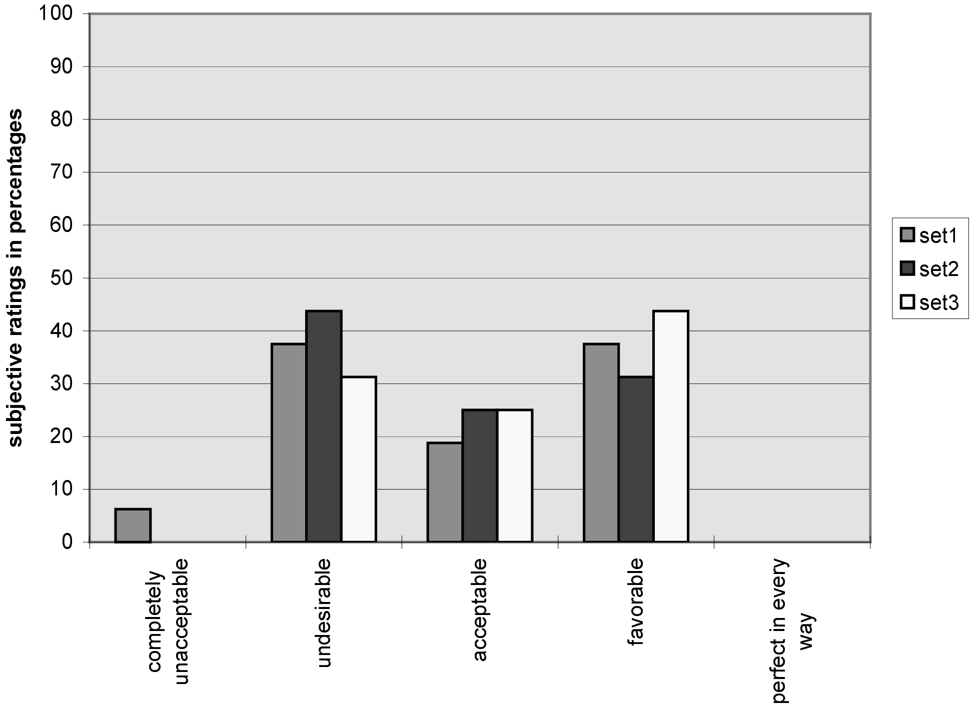


figure 8.31 Acceptability on the aspect that there were no priority rules (but all aircraft deviate)

8.7 Objective data

8.7.1 Conflict times

The conflict time is the time a predicted loss of separation exists. In other words: it is the time from the conflict alert until the conflict had been solved and disappeared from the display. The mean conflict times[29] across all sessions as a function of traffic density are shown in figure 8.32. The mean conflict time during single density was 28.8s, during double density was 25.3s, during triple density was 24.6s.

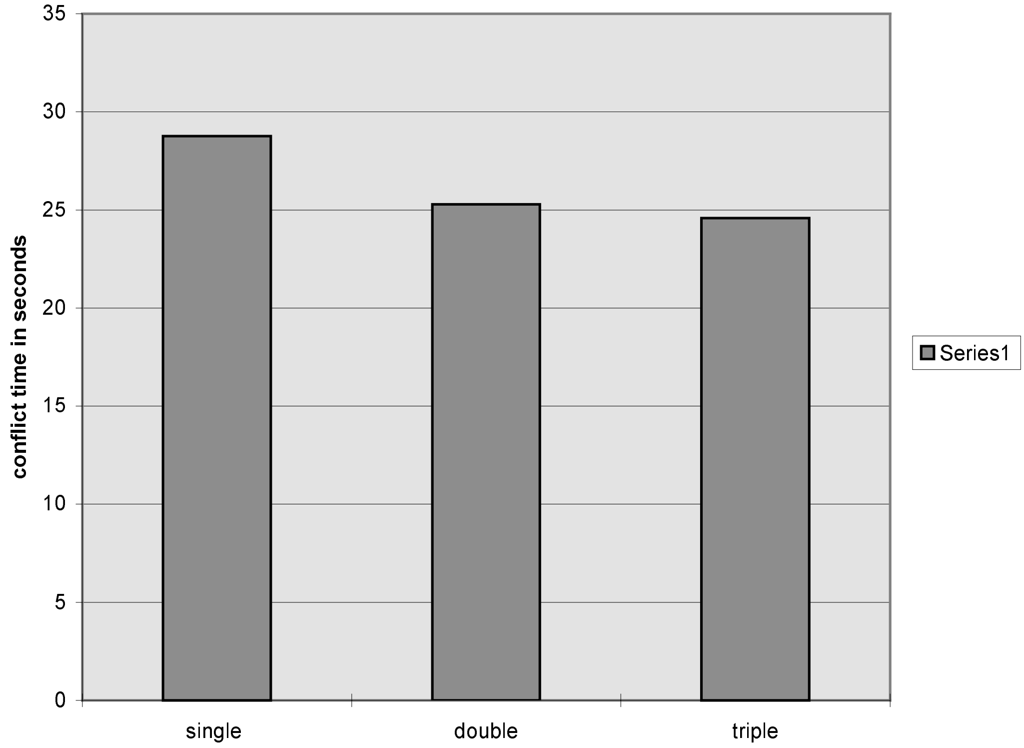


figure 8.32 Mean conflict times as a function of traffic density

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[29] All conflict times below 10 seconds were filtered out, because of they could represent nuisance. In this first experiment thre was no filtering present in the ASAS system, yet. In the second phase trilas this nuisance alerts had disappeared due to the conflict filter.

The mean conflict times across all sessions as a function of nominal conditions versus non-nominal conditions are shown in figure 8.33. The mean conflict time during nominal conditions was 21.1s, during non-nominal conditions was 31.5s.

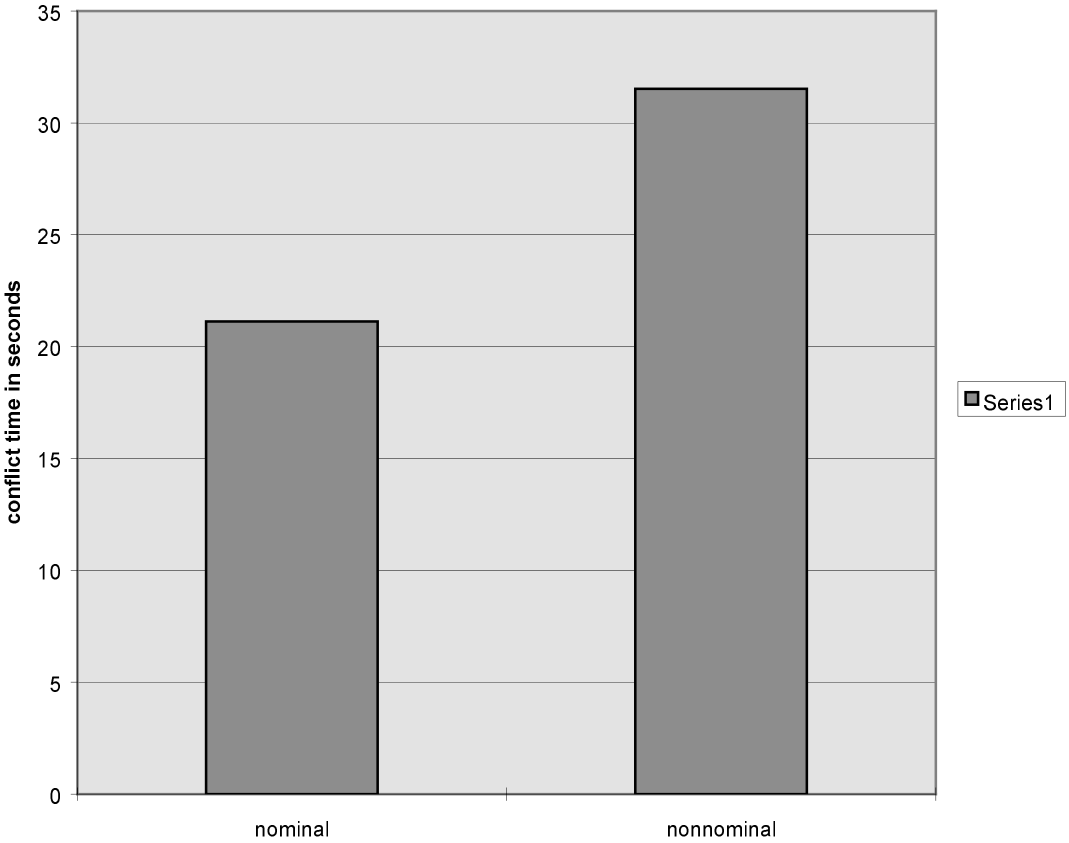

figure 8.33 Mean conflict times as a function of nominal conditions versus non-nominal conditions

Mean conflict times across all sessions as a function of the three different modes are shown in figure 8.34. The mean conflict time during Manual mode was 25.1s, during Execute combined mode was 25.8s, during execute separately mode was 28.2s.

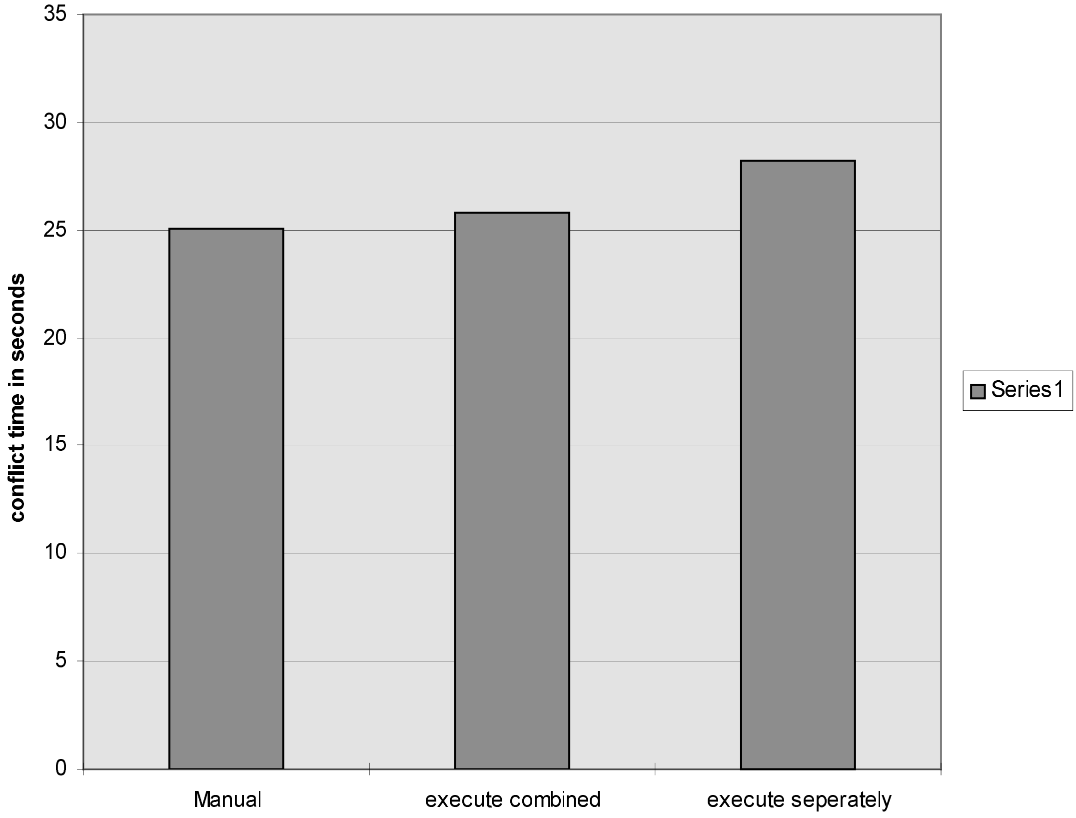

figure 8.34 Mean conflict times as a function of the three different modes

Mean conflict times across all sessions as a function of the three following sets are shown in figure 8.35. The mean conflict time during set 1 was 23.0s, during set 2 was 29.4s, during set 3 was 26.2s.

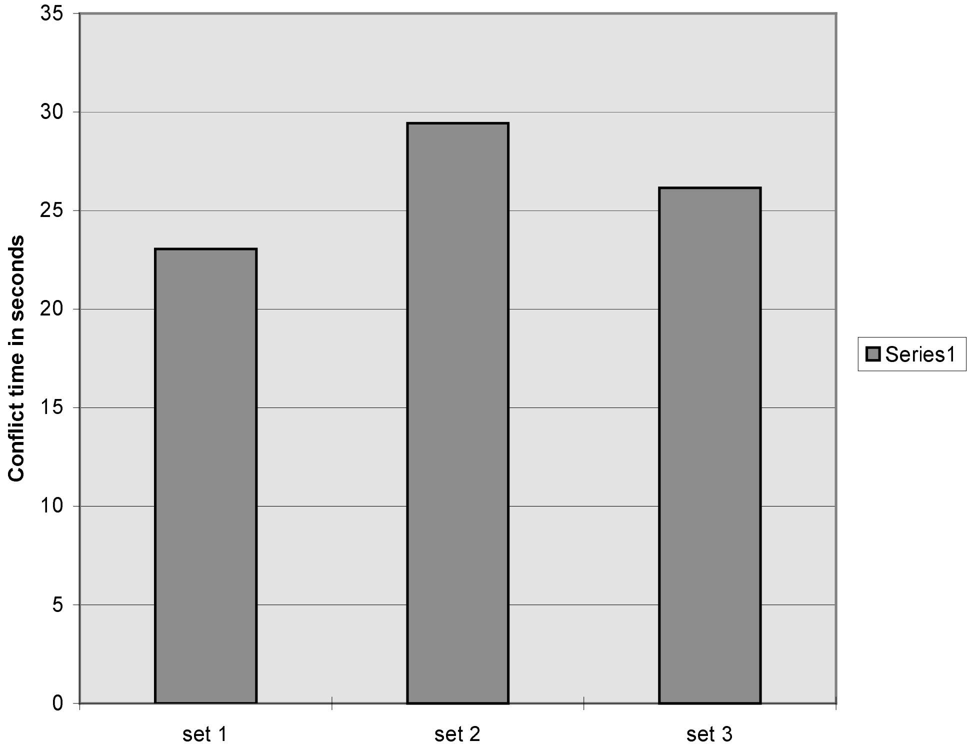

figure 8.35 Mean conflict times as a function of the three following sets

8.7.2 *Eye-Point-Of-Gaze Data*

The percentages of the total fixation duration of the Pilot Flying and Pilot-Non-Flying across all sessions and 13 subject pilots[30] on the Primary Flight Display as a function of the three following sets are shown in figure 8.36. The exact results are shown in table 5

	Set 1	Set 2	Set 3
PF	9.8	8.8	8.7
PNF	7.0	7.1	7.4

Table 5 Percentage fixation duration on the Primary Flight Display as a function of the three following sets.

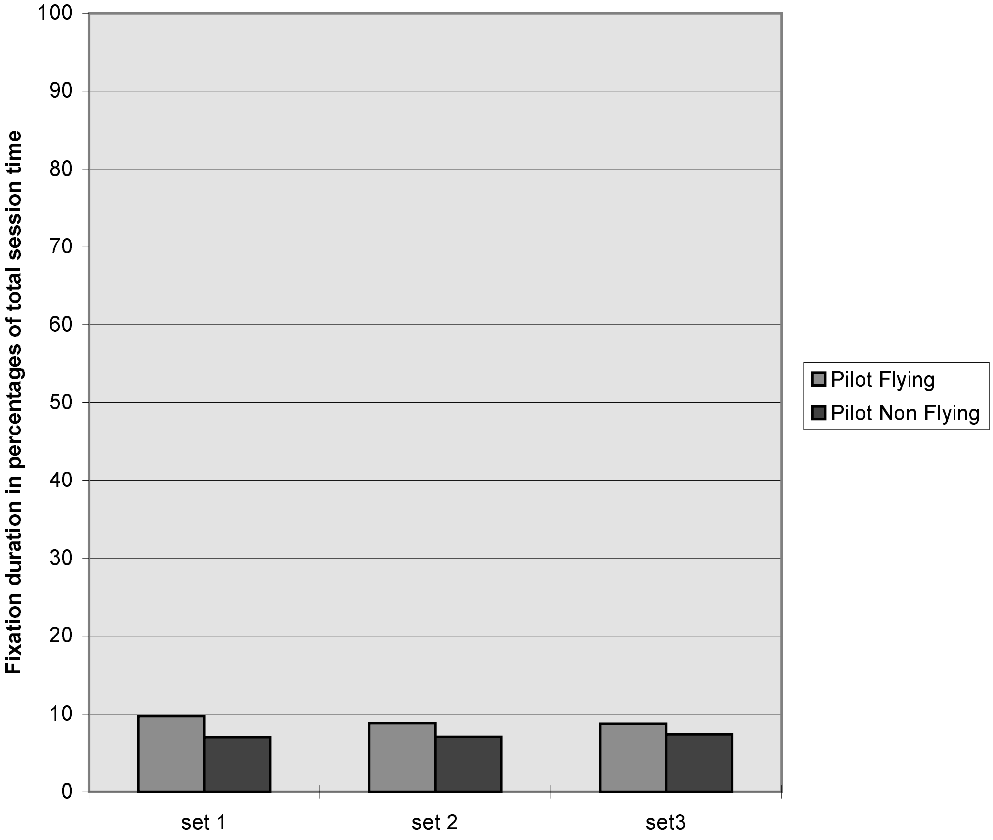

figure 8.36 Percentage fixation duration on the Primary Flight Display as a function of the three following sets

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[30] 5 of 18 pilots gave inaccurate data and were therefore not used for the data analysis

The percentages of the total fixation duration of the Pilot Flying and the Pilot-Non-Flying across all sessions and 13 subject pilots on the Navigation Display as a function of the three following sets are shown in figure 8.37. The exact results are shown in table 6.

	Set 1	Set 2	Set 3
PF	50.8	51.0	49.2
PNF	43.7	50.9	47.6

Table 6 Percentage fixation duration on the Navigation Display as a function of the three following sets

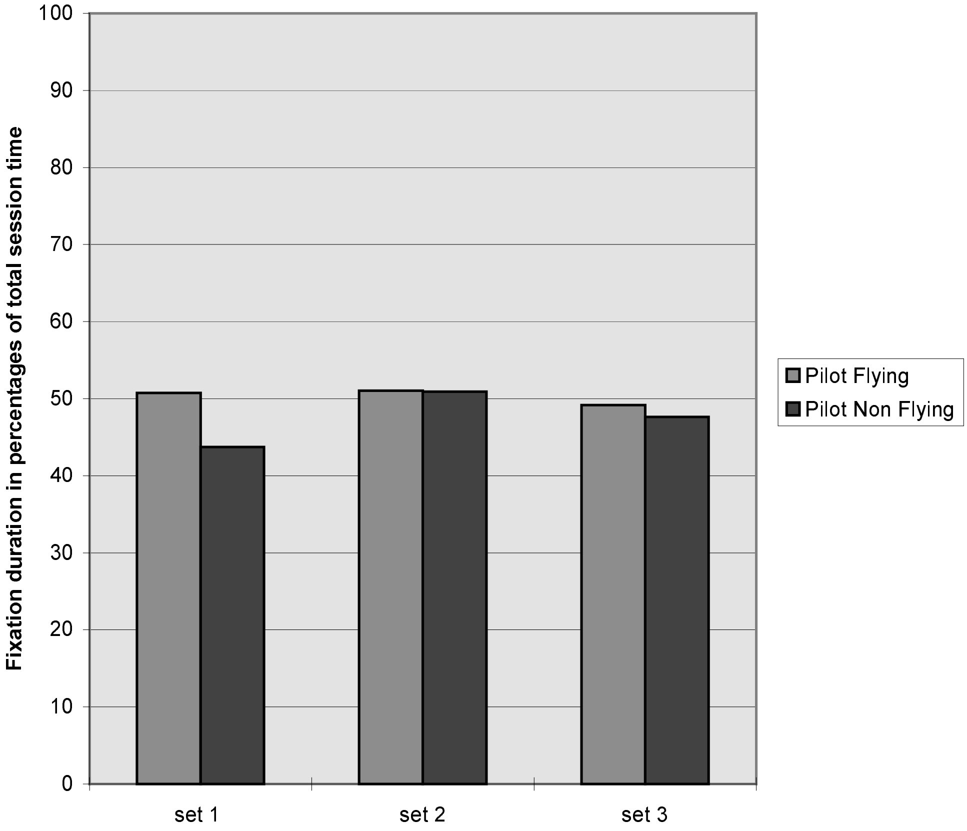


figure 8.37 Percentage fixation duration on the Navigation Display as a function of the three following sets

The percentages of the total fixation duration across all sessions and 13 subject pilots on the Vertical Navigation Display as a function of the three following sets are shown in figure 8.38. The percentage of the total fixation duration on the Vertical Navigation Display during set 1 was 11.4, during set 2 was 4.4, during set 3 was 7.1.

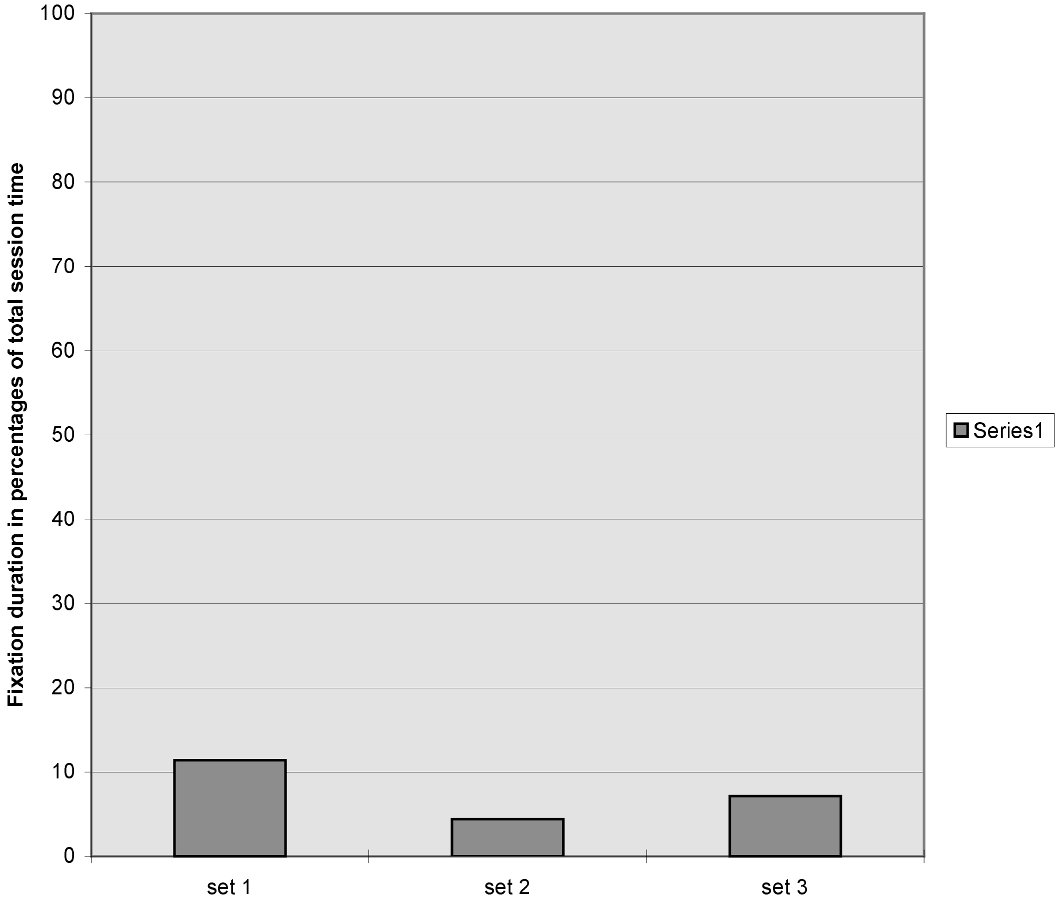


figure 8.38 Percentage fixation duration on the Vertical Navigation Display as a function of the three following sets

The percentages of the total fixation duration across all sessions and 13 subject pilots on the Vertical Navigation Display during conflicts as a function of the three following sets are shown in figure 8.39. The percentage of the total fixation duration during conflicts on the Vertical Navigation Display during set 1 was 12.0, during set 2 was 5.8, during set 3 was 8.4.

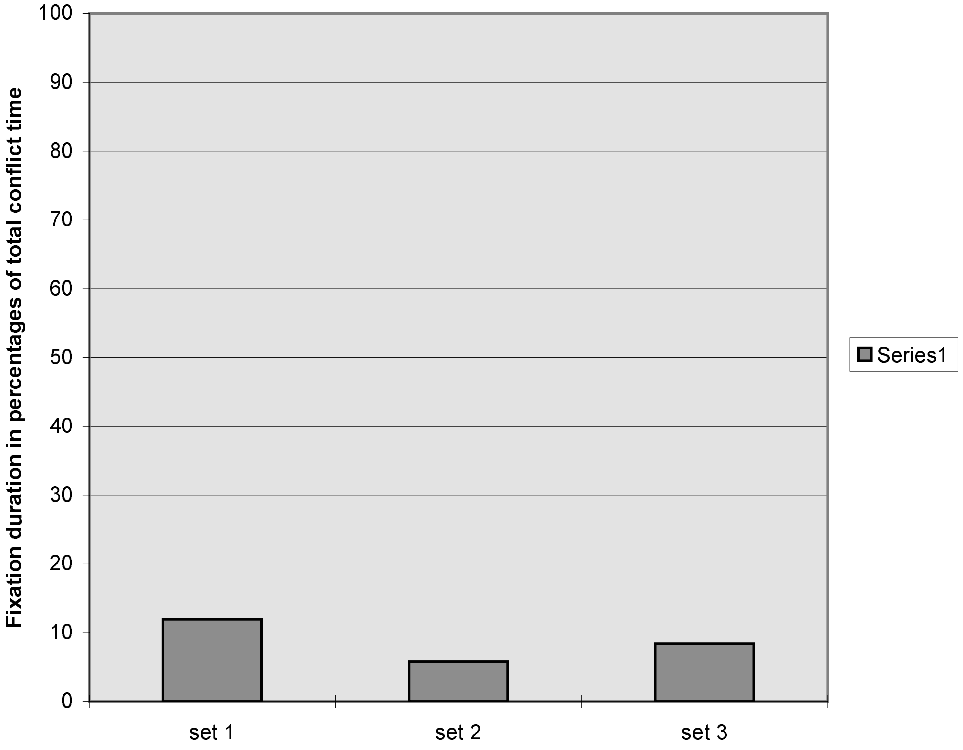


figure 8.39 Percentage fixation duration on the Vertical Navigation Display during conflicts as a function of the three following sets

8.7.3 Analyses of Manoeuvres

Heading, speed, altitude and combinations thereof were used to resolve conflicts. The percentages for the frequency of each parameter as a function of the three different modes across all sessions, are shown in figure 8.40. The exact results in percentages are shown in table 7.

	Manual	Execute combined	Execute separately
Heading	57.9	72.0	83.0
Speed	15.4	47.5	57.9
Altitude	41.4	75.9	28.8

Table 7 Percentages of the use of each parameter to resolve conflicts as a function of the three different modes.

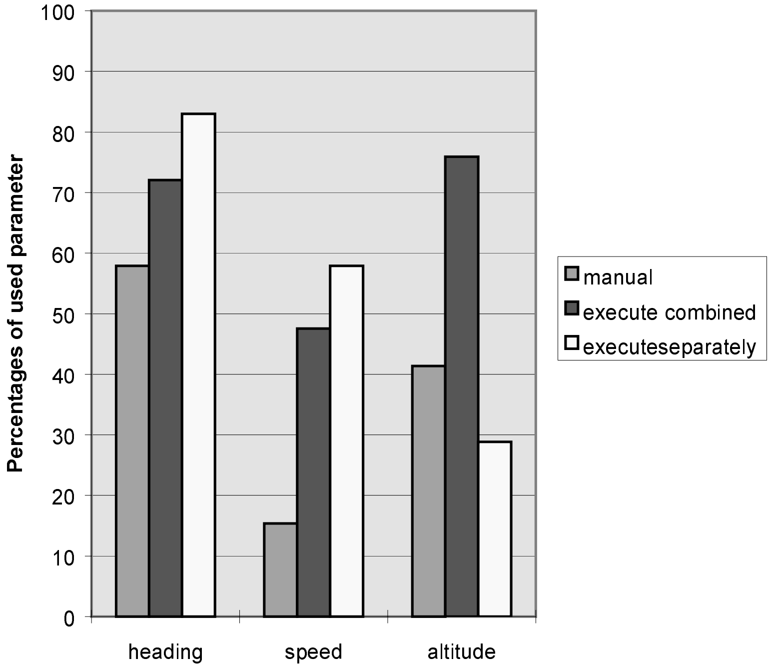


figure 8.40 Percentages of the use of each parameter to resolve conflicts as a function of the three different modes

8.7.4 *Intrusion in to the protected zone*

The following table gives an enumeration of all the intrusions in to the protected zone, that were not initiated on purpose as part of the experiment.

S=Single Density	M=Manual mode	N=Nominal conditions
D=Double Density	E=Execute combined	NN=Non Nominal conditions
T=Triple density	A=Execute seperately	

Session	min. sep. distance (nm)	min. sep. altitude (ft.)	intrusion duration (s)
107 ETN	4.29	815	18
309 MDN	3.42	914	8
701 MSN	4.55	499	114
701 MSN	4.77	119	341
706 MSNN	no data	no data	4
709 ETN	no data	no data	12
711 ETNN	4.23	692	38
713 ATNN	no data	no data	12
715 ADNN	no data	no data	9
718 ADN	no data	no data	18
814 MTN	4.77	9.7	76
817 MSNN	4.83	618	20

Table 8 Intrusions in to the protected zone

One of the non-nominal conditions introduced in the scenarios was an aircraft performing an emergency descent through the protected zone of the subject aircraft. Apart from these deliberate intrusions, table 8 shows the intrusions which were not prescribed by the scenario. Table 8 shows the minimum separation distance, minimum separation altitude and intrusion duration. As can be seen, the intrusions are mainly grazes of the protected zone, either vertically or horizontally.

These grazes occurred in cases of sudden manoeuvring of aircraft already close to the subject aircraft, either due to reaching top of descent of the other aircraft or lateral manoeuvring of the other aircraft due to clear-of-conflict situations. Some grazes occurred in non-nominal conditions (NN) where own conflict detection and/or resolution was failed.

Note that if all intrusions of crew 7 are neglected and all intrusions in non-nominal conditions (NN) are neglected, three grazes of the protected zone remain. Taking out the crew 7 results is considered valid as this crew was not properly trained due to late arrival of the crew.

A comment from pilots was that they lacked the information to prevent short term conflicts which can even lead to intrusions. The traffic information on the navigation alone apparently was not sufficient. The next chapter describes an additional system that has been developed to solve this problem.

8.8 Concluding remarks

From the results the most striking are the low workload ratings even when the high density traffic scenarios are included. The average workload rating of 29 on the RSME scale is comparable with the rating of 27 given during earlier trials under R/T conditions and a low traffic density. This means that even inclduing high density scenarios with triple the traffic density and then triple the conflict rate on top of that, does not show any significant increase in workload during the cruise phase.

The acceptability is also relatively high considering the relatively short amount of training and exposure the new airborne separation task.

Another observaton is the high amount of horizontal maneuvers (heading and speed). In general the vertical maneuver is preferrable for a number of reasons: the 1:30 altitude-diameter ratio of the protected zone, the efficiency in fuel and time. In the debriefs the pilots sometimes commented they were concerned with passenger comfort, leaving the optimum flight level or, very often, only saw the 2-dimensional picture they were used to on the horizontal navigation display. The advantage of the vertical maneuvers were often not known and should have been stressed more during the briefings.

Another comment of the subject pilots was they were lacking knowledge about the intentions of aircraft that were climbing below them (typical behavior of the problem aircraft in the scenarios). The often called these aircraft over the radio to verify the intended flight level. Displaying the slected altitude would greatly enhance the situational awareness and reduce voice radio comunications. The next chapter describes an additional system called predictive ASAS or PASAS, that solves this problem in a different way and enables avoiding short-term conflicts and the resulting intrusions.

9 Conflict Prevention: Predictive ASAS

9.1 Need for an additional system

Using the Airborne Separation Assurance System (ASAS) in the way it was used during the first phase experiments yielded some problems. Because only a CD&R function was available, airborne separation was purely reactive. Especially pilots with an air force background were able to predict problems further ahead or due to manoeuvres.

In the debrief pilots noted two problems with this approach:
1. They were unable to tell what the effect of a manoeuvre (for example a recovery manoeuvre) was.
2. They missed intent information of other aircraft especially vertical ("will he level off below me or not").

There was also a need for a rule to prevent short-term conflicts which potentially can cause intrusions (see chapter 8). The following rule was proposed:

"Manoeuvring in a way that will trigger a conflict within the look ahead time should be avoided as much as possible".

To be able to do this, there clearly is a need to know which manoeuvres will lead to a predicted conflict.
The predictive ASAS system has been designed to provide this information without requiring any crew action like "probing' or "trying to manoeuver". Such a system is sometimes referred to as a 'Conflict Prevention' system.

PASAS shows amber and red bands on the heading, speed and vertical speed scale. These bands indicate "no go" zones. When a heading value is selected inside an amber band, this wil lead to an amber conflict (i.e. a conflict between 3 and 5 minutes from now).

These bands can be used to implement the extra rule. It also facilitates the recovery manoeuver which was not very well supported in the version of the user-interface without PASAS.

If all equipped aircraft are fitted with PASAS, there is no longer a need to know intent information, because nobody will turn (or climb/descend) into a conflict. Any "false alerts" due to the lack of intent are no real false alerts. It should be avoided to aim a speed vector at anybody which would trigger a conflict even if the intention is to turn or level off soon. This will prevent near-conflicts if the intents change. ('better safe than sorry"). (See figure 9.1)

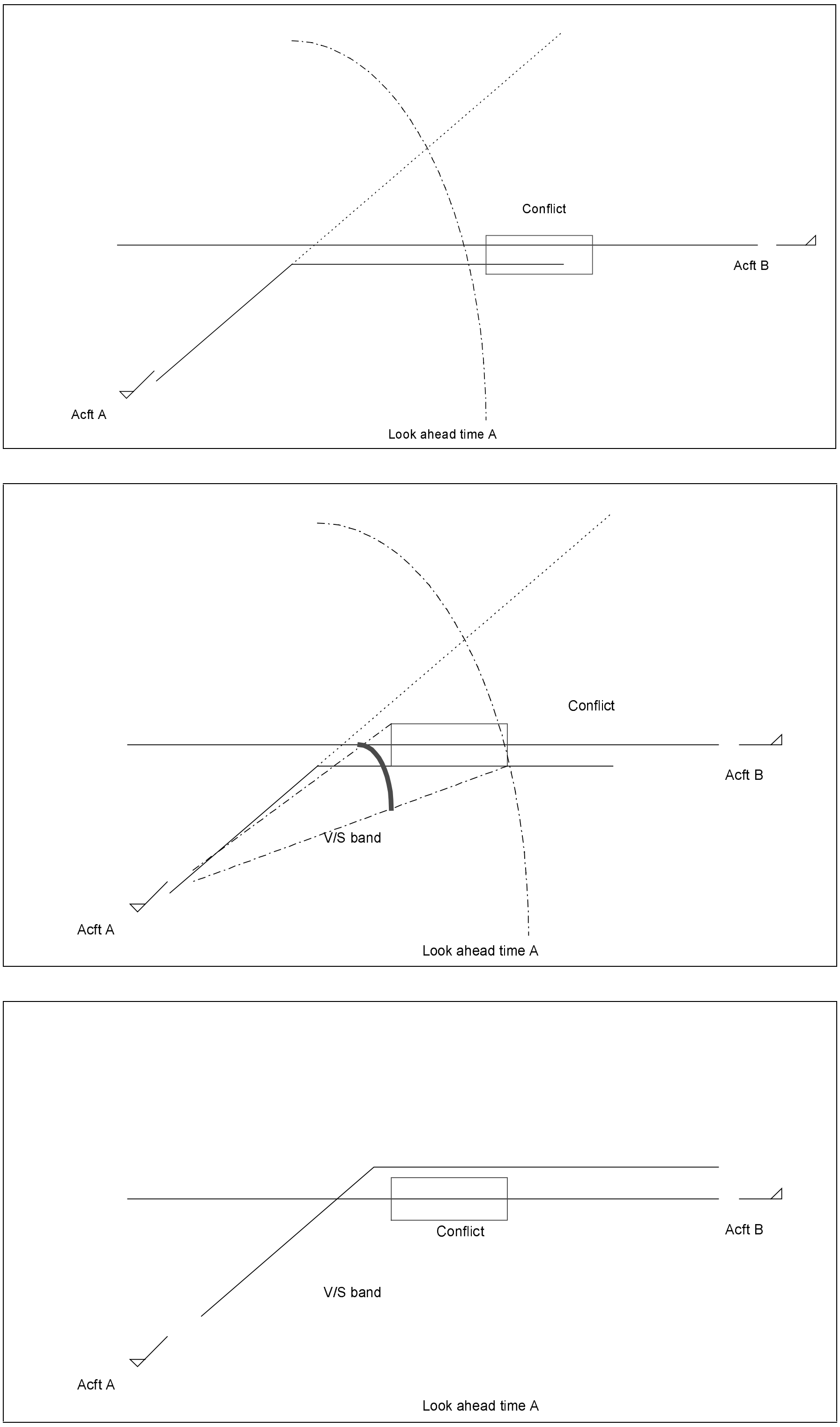


figure 9.1 Sequence illustrating effect of predictive ASAS to prevent conflicts which could otherwise only be prevented by exchanging intent information

9.2 Display Design

The PASAS bands have been added to the primary flight display (PFD) (speed, heading and vertical speed and the navigation display (ND)(heading).

The figures below show the resulting displays

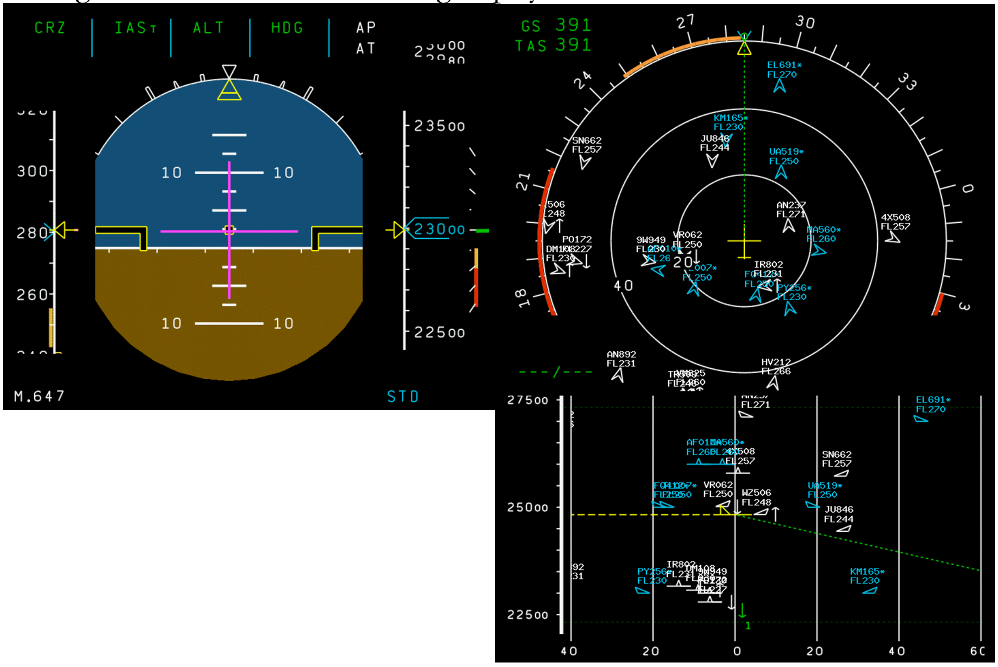


figure 9.2 Displays with PASAS symbology: amber and red bands on speed, vertical speed and track scale

There is no symbology to correlate the PASAS bands with the traffic symbol causing the band. Though this is not required, this could enhance the situational awareness. Two ways to correlate this have been considered:

1. Call signs near bands on PFD & ND
2. Lines on navigation display

Both solutions would lead to too much clutter and have not been implemented for that reason.
In most cases crews were able to judge which aircraft caused vertical speed or speed bands. The heading bands were harder to correlate.

9.3 Algorithms

9.3.1 Calculating vertical speed bands

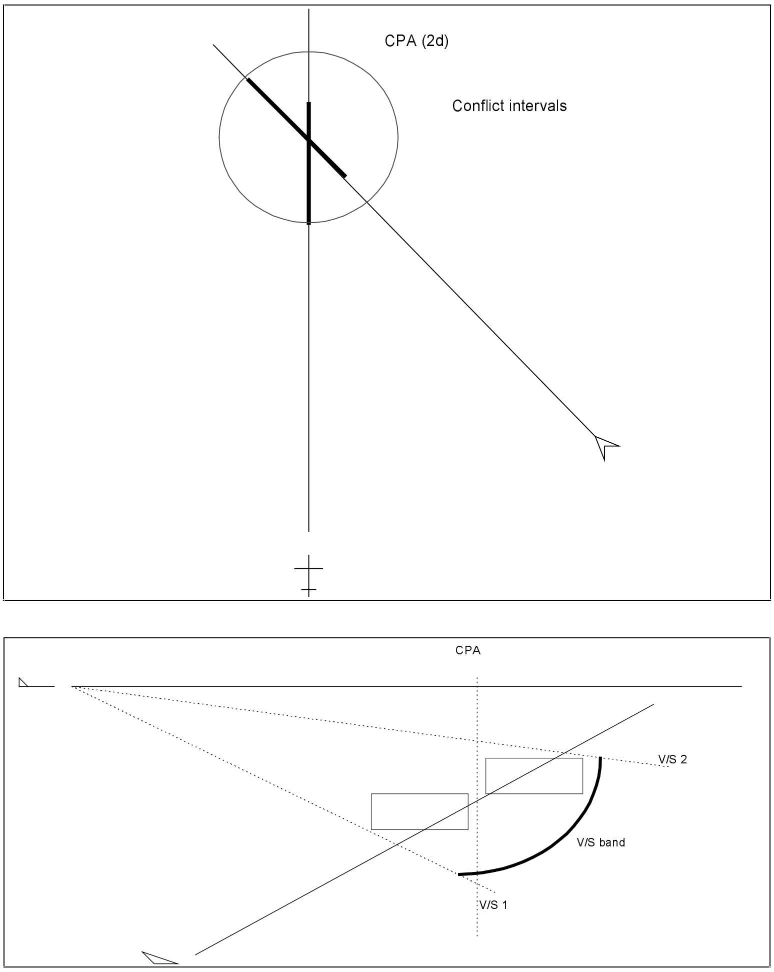


figure 9.3 Vertical speed bands result from apparent conflicts on the horizontal plane

Assume our own ship is flying level. The top figure shows a top view of the situation. In this two-dimensional picture there is a conflict for a certain interval. However from the side view it is clear that this is not a real conflict, because the intruder will pass below us during the time we are less than 5 nautical miles apart. It can also be seen that there is a range of vertical speeds which would cause a (three-dimensional) conflict with this aircraft. Calculating the lowest and highest vertical speed allows us to draw a no-go band (or two if an other amber and a red band is required) when this conflict is within the look ahead time (or the part that is in the look ahead time).

To calculate this the following steps are required:
- Calculate relative speed and position
- Project position and speed on plane of speedvector and horizontal line perpendicular to the speed (the “gamma plane”)
- Calculate whether minimum distance is below required separation
- Calculate conflict interval
- Limit interval to look ahead time
- Calculate altitudes of both aircraft at begin and end of interval

- Calculate corresponding vertical speeds.

9.3.2 Calculating speed bands

The speed bands are calculated by detecting conflicts in the (vertical speed, azimuth) plane. An apparent conflict in this plane can be translated to a ground speed, which would trigger a conflict. This is calculated by performing the following steps (see also figure below):

- Calculate vertical conflict interval within look ahead time
- Check whether there is an overlap with lateral (azimuth) conflict
- Calculate angles to edges of own protected zone in horizontal plane
- Calculate speed changes required to bend relative speed in direction of front and back edge
- Calculate resulting ground speeds
- Convent ground speeds to indicated airspeed

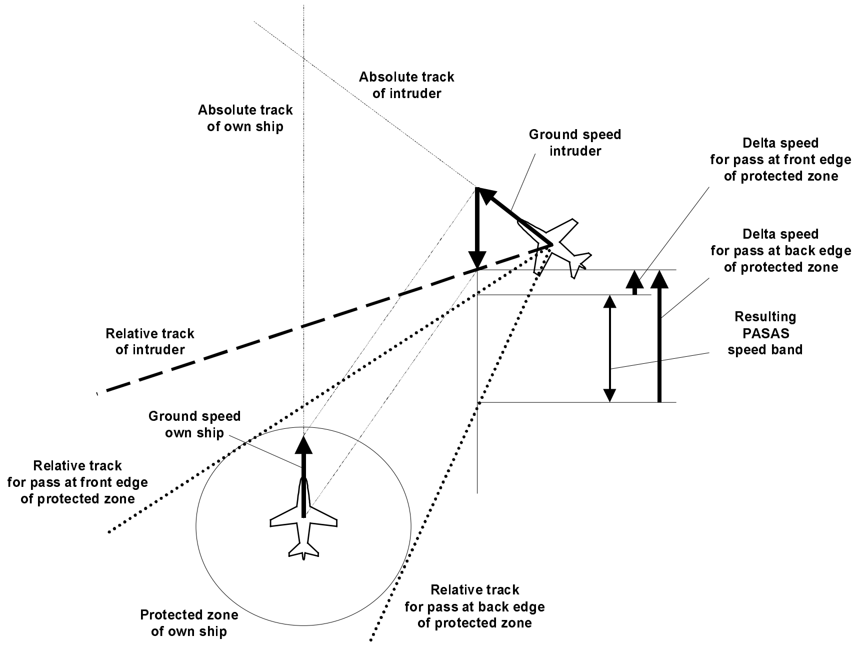


figure 9.4 Calculation of speed bands

After this calculation some checks on signs, exception and unrealistic values are performed before registering the speed band.

9.3.3 Calculating heading bands

For the heading bands a potential conflict in the (speed, elevation) plane can be converted to one or two heading bands. Two potential heading bands can result caused by either turning to the aircraft or turning away from the aircraft.

For this calculation the following steps are taken:
- Calculate the one or two direct hits (collisions) headings by matching the speed component perpendicular to the bearing
- Calculate angle to front and back edge in this direction
- Convert angles to heading bands

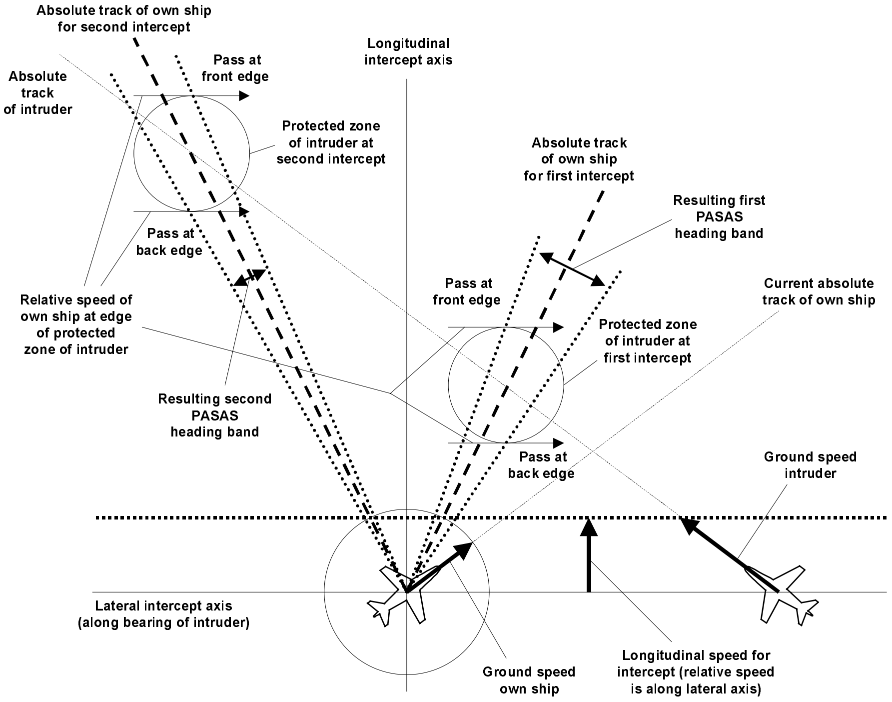


figure 9.5 Heading band calculation

The limiting vertical conflict interval and lookahead time require some additional checks on signs, limits and exceptions. Then the band is registered.

9.3.4 Output

The resulting output is a buffer with bands for vertical speed, speed and heading for both amber and red conflicts. Unrealistic values are removed. The look ahead time for the amber bands is set slightly higher than the CD&R lookahead time: 5 minutes and 20 seconds, for the red conflicts it is equal to the corresponding CD&R treshold of 3 minutes. The amber bands should be drawn before the red ones because the [0 , 5:20] interval encapsulates the [0 , 3:00] interval.

No filter logic is applied. The effect of the curve towards a heading or vertical speed is ignored. Heading bands far from the current heading might show a minor movement due to this omission. The effect of the curve could be included by applying a function including the speed on the heading bands.

Another omission is altitude bands. Because altitude does not directly correspond to an angle they can only be calculated as a derivative during the vertical speed calculation assuming a standard vertical speed, followed by a level flight.
The definition of altitude bands from the user point of view is: which altitude selection would lead to a conflict after levelling off and/or during the climb/descent to the altitude.

9.4 Miscellaneous remarks

Tha PASAS system as described so far only predicts the effect of a manoever. A better name might have been "conditional ASAS" because it is used for what-if analysis. Within the RTCA SC-186 committee it is refereed to as 'Conflict Prevention'. There is however a side effect of this system which makes it truly predictive. When the PASAS system is on every conflict alert is preceeded by one or more of the PASAS-bands growing towards the current value. For instance a conflict that happens a minute further away than the look ahead time, could be moved inside the look ahead time by turning towards this aircraft, hence there will be a heading band on the heading scale. When the conflict gets closer to the look ahead time, the required heading change will decrease so the band moves (or grows) towards the current heading (see figure 9.6)

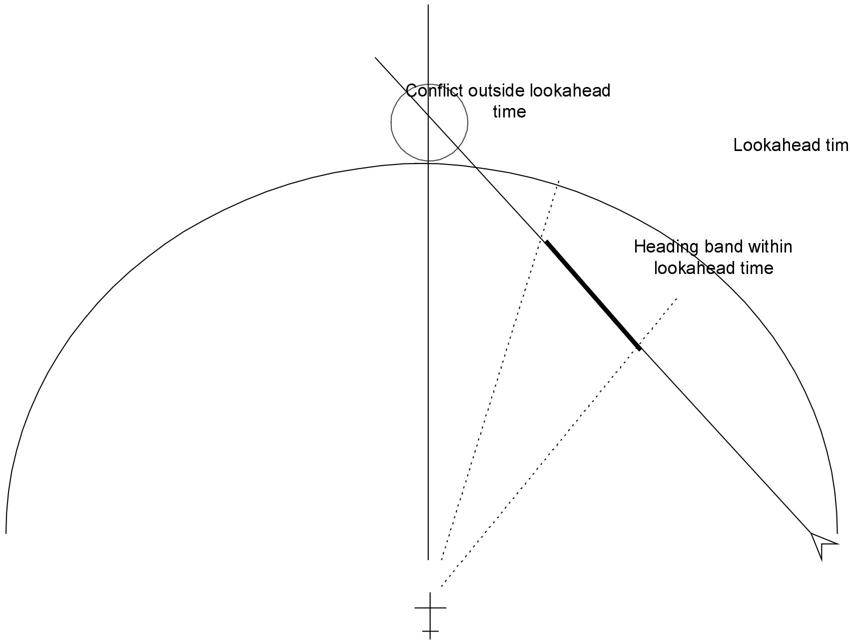


figure 9.6 A conflict is preceeded by PASAS bands growing towards the current value on e.g. the track scale

In case of exact head-on conflict there will not be a growing heading band, but the speed band will start to appear at higher speeds which would move the conflict inside the lookahead time. This would appear rather quickly. To avoid this short notice and to avoid missing minor intrusions, the amber lookahead time of PASAS has been increased to 5:20 minutes. This means an amber band will always appear, and enclose the current heading, speed or vertical speed, and predict a conflict.

As an addition, altitude bands may be added to the PASAS system, to enhance the situational awareness and improve the possibility to correlate bands to Traffic symbols for level flying aircraft. Other additions to improve the correlation are still under investigation.

The PASAS still lacks the filters as are used in the conflict detection module. Because bands are merged at the end of the PASAS algorithm the connection to the traffic, causing the bands is lost. Therefore PASAS might require another type of filter.

10 Mixed Equipage concepts

10.1 Transition Issue

Duing the phase I trials all aircraft in the sector were equipped with an airborne separation assurance system (ASAS). This simplifies the question of feasibility. If certain airspaces are labelled 'Free Flight Airspace' (FFAS, see figure 10.1) and only equipped aircraft are allowed to enter this airspace, the feasibility in cruise phase is supported by the results of the phase I trials. Denying aircraft without ASAS access to this airspace needs to be supported by strong arguments. If it is possible to allow both equipped and unequipped aircraft to share the same airspace, it is preferrable. In any situation, there will be a transition (in time) to the situation where a sufficient number of aircraft is equipped to justify excluding non-equipped aircraft. In the phase II trials this transitional situation of mixing equipped with non-equipped aircraft was one of the two topics addressed.

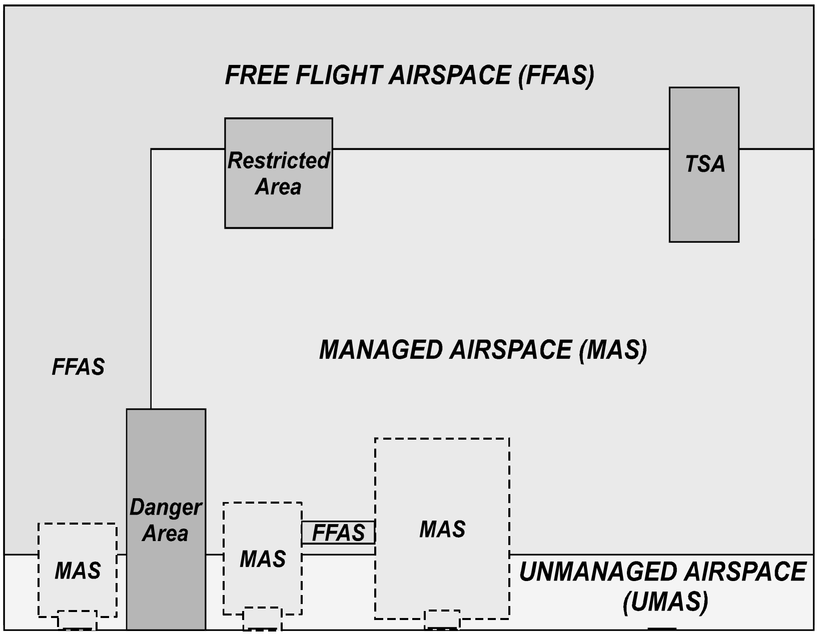


figure 10.1 EATCHIP operation concept (picture by Eurocontrol)

In the transition phase of equipping aircraft, it should already be rewarding for an airline to equip aircraft with ASAS. If it is not economically beneficial to equip aircraft during the transition phase, there will not be a drive to equip aircraft. The procedure used to handle the mixed equippage situation should therefore provide benefits for the equipped aircraft.

One can distinguish two transitions to Free Flight:

1. Transition in time, a certain period (potentially twenty years or more) in which aircraft are being equipped and the transition in time from the current ATM system with only Managed Airspace and Unmanaged Airspace to a future ATM system with Managed Airspace (MAS), Unmanaged Airspace

(UAS) and Free Flight Airspace (FFAS) is taking place. This period includes the introduction of FFAS.

2. Transition in space, one aircraft transitioning from Managed Airspace (MAS) to Free Flight Airspace (FFAS) and vice versa. This transition will always be there, even when the future ATM system with FFAS is in place.

This chapter deals with the transition in time, though the transition in place is addressed by one of the procedures where the airspaces are separated by altitude (see section 10.2)

The next sections will describe the three ATM procedures or concepts to handle mixed equippage that were designed for and evaluated in the phase II flight simulator trials. All three ATM concepts were designed to benefit the equipped aircraft, without excluding the unequipped aircraft.

The concepts assume the unequipped aircraft can be tracked with a certain (probably lower) accuracy on the traffic display of the equipped aircraft. The means to electronically "see" the unequipped aircraft is Traffic Information Service – Broadcast (TIS-B) rather than ADS-B. TIS-B assumes a ground station will uplink radar data of the unequipped aircraft in the same format as ADS-B does.

10.2 Concept F: Flight Level Split

In this condition, the airspace above a certain altitude (the “Lower Free Flight level”) is reserved for equipped aircraft only. A transition layer just above the Lower Free Flight level is used as a buffer zone for aircraft transitioning to and from Free Flight, see figure figure 10.2.

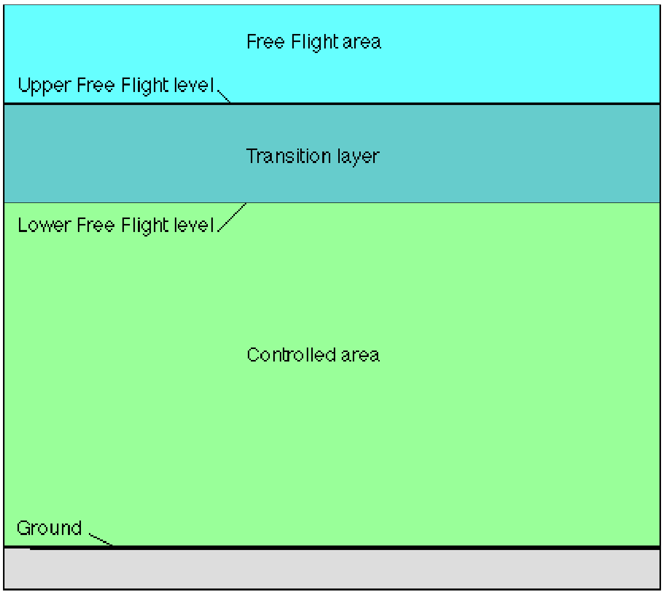


figure 10.2 Flight Level split ATM procedure

This buffer zone is employed to avoid predicted conflicts and possible intrusions of protected zones between free flying and controlled aircraft if only a single Free Flight Level would be used. Flying high has a clear economic advantage for cruising aircraft. Another advantage of this method is that it allows a gradual transition to free flight by lowering the altitude limit, similar to the National Route Program in the US, making it more acceptable when introduced.

This procedure is very different from the other mixed equippage procedures since the equipped and unequipped aircraft are separated in the vertical direction. This procedure was also included in the phase II trials to study the other transition issue: from managed airspace to unmanaged airspace and vice versa ('transition in place').

10.3 Concept A: Protected Airways ATM concept

In this concept, the airspace structure remains largely intact. Airways are still present for controlled, unequipped aircraft. The ASAS equipped aircraft, however, have the right to leave the airways for direct shortcuts to their destinations, whereas the controlled aircraft have to stay within the airways.

Free Flying aircraft have the right to cross an airway but only if they ensure conflict-free passage.

The advantage of ASAS equipage is direct routing, depending however on the efficiency of the conventional airway structure. This operational concept is illustrated in figure 10.3.

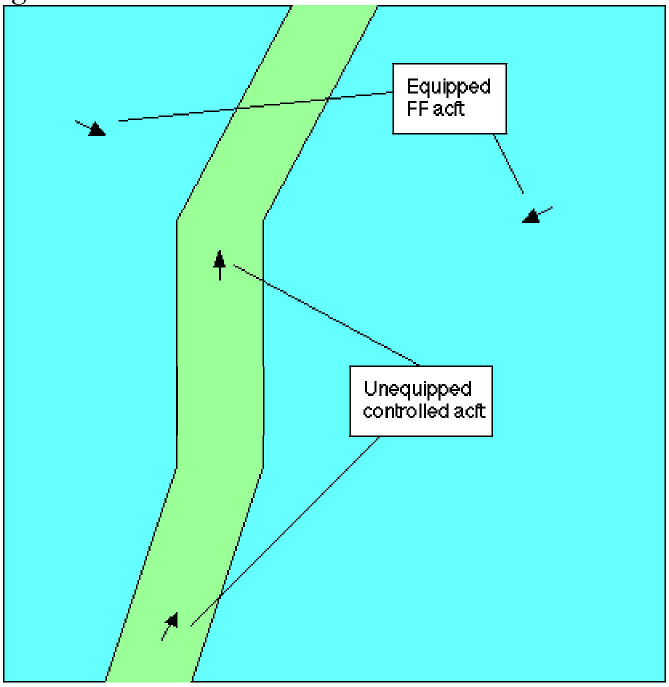


figure 10.3 Protected Airways ATM procedure

10.4 Concept M: Fully Mixed

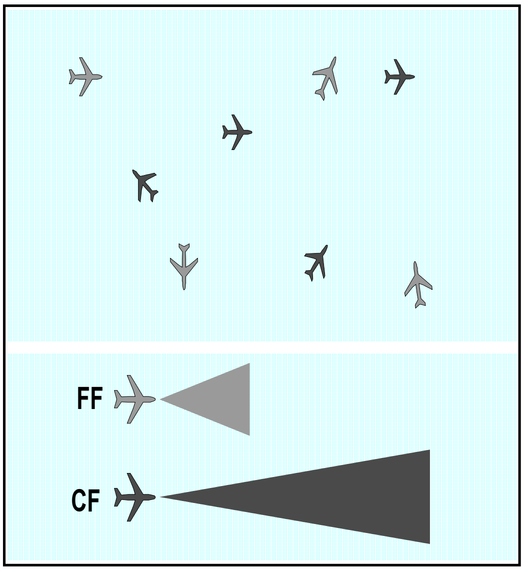


figure 10.4 Fully Mixed ATM concept: longer look-ahead time for controlled flights

In this case, all aircraft are able to fly direct routing. The controlled aircraft are monitored by the ground (ATC) using the same conflict detection module as is used in the airborne ASAS. ATC performs the conflict resolution task for the unequipped aircraft. By using a substantially longer look-ahead time for the conflict probing for the unequipped aircraft, these aircraft will always avoid ASAS equipped aircraft without a need for the equipped aircraft to maneuver. If all works as intended, the equipped aircraft will never detect a conflict with an unequipped aircraft because this will be resolved before it will be in the look-ahead time of the ASAS equipped aircraft. The equipped aircraft have effectively right-of-way and will not even get a conflict alert.

10.5 Other concepts

The concepts described here are aimed at providing intrinsic benefits to the equipped aircraft. It is also possible to create this benefits artificially via for example ATC fees. This allows the designer of the ATM procedures to focus on other aspects like efficiency and safety without the ‘benefit’-restriction as used in the ATM procedures for the phase II trials.

11 Phase 2 Flight Simulator Trials

11.1 Research Questions

This chapter describes the 1998 human-in-the-loop simulation experiment conducted at NLR and discuss both subjective and objective results obtained from this experiment.

As described in the previous chapter, one can distinguish two transitions to Free Flight:

1. Transition in time, a certain period (potentially twenty years or more) in which aircraft are being equipped and the transition in time from the current ATM system with only Managed Airspace and Unmanaged Airspace to a future ATM system with Managed Airspace (MAS), Unmanaged Airspace (UAS) and Free Flight Airspace (FFAS) is taking place. This period includes the introduction of FFAS.

2. Transition in space, one aircraft transitioning from Managed Airspace (MAS) to Free Flight Airspace (FFAS) and vice versa. This transition will always be there, even when the future ATM system with FFAS is in place.

Major research questions concerning the transition in time are:

- How to cope with a mixed equipped scenario where part of the fleet is ASAS equipped and another part is not ?
- Will the fleet eventually all be equipped or will a part of the fleet remain unequipped (e.g. general aviation) ?
- How to stimulate equipping the fleet other than by regulatory requirement ?

Major research questions concerning the transition in space are:

- What is the role and responsibility of the ground controller and pilot ?
- What will the operating procedure be to transition to/from FFAS ?

The aim of the 1998 human-in-the-loop experiment was to explore the human factors issues of several solutions of the future ATM system, covering all research questions raised. The transition towards Free Flight in time is reflected by the percentage of equipped aircraft in the traffic scenarios used in the experiment (25% and 75%). The transition to Free Flight Airspace (in space) was studied using different ATM operational concepts or scenarios, especially designed for this study. During the 1998 experiment, the results from the 1997 experiment and the subsequent cost/benefit analysis (chapter 13) were taken into account as well. The main adjustment to the ASAS equipment was the introduction of Predictive ASAS (PASAS), a system to prevent separation violation due to sudden maneuvers of nearby aircraft. The main result of the cost/benefit analysis was that vertical maneuvers are the most efficient maneuvers to use, whereas the 1997 human-in-the-loop experiment showed a clear preference for horizontal resolution maneuvers. This observation led to explicitly training the pilots in the 1998 human-in-the-loop experiment to use vertical resolutions if possible.

11.2 Experiment Configuration

The configuration used for the phase 2 trials consists of the configuration of the phase I trials plus an ATC console. The resulting configuration is shown in figure 11.1.

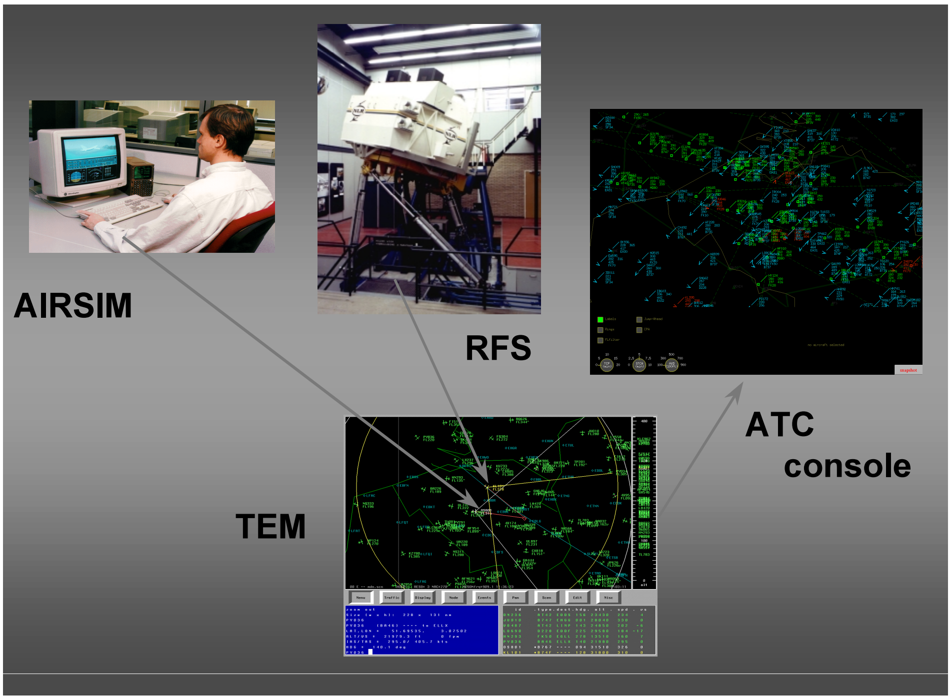


figure 11.1 Experiment configuration in phase 2 trials

The architecture of the simulation configuration is shown in figure 11.2 and figure 11.3. Apart from this infrastructure several other developments were required to enable the phase 2 trials. An additional system called 'predictive ASAS' (see chapter 9) was added to the user interface. For the simulation of a mixed equippage environment the traffic manager was enhanced with several features to enable the simulation of ATC controlled traffic (equippage levels, navigation modes, conventional routes, automatic R/T generation for altitude requests, etc.).

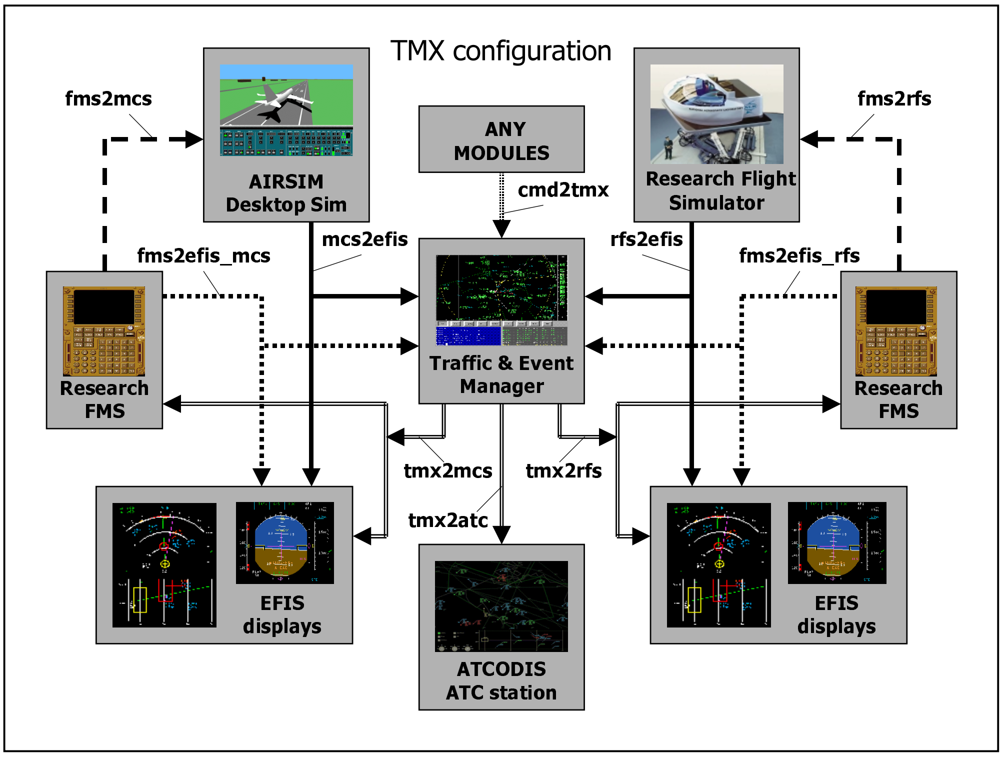


figure 11.2 Modules in simulation configuration

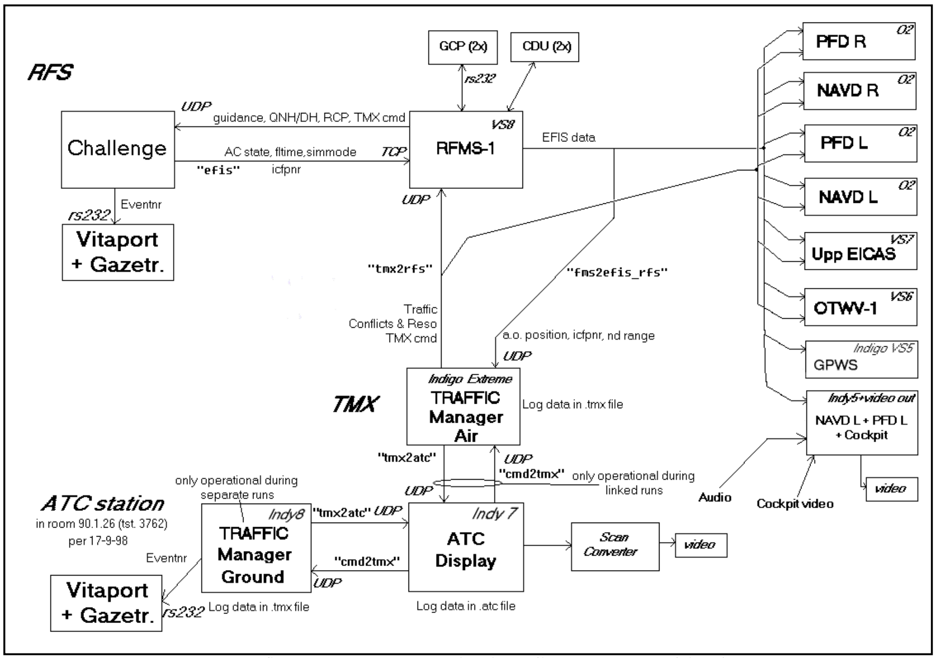
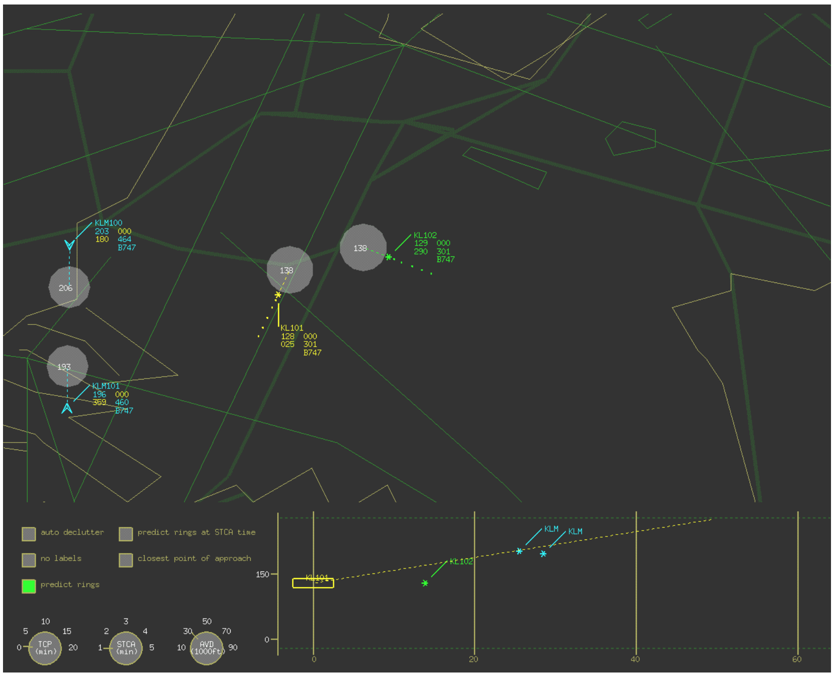


figure 11.3 Communication diagram as used in the development of the phase 2 trials

11.3 Experimental ATC station

To investigate the mixed equippage scenarios ground controlled aircraft were a part of the scenarios. In a part of the trials, the experiment manager would serve as ATC-er assisted by an NLR employee serving as the controlled aircraft. An other part of the trials an air traffic controller was the subject in a ground experiment. For these ground trials some runs were combined with the airborne trials. In these scenarios the research flight simulator was one of the free flying aircraft. In case if the 'Flight Level' ATM procedure (see section 10.2) the hand-over from and to the Free Flight sector was performed by the air traffic controller. Apart from this situation the interaction between the subject crew in the flight simulator and the subject air traffic controller is limited.

The ground side was also included to see whether the procedure preferred by the airborne crew would be acceptable to the controller and vice versa. Another area of interest was the Human-Machine Interface (HMI) aspects of monitoring a Free Flight airspace. For this reason a specific HMI prototype has been developed including a tool similar to the airborne ASAS to be able to separate the 'Full Mix' scenarios (see section 10.4). The HMI is shown in figure 11.4.



☐ auto declutter
☐ predict rings at STCA time
☐ no labels
☐ closest point of approach
☑ predict rings

figure 11.4 Prototype controller's human machine interface

11.4 Subjects

Six subject pilots from major European airlines participated in the NLR 1998 human-in-the-loop Free Flight with Airborne Separation Assurance experiment. The subject pilot was asked to act as the captain (Pilot-Non-Flying, PNF), but to leave the control of the Mode Control Panel and the Flight Management System to the First Officer (Pilot-Flying, PF). The First Officer was a pilot hired by the NLR who was instructed to behave passively and not to influence the subject pilot. The subject pilot was instructed that the task of traffic awareness was his/hers alone.

The average subject pilot had 3500 hours flying experience, of which 2500 hours glass cockpit.

11.5 Experiment matrix

In the Free Flight 1998 experiment, each subject pilot was assumed to fly 12 experiment runs, 4 runs with the flight level ATM procedure, 4 runs with the fully mixed ATM procedure and 4 runs with the protected airways ATM procedure. However, during the experiments with the first two subject pilots, it became clear that the high traffic density scenarios combined with the flight level ATM procedure could not be handled by the experiment leader and air traffic controller. It was therefore decided after the second subject pilot to fly the remaining four subject pilots with the medium density scenario only for the flight level ATM procedure.

Initially, the experiment scenarios used for the first two subjects was low and high density. As the low density scenario did not cause any conflicts in the scenario, it was decided after the second subject pilot to fly the remaining 4 subject pilots with medium and high traffic densities.

Due to the changes in the experiment conditions after subject pilot 2, only the data for subject pilot 3 to 6 was considered valid for analysis. The remaining experiment matrix therefore is shown below in Table 11.1. The first character expresses the ATM procedure with "a" for protected airways (red), "f" for flight level (blue) and "m" for the mixed ATM procedure (green). The second character shows the traffic densities, "h" for high density, "m" for medium density. The numbers indicate the level of ASAS equipage, 25% and 75%. Finally the "a" is added for the "airborne" scenarios.

crew\run	1	2	3	4	5	6	7	8	9	10
3	mm75a	mh75a	mm25a	mh25a	fm25a	fm75a	am75a	ah25a	am25a	ah75a
4	am25a	ah75a	ah25a	am75a	fm75a	fm25a	mh25a	mm25a	mm75a	mh75a
5	fm25a	fm75a	mh75a	mm25a	mm75a	mh25a	am75a	am25a	ah25a	ah75a
6	fm75a	fm25a	am75a	ah75a	ah25a	am25a	mm25a	mh75a	mm75a	mh25a

Table 11.1 Experiment matrix

As a consequence of the adjusted experiment matrix, the ATM procedure effect and equipage effect can only be investigated for medium traffic density, see Table 11.2. The effect of traffic density can only be investigated for the protected airways and fully mixed ATM procedure, see Table 11.3.

crew\run	1	2	3	4	5	6
3	mm75a	mm25a	fm25a	fm75a	am75a	am25a
4	am25a	am75a	fm75a	fm25a	mm25a	mm75a
5	fm25a	fm75a	mm25a	mm75a	am75a	am25a
6	fm75a	fm25a	am75a	am25a	mm25a	mm75a

Table 11.2 Experiment matrix for ATM procedure effect and equipage effect

crew\run	1	2	3	4	5	6	7	8
3	mm75a	mh75a	mm25a	mh25a	am75a	ah25a	am25a	ah75a
4	am25a	ah75a	ah25a	am75a	mh25a	mm25a	mm75a	mh75a
5	mh75a	mm25a	mm75a	mh25a	am75a	am25a	ah25a	ah75a
6	am75a	ah75a	ah25a	am25a	mm25a	mh75a	mm75a	mh25a

Table 11.3 Experiment matrix for traffic density effect

11.6 Data recording

The data recorded during the experiment was reasonable extensive. Questionnaires were used for subjective measurements. During the experiment, every subject pilot was asked to fill in the following questionnaires:

- Pilot Experience Questionnaire, once during experiment briefing
- Pilot Sleeping Questionnaire, once every day
- Run Questionnaire, once every run, giving information on:
    - Rating Scale of Mental Effort (RSME)
    - acceptability
    - true/false answers on statements
    - safety
    - conflicts and resolution maneuvers (and why)
    - additional pilot and observer comments
- Post Trial Questionnaire, after every ATM procedure, giving information on the acceptability and criticality of the elements of the Human Machine Interface, including additional pilot and observer comments

These questionnaires can be found in Appendix B.

Apart from questionnaires, the following data was recorded during the experiment:

- intrusions of the protected zone of the subject aircraft
- Eye-Point-Of-Gaze (EPOG) data, using eye-tracking equipment

11.7 Results

11.7.1 Subjective data

Most subjective data is presented graphically in so called "frequency tables". Frequency tables represent the simplest method for analyzing categorical data. They are used as an exploratory procedures to review how different categories of values are distributed in the sample. Since most questionnaire results are formatted as categorical variables, these frequency tables are used to present the results.

The workload data is investigated statistically using ANOVA techniques.

11.7.1.1 Acceptability

The bar chart in figure 11.5 shows the ATM procedure effect on the acceptability, presented as frequency table.

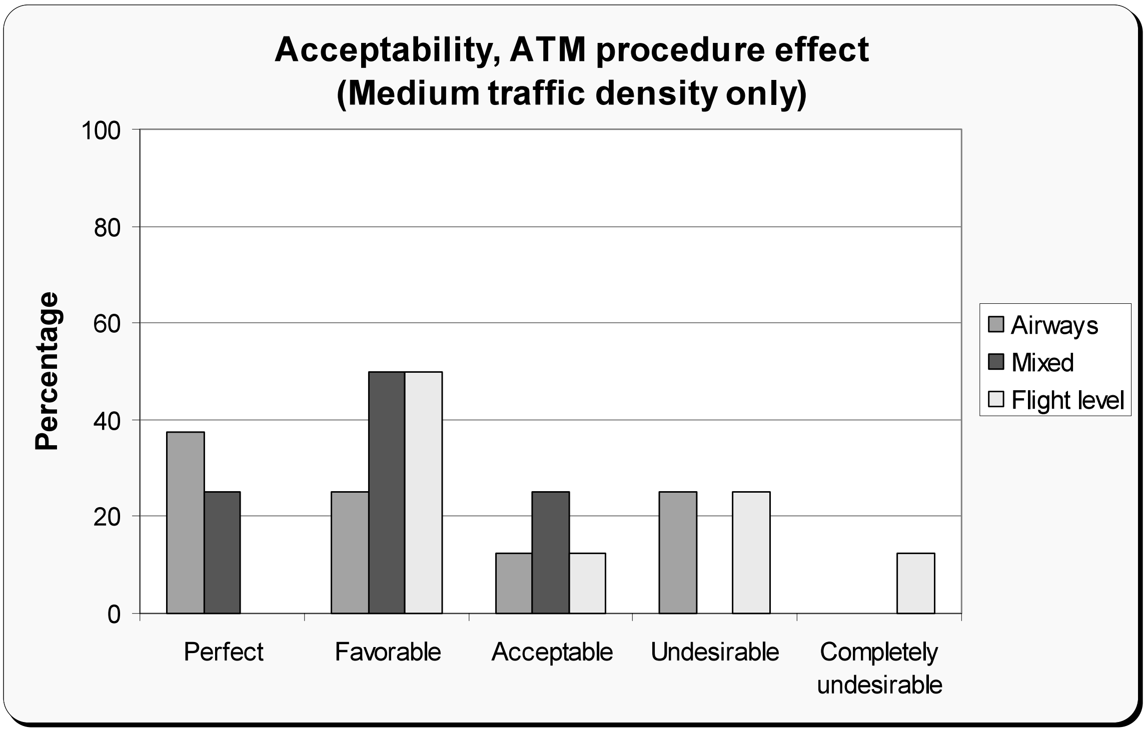


figure 11.5 ATM procedure effect on acceptability.

The bar chart in figure 11.6 shows the traffic density effect on the acceptability, presented as frequency table.

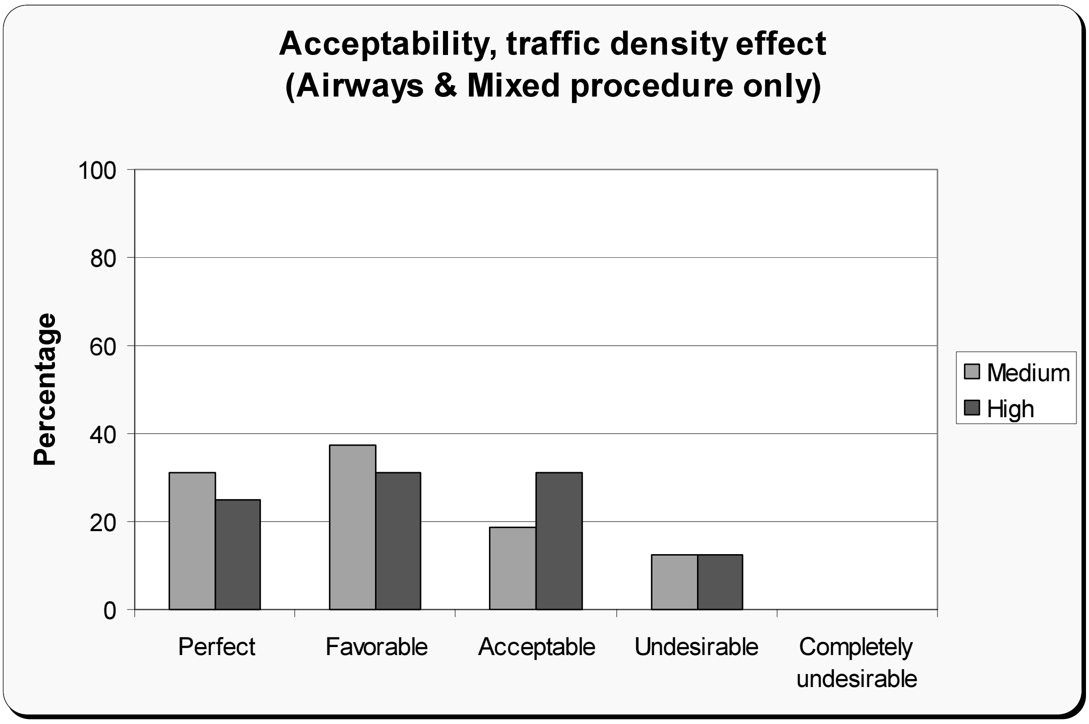


figure 11.6 Traffic density effect on acceptability

The bar chart in figure 11.7 shows the equipage effect on the acceptability, presented as frequency table.

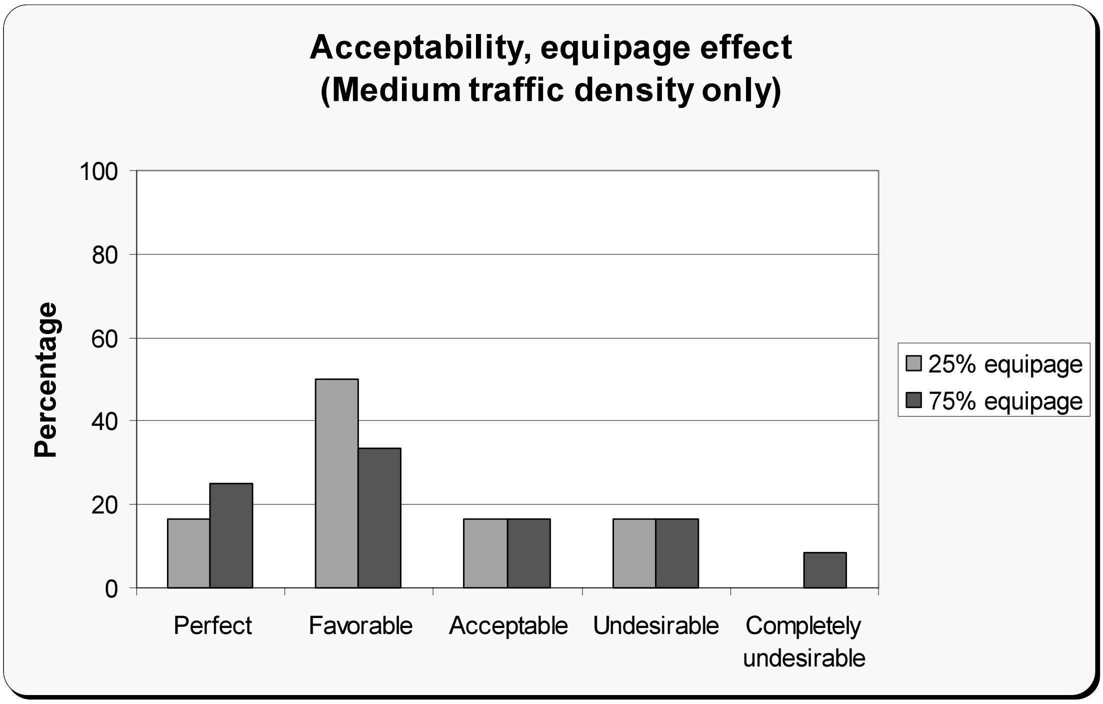


figure 11.7 Equipage effect on acceptability.

The bar charts in figure 11.8 to figure 11.10 show the ATM procedure effect, traffic density effect and equipage effect on the acceptability. These figures show the results for “acceptable or better”.

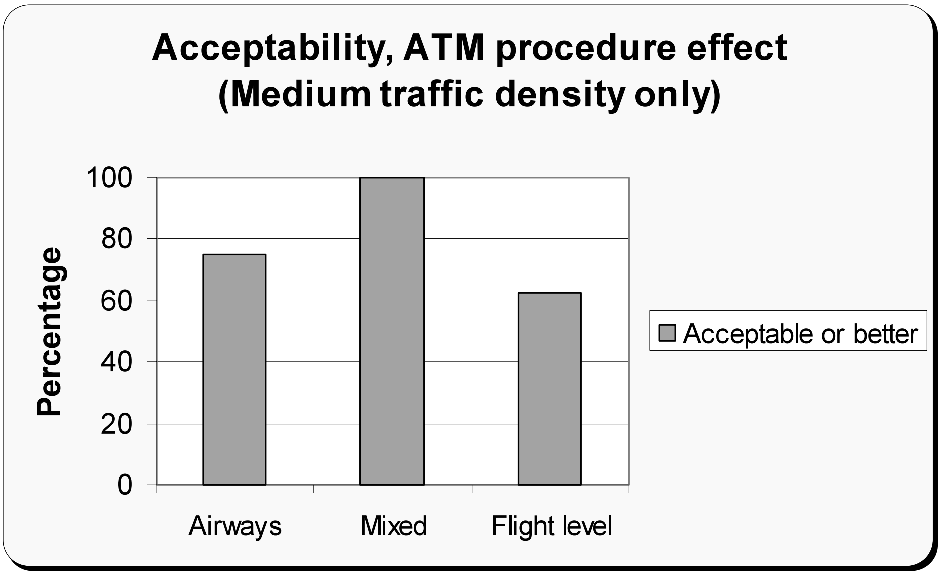


figure 11.8 ATM procedure effect on “acceptable or better” results.

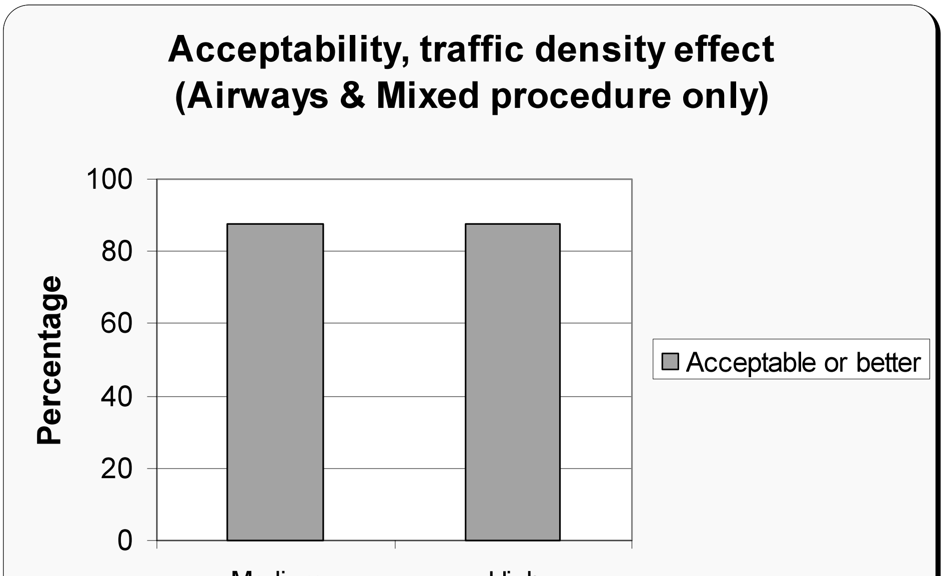


figure 11.9 Traffic density effect on “acceptable or better” results.

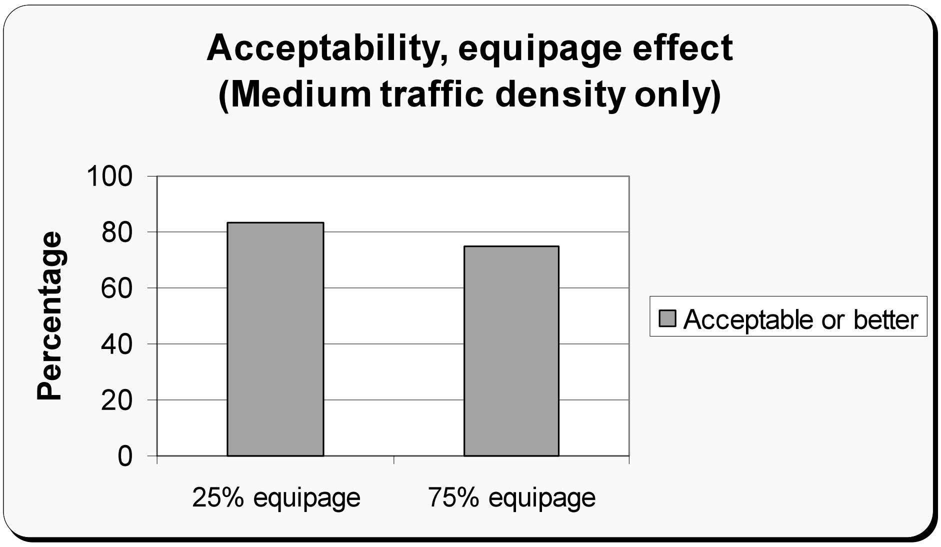


figure 11.10 Equipage effect on "acceptable or better" results.

As can be seen from these results, the ATM procedure has a clear effect on the acceptability levels, indicating that the fully mixed ATM procedure is most acceptable and the flight level ATM procedure is least acceptable. The traffic density and equipage have little effect on acceptability.

11.7.1.2 True/False answers

Four True/False questions were used in the questionnaire:

- I think I could safely gurantee the airborne separation with the set-up just flown
- I manoeuvred more than normally
- I exceeded passenger comfort levels
- I flew economically
-

The results from the True/False questions are presented in figure 11.11 to figure 11.13, indicating the ATM procedure effect, traffic density effect and equipage effect. Shown are the frequencies of the questions answered with "YES".

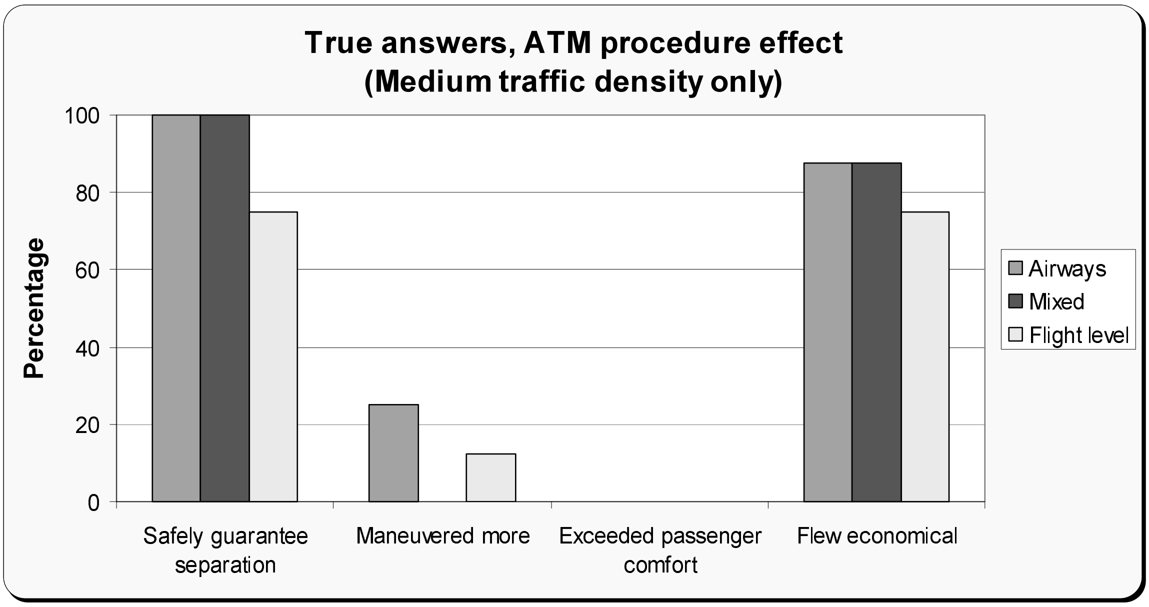


figure 11.11 ATM procedure effect on answers to True/False questions

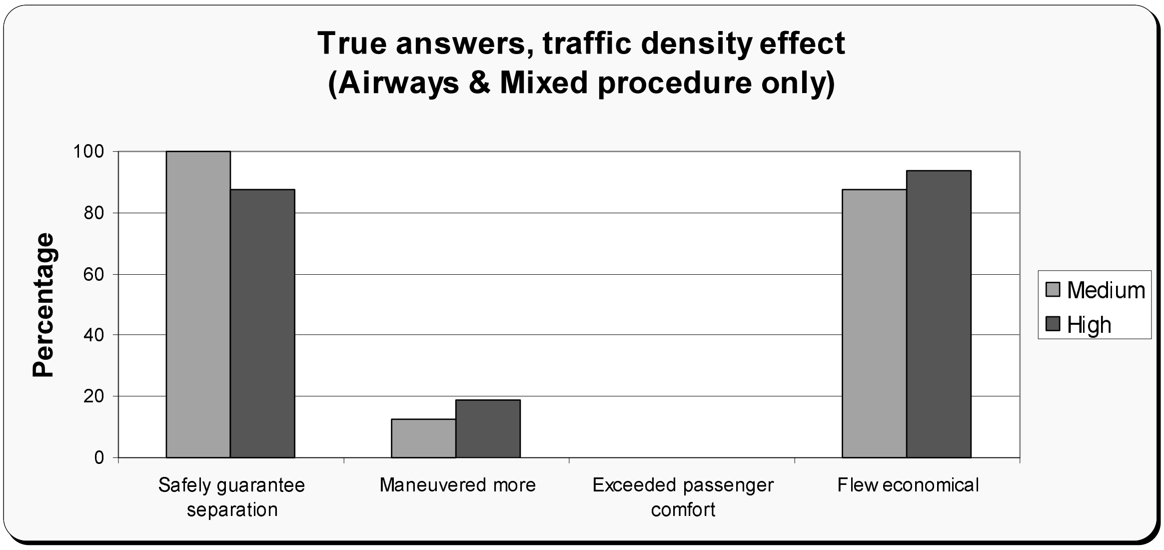


figure 11.12 Traffic density effect on answers to True/False questions

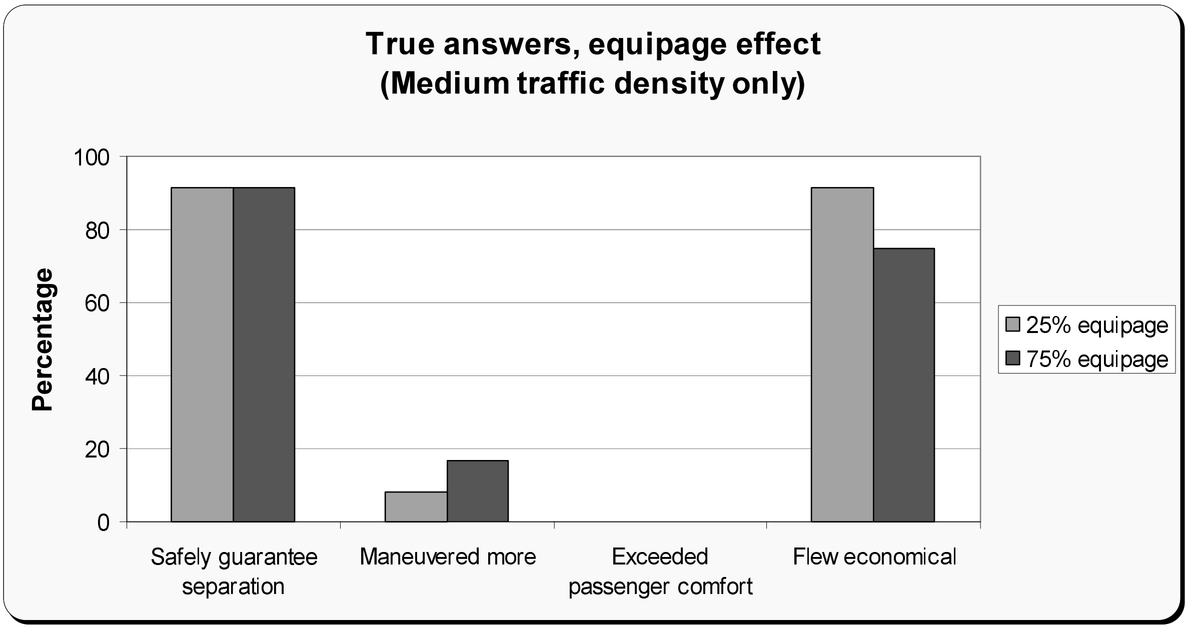


figure 11.13 Equipage effect on answers to True/False questions

It can be concluded from figure 11.11 to figure 11.13 that the ATM procedure, traffic density and equipage levels have little effect on the answers to the True/False questions. As can be seen, most pilots felt they can safely guarantee separation (>80% of responses), they did NOT maneuver more than normally (>90% of responses), they did NOT exceed passenger comfort levels (100% of responses), and they flew economically (>80% of responses).

11.7.1.3 Safety

The bar charts in figure 11.14 to figure 11.16 show the effect of the ATM procedure, the traffic density and equipage level on perceived safety.

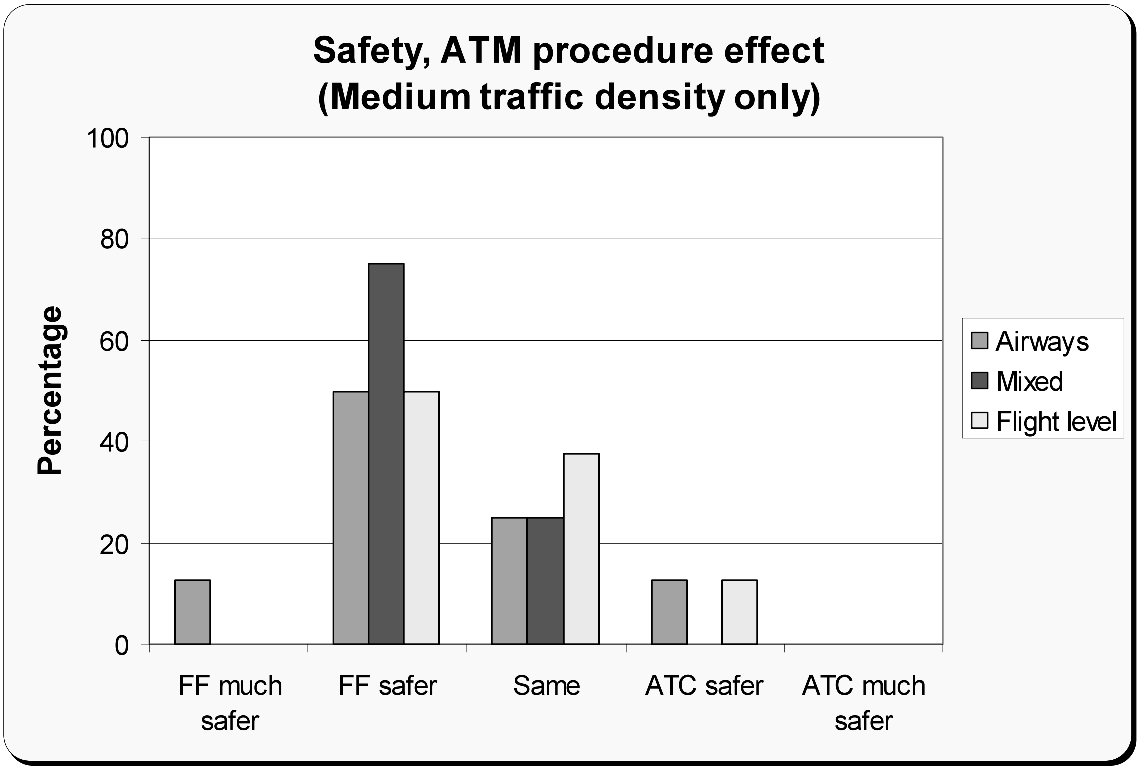


figure 11.14 ATM procedure effect on perceived safety

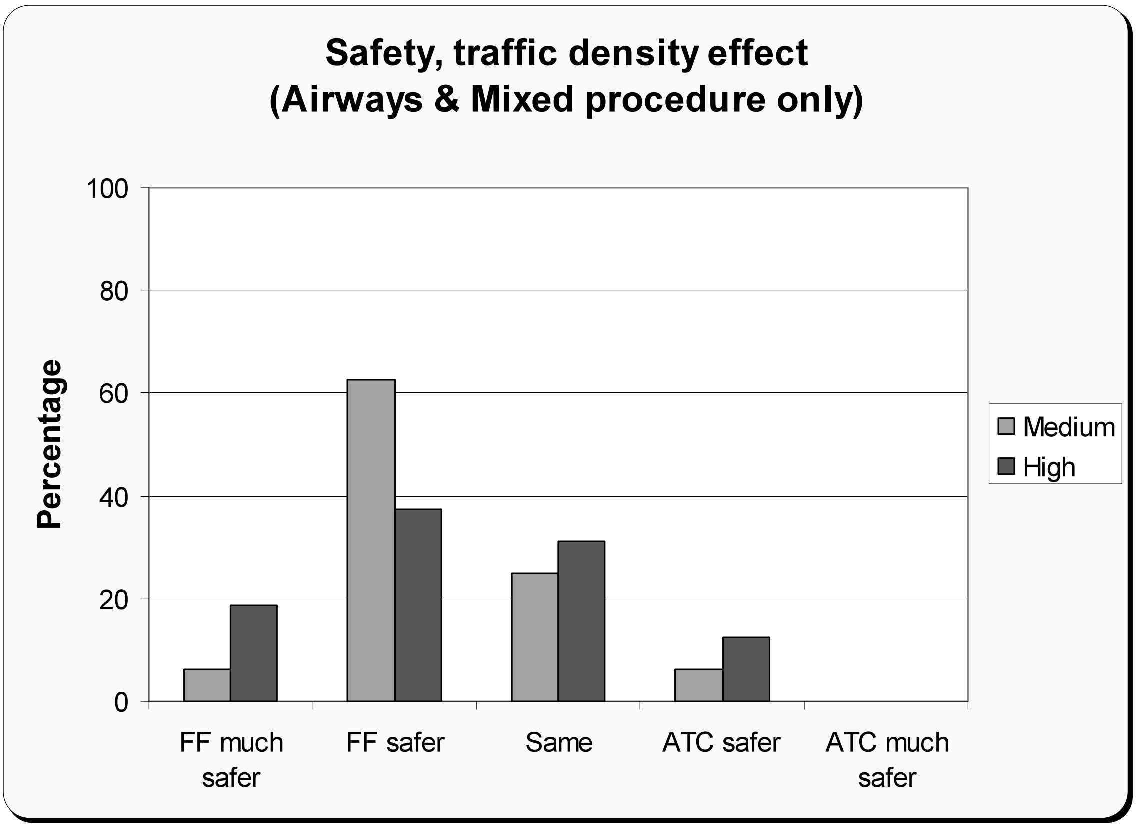


figure 11.15 Traffic density effect on perceived safety

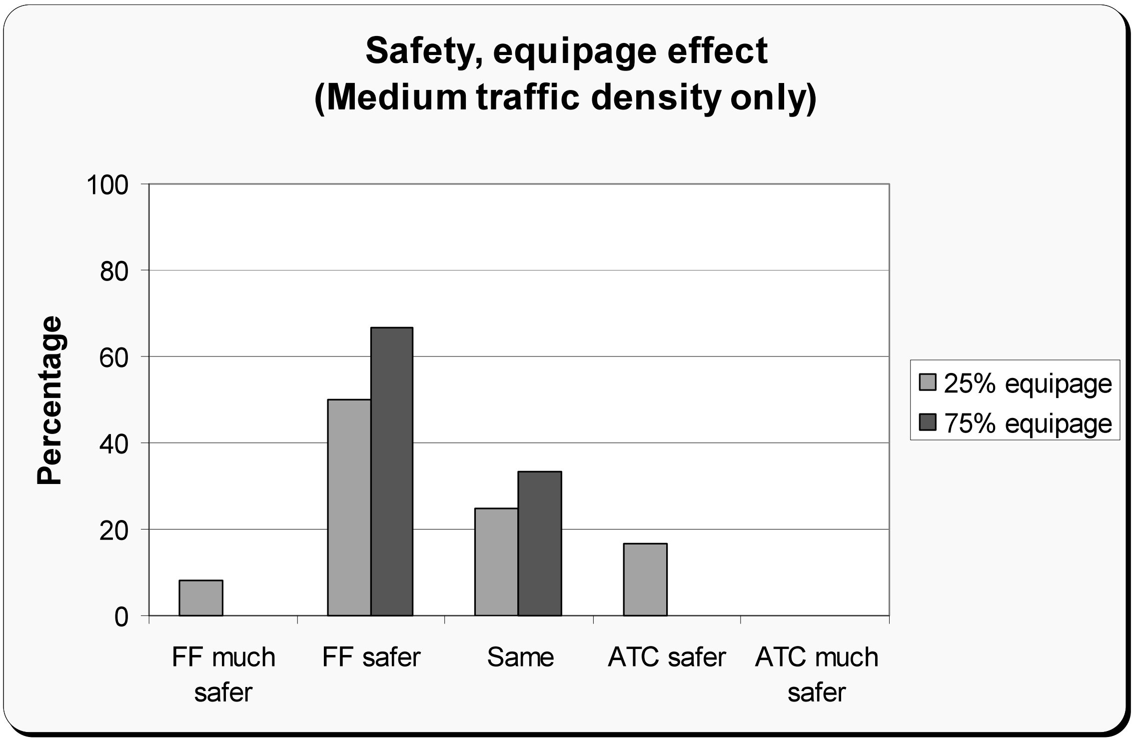


figure 11.16 Equipage level effect on perceived safety

The bar charts in figure 11.17 to figure 11.19 show the ATM procedure effect, traffic density effect and equipage effect on the perceived safety, indicating "Free Flight as safe as ATC, or better".

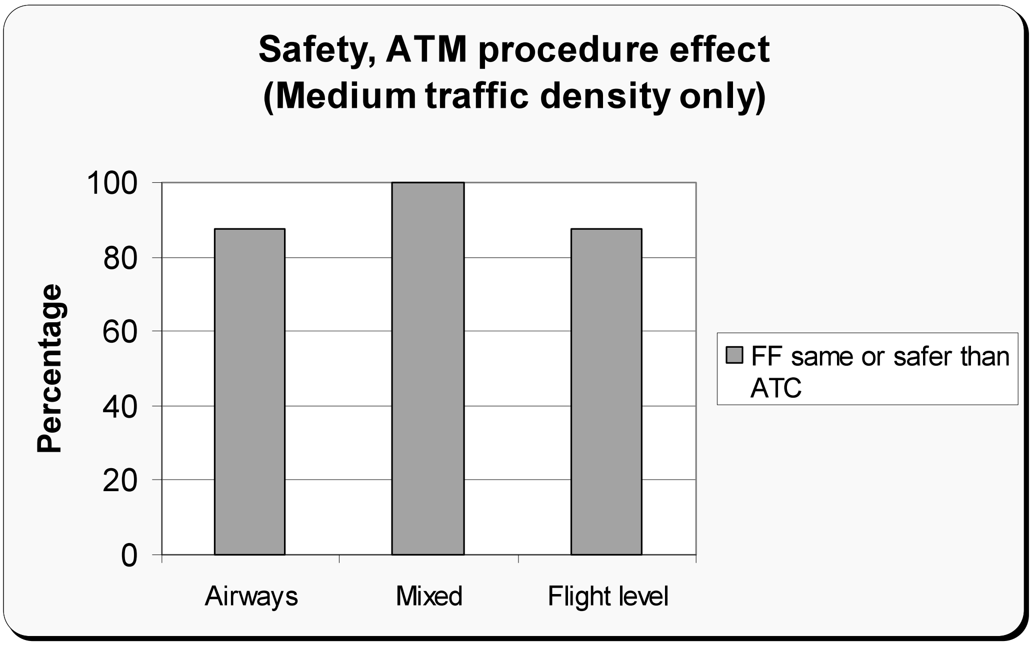


figure 11.17 ATM procedure effect on "same as ATC or better" results

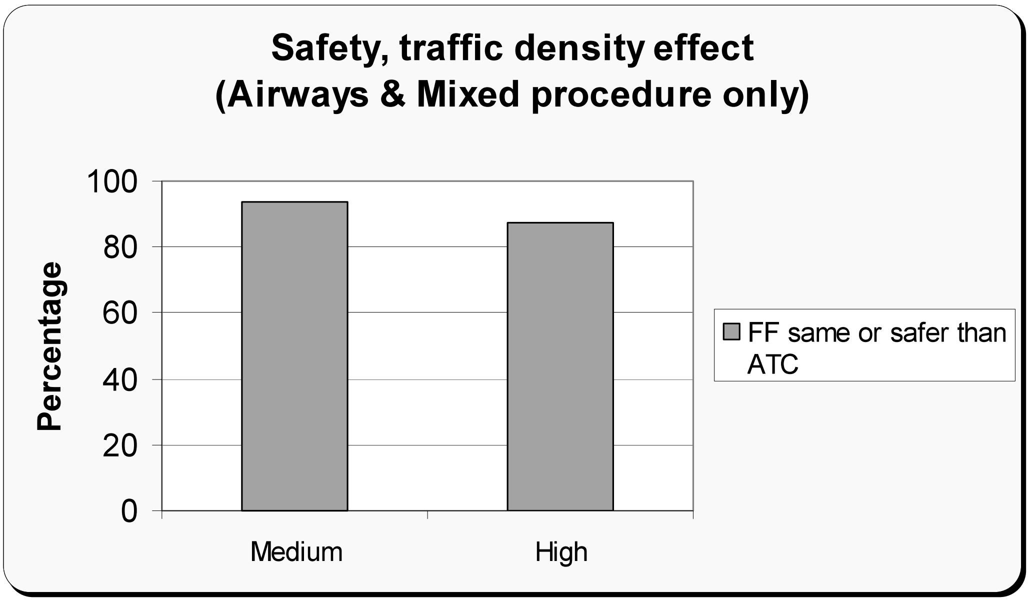


figure 11.18 Traffic density effect on "same as ATC or better" results

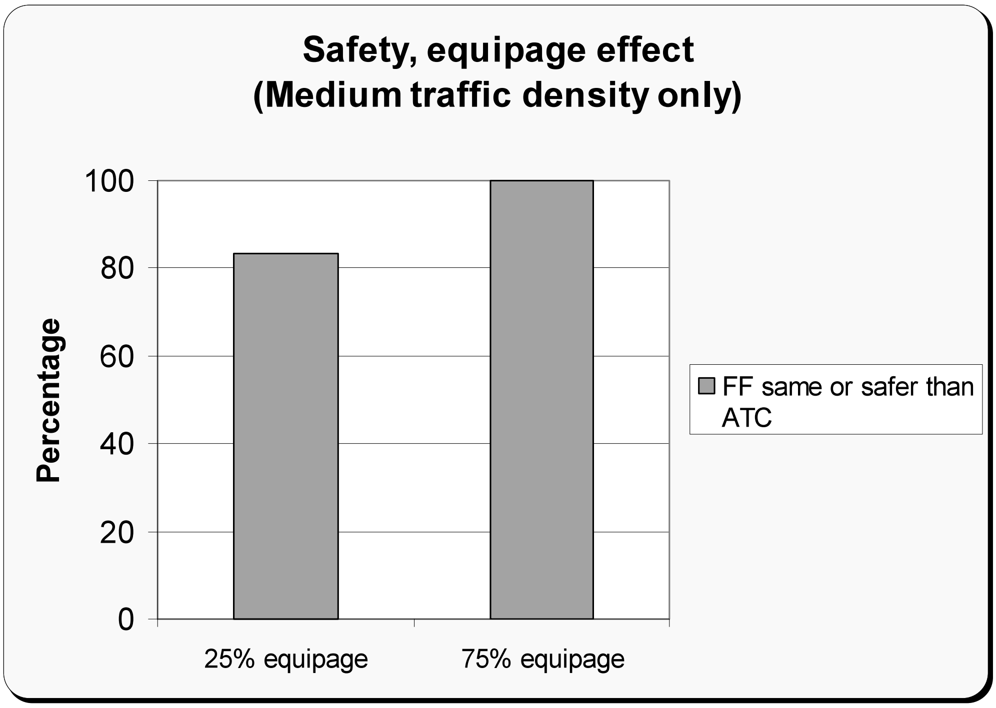


figure 11.19 Equipage effect on "same as ATC or better" results

The ATM procedure has a clear effect on the perceived safety. The fully mixed ATM procedure is favored regarding safety. Perceived safety is slightly reduced with increasing traffic density as expected, while equipage level has a clear effect on safety. Perceived safety is reduced with low equipage level. This result was not expected. It shows that the transition towards Free Flight in time has a positive effect on the perceived safety.

11.7.1.4 Resolution maneuvers

The bar charts in figure 11.20 to figure 11.22 show the effect of the ATM procedure, the traffic density and equipage level on the conflict resolutions.

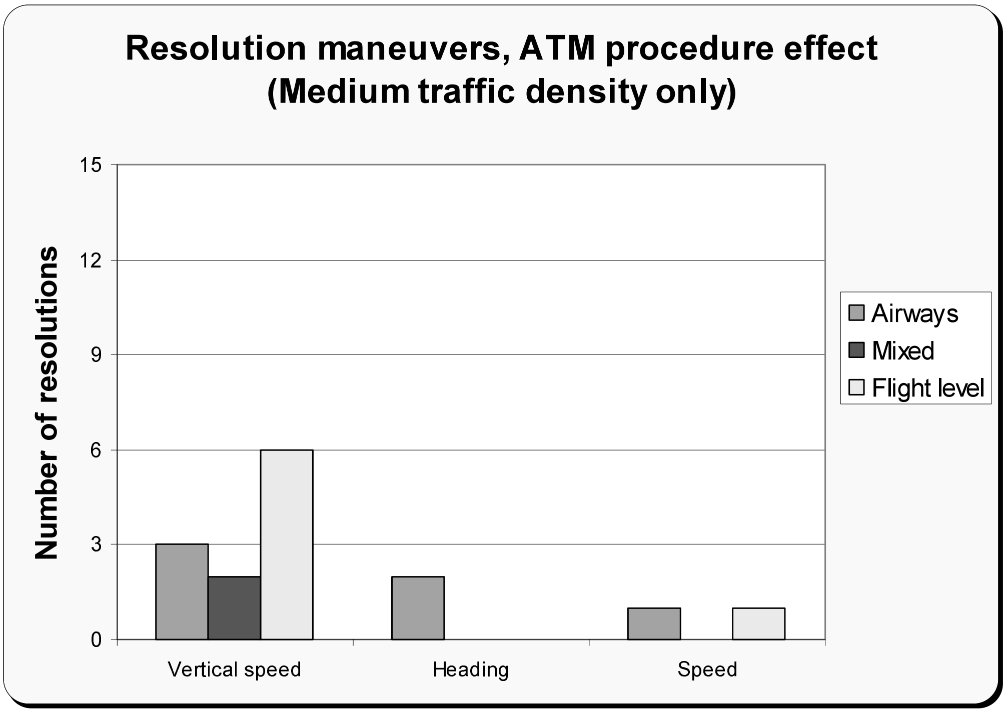


figure 11.20 ATM procedure effect on conflict resolutions

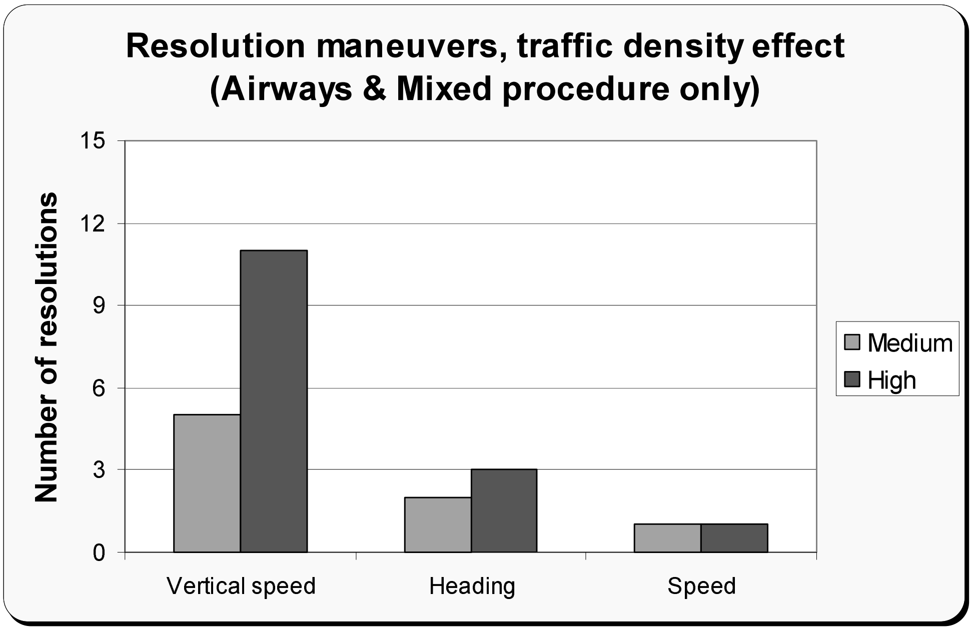


figure 11.21 Traffic density effect on conflict resolutions

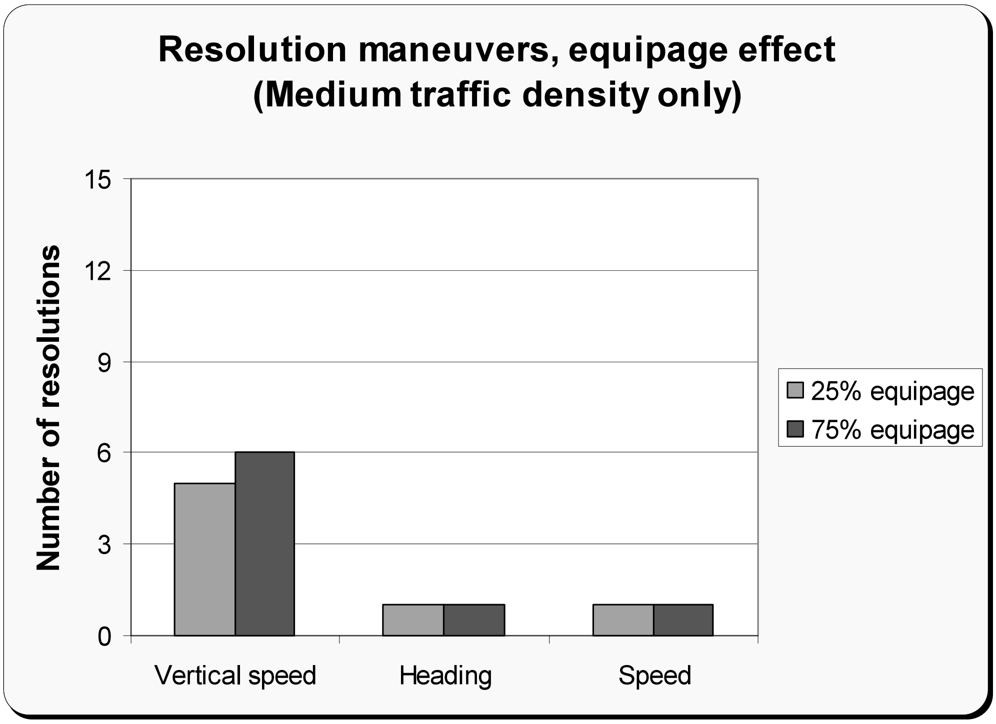


figure 11.22 Equipage effect on conflict resolutions

It can be concluded that vertical speed is the overall preferred resolution method, in contrast to the results from the 1997 Free Flight experiment where heading was the most preferred resolution maneuver, see figure 11.23. This can be explained by the explicit training of the subject pilots to use the vertical speed mode to resolve conflicts. The reason to train pilots this way was the economical benefit of the resolution maneuver over the horizontal maneuver, as indicated in the study described in chapter 13.

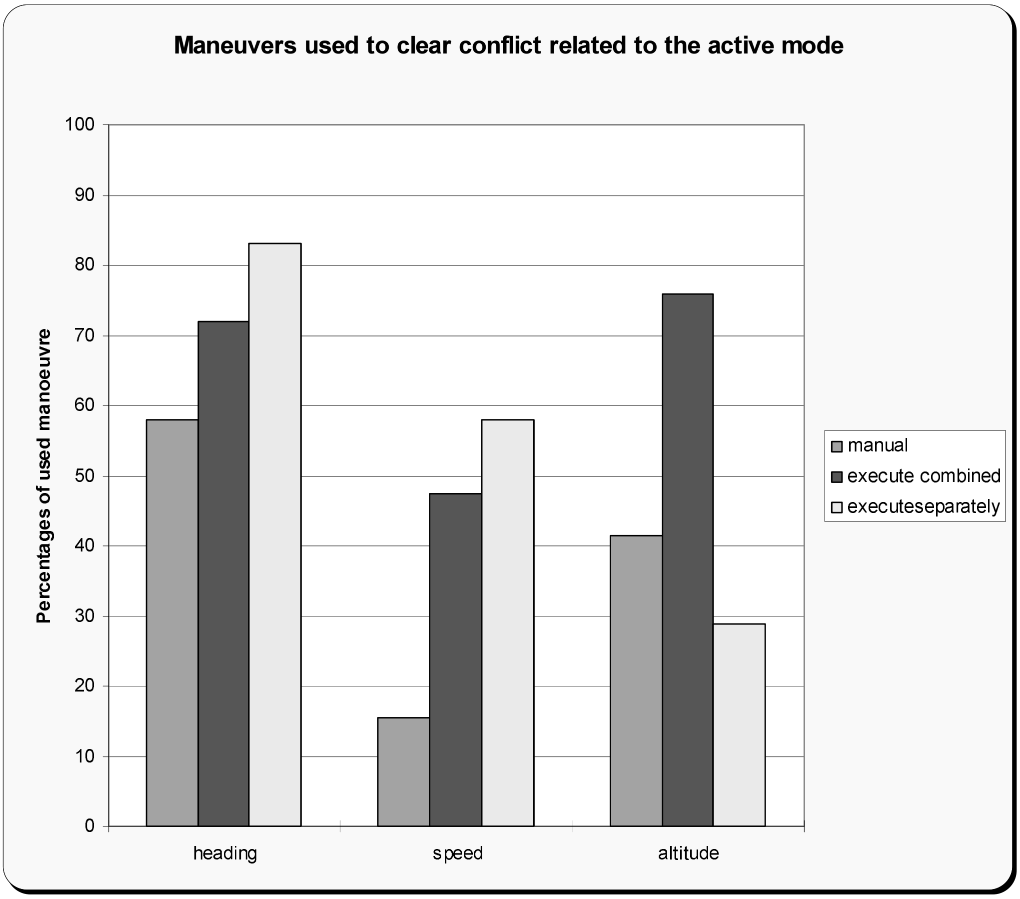


figure 11.23 Conflict resolutions from 1997 experiment

As can be seen, the number of resolutions increases with traffic density as expected. The preference for vertical speed does not change. Similarly, the ATM procedure has effect on the number of conflict resolutions, but not on the vertical speed preference. As expected, the fully mixed ATM procedure results in the least conflict resolutions as the non equipped aircraft are "vectored away" from the equipped aircraft, 3 minutes prior to the moment the equipped aircraft see the conflict between equipped and non-equipped aircraft. The equipage level has little effect on the resolution maneuvers.

11.7.1.5 Human Machine Interface (HMI)

After every ATM procedure, the subject pilots were asked to fill in a questionnaire on the Human Machine Interface acceptability and criticality. The results could be entered on a scale from 1 to 5:

Acceptability:
1 = completely unacceptable
2 = undesirable

3 = acceptable
4 = favorable
5 = perfect in every way

Criticality:

1 = not at all critical
2 = not really critical
3 = critical
4 = very critical
5 = extremely critical

An example of the results is shown in figure 11.24 and figure 11.25. The ATM procedure effect is shown on acceptability and criticality of the presentation of conflicts.

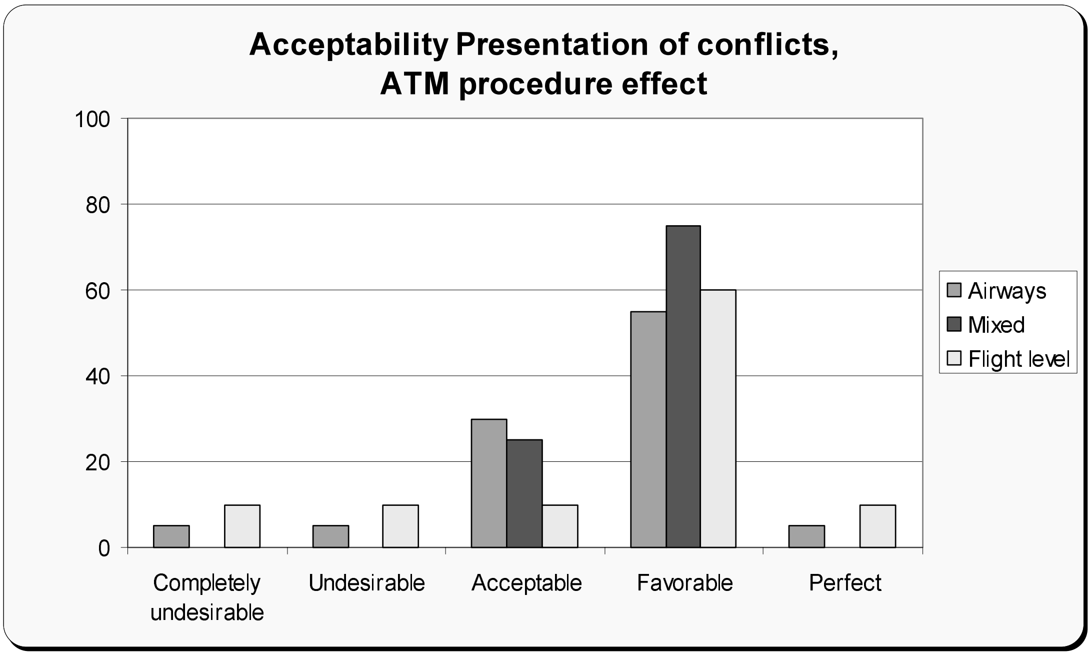


figure 11.24 ATM procedure effect on acceptability of the presentation of conflicts

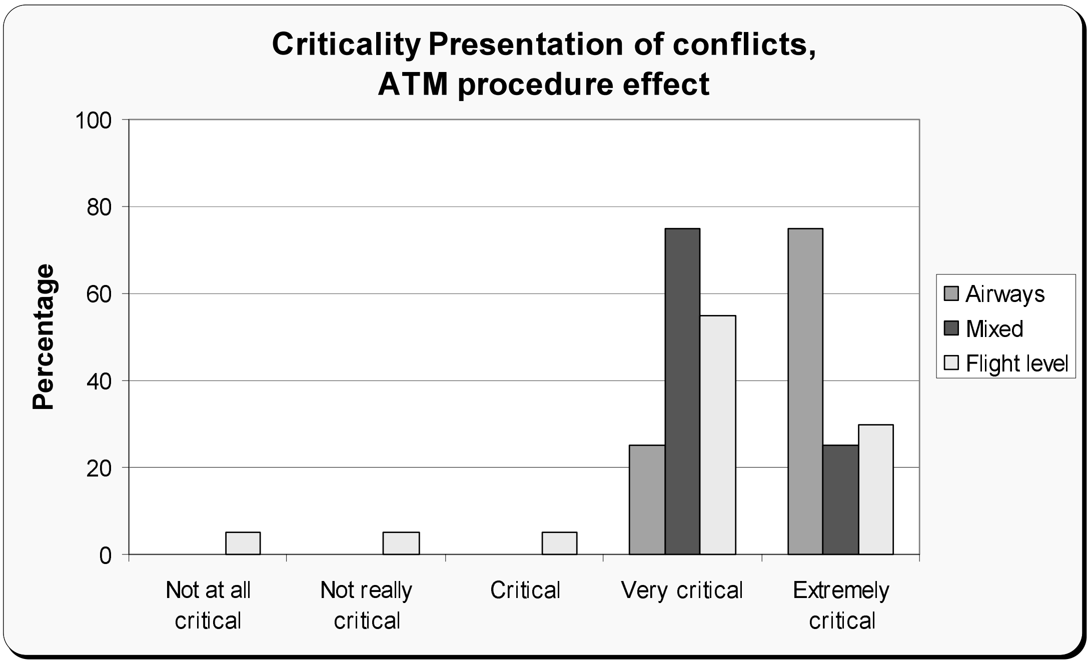


figure 11.25 ATM procedure effect on criticality of the presentation of conflicts

Other HMI elements questioned were:

- Horizontal Display of Traffic
- Vertical Display of traffic
- Presentation of Conflicts
- Presentation of Resolutions
- Presentation of Predictive ASAS
- Aural Alerts
- Glare Shield Alert Light

Based on the answers and the scale of 1 to 5 indicated to the subject pilots, orders can be determined of acceptable and critical HMI elements. Using numbers for these categorical data is not allowed to be used as average, however it is assumed to be acceptable to used the scale to derive an order. These orders are shown in figure 11.26 and figure 11.27.

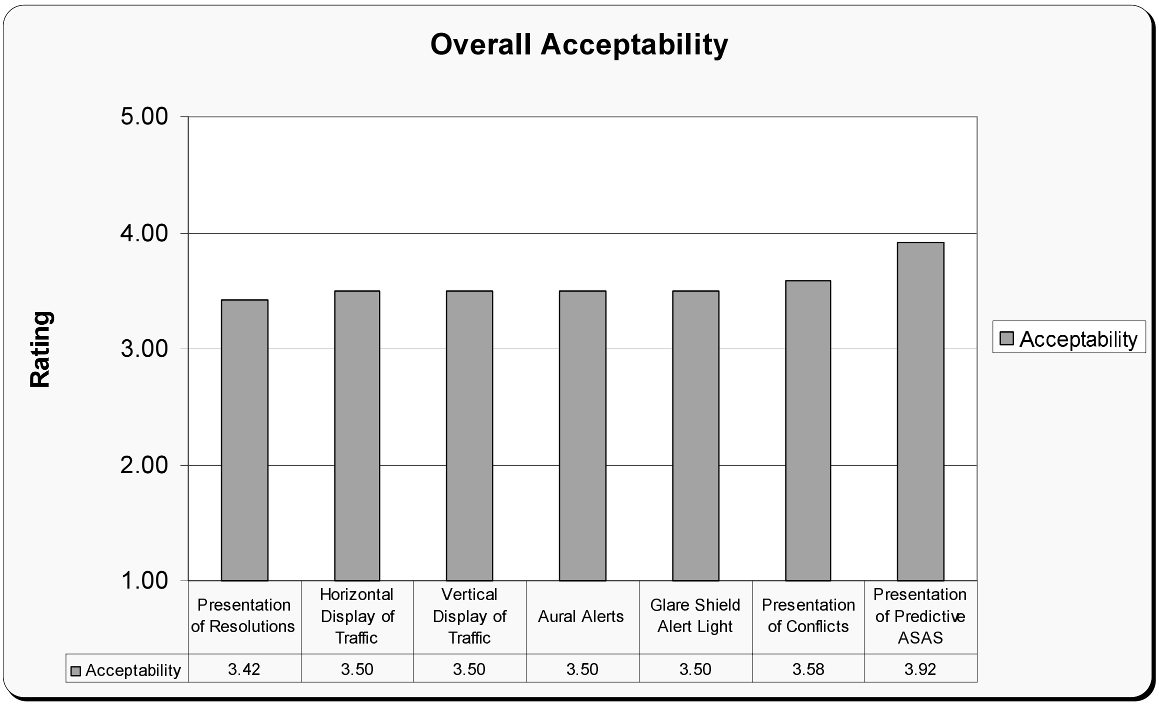


figure 11.26 Acceptability order of HMI elements

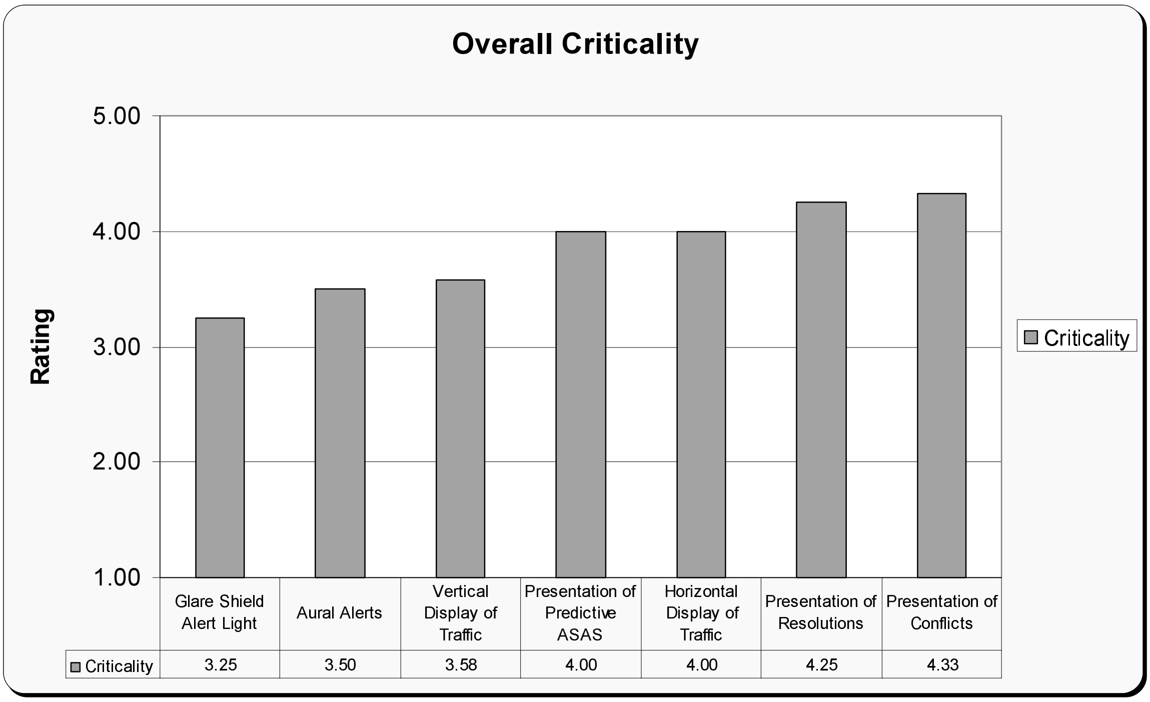


figure 11.27 Criticality order of HMI elements

These orders indicate that:

- Predictive ASAS is very well accepted, while very critical. Predictive ASAS presentations do not need very much further attention in future research.
- the aural alerts and glare shield alert light are the least critical, while better than acceptable. No need for much further attention in future research.
- the horizontal display of traffic is very critical, but just slightly better than acceptable. The horizontal display of traffic therefore needs attention in future research. Combining with the pilot comments, clutter seems the problem with the horizontal traffic display.
- the presentation of resolutions is least accepted, while between very and extremely critical. The presentation of resolutions clearly needs further attention.
- although the presentation of conflicts is rated better than acceptable, it is also rated the most critical. There is no need for further change here, though it might be improved.

11.7.1.6 Workload

Workload has subjectively been measured using the Rating Scale of Mental Effort (RSME), see also the questionnaires in appendix . The RSME results are normalized to Z-scores to control for individual differences. A statistical analysis has been performed analysing the variances of the different calculated means, so called ANOVA techniques, to determine statistical significant differences between means. Main effects and two-way interactions of the different experimental variables are presented on the workload data. The mentioned p-values represent the probability of incorrectly accepting a result as valid. Statistical significance was defined, by standard convention, as $p < 0.05$.

Due to the limited amount of subjects, none of the subjective data reached significance. Trends in the data are presented, based on the data which nearly reached significance ($p<0.10$).

Main effects are shown for traffic density (figure 11.28) and equipage level (figure 11.29) and a two-way interaction between ATC procedure and equipage is shown (figure 11.30) (all only for protected airways and mixed equipped ATC procedures).

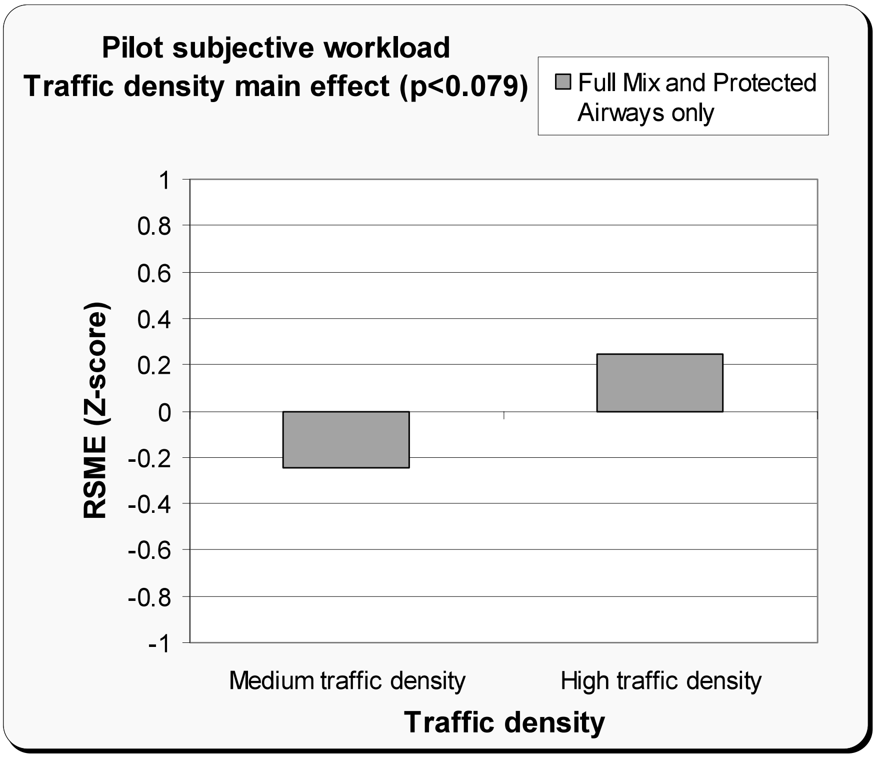


figure 11.28 Traffic density main effect on workload rating

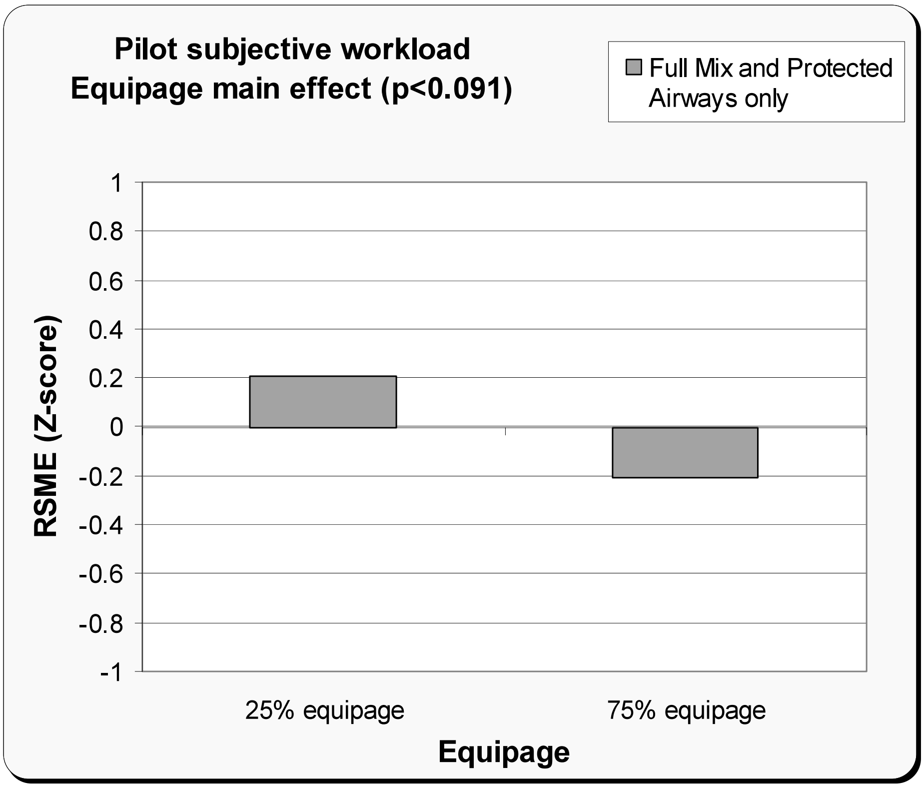


figure 11.29 Equipage main effect on workload rating

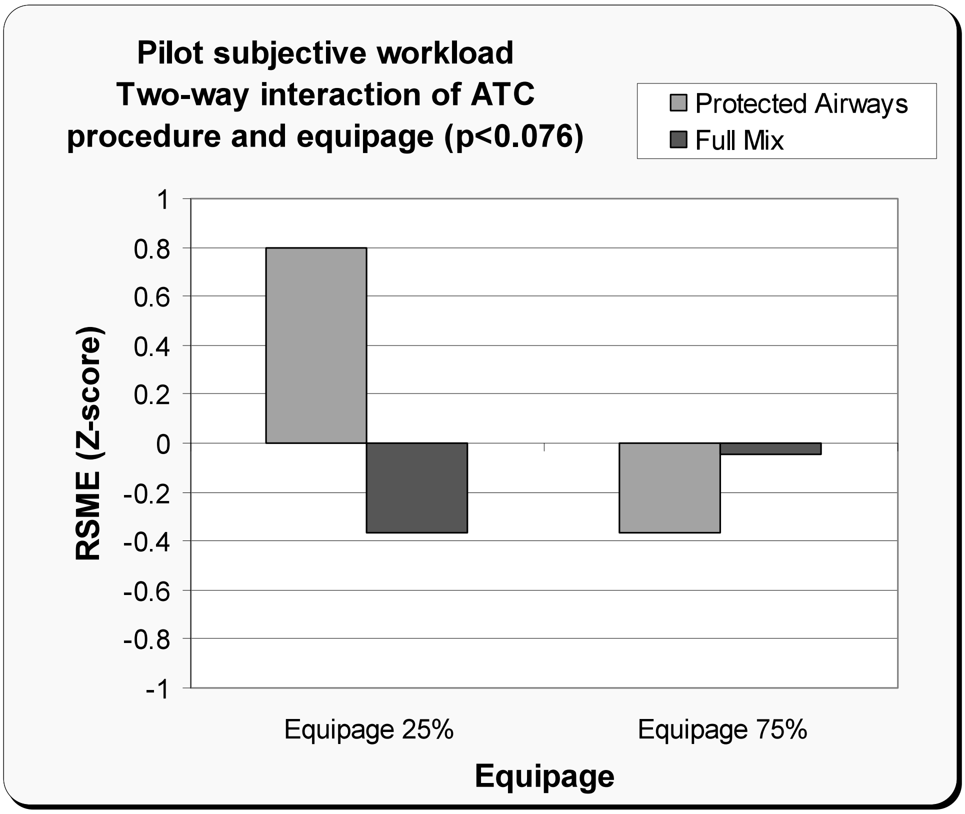


figure 11.30 Two-way interaction between ATC procedure and equipage

The ATC procedure main effect in the medium traffic density cases only is shown in figure 11.31.

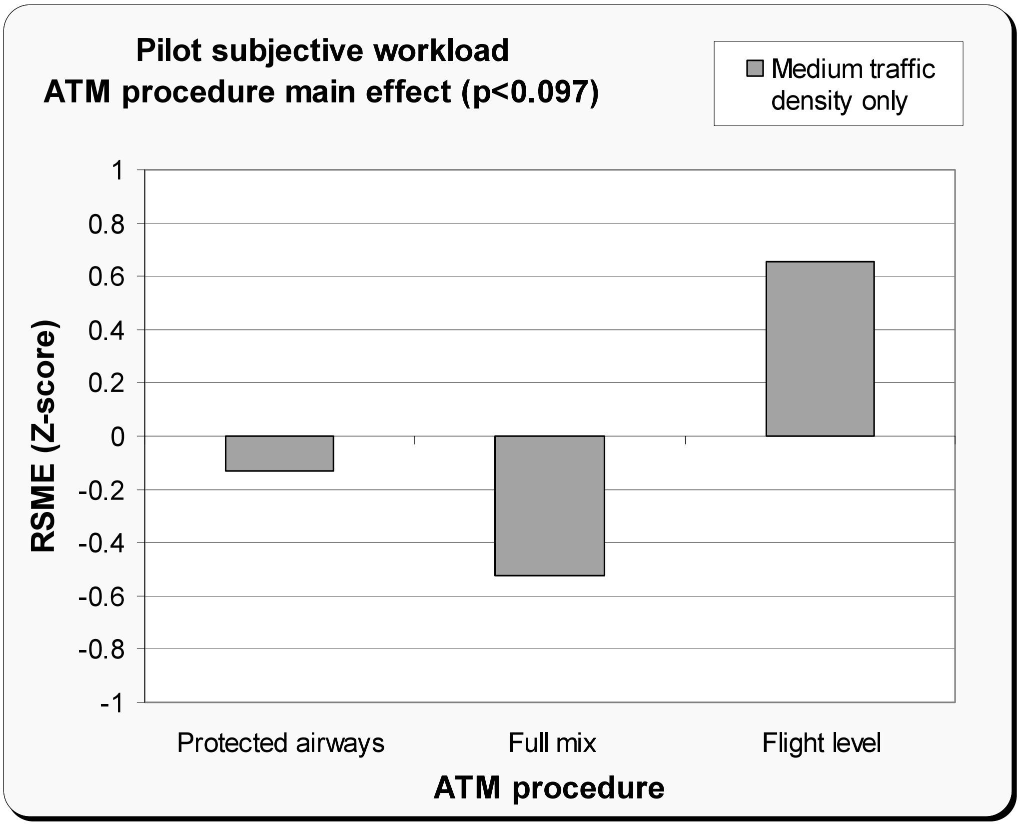


figure 11.31 ATC procedure main effect at medium traffic density only

The results shown in figure 11.28 to figure 11.31 indicate that:

- Higher traffic density results in more workload for the pilots (figure 11.28), as expected.
- Higher level of equipage results in lower workload (figure 11.29). This effect was not expected initially, but it can be explained. It was expected that in scenarios with more aircraft equipped, pilots in the equipped subject aircraft (RFS) will have to "handle" more aircraft. It was expected that pilots would neglect the unequipped aircraft controlled by ATC. This assumption has proven to be incorrect. Pilots in the subject aircraft did not neglect the unequipped aircraft since these aircraft could maneuver unexpectedly, especially in the protected airways ATC procedure. This effect is also clearly expressed in figure C from which it is evident that the protected airways ATC procedure is to blaim for this result.
- The protected airways ATC procedure is very sensitive to equipage level (figure 11.30). Lower equipage results in more workload for the pilots as explained in the previous bullet. A transition issue (in time) is clearly addressed with the protected airways ATC procedure. The protected airways ATC procedure is therefore not a candidate for the transition to a new ATM system with Free Flight Airspace.

- The fully mixed ATC procedure is in favour over the protected airways and flight level procedure, based on the ATC procedure main effect (figure 11.31).

To conclude, based on the subjective workload measurements, the protected airways ATC procedure has some clear drawbacks regarding transition issues. The flight level procedure has the highest workload, so the fully mixed procedure is most favoured as candidate ATM system with Free Flight capabilities from a workload point of view.

11.7.1.7 Pilot and Observer Comments

Pilot comments expressed on the questionnaires and verbally have been compiled to a list of issues. This list of issues should be given attention and possibly resolved before any future experiments.

- "Which aircraft causes the PASAS bands?" was asked often.
- Clutter of overlapping labels on the ND (major comment).
  Pilot suggestions:
  - option to declutter display and remove aircraft which can not cause a conflict logically (e.g. heading away from our heading, above our aircraft and climbing)
  - option to remove controlled aircraft from display in Flight Level scenario
- Rather relative altitude in stead of absolute altitude in labels, also for declutter purposes
- Pilot very cautious with ATC controlled aircraft in Protected Airways scenario, due to possibly unexpected behavior of ATC controlled aircraft
- Vertical ND only used when conflict is presented
- PASAS too sensitive for own aircraft maneuvers
- Conflict with aircraft outside range setting requires range setting change => automatic range adjustment ?
- Request to be able to silence a repeated conflict.
- Request to have conflict/resolution longer on ND.
- Take all aircraft into account when resolving a conflict to assure not to be in trouble with other aircraft after resolving the conflict

The major comment pilots had, was the cluttered navigation display. All subject pilots complained about this. Of course pilots are accustomed to a nearly black display right now, but still this should be given attention in future. Furthermore it can be concluded that the Human Machine Interface is acceptable but should be further optimized and tuned.

11.8 Objective data

11.8.1 Intrusions

From the recorded data it can be concluded that the subject aircraft experienced 2 intrusions of the protected zone. The intrusions were experienced with different subject pilots, but both in a flight level ATM procedure. When analyzing the intrusions further, it was found that the intrusions were both at the beginning of the scenario, when the aircraft was at FL220, well below the transition layer starting at FL260, going up. It can therefore be concluded that these intrusions were caused by the experiment leader "controlling" the subject aircraft below FL260 in the flight level ATM procedure.

Taking this into account, it can be concluded that there were no intrusions reported caused by the subject pilots. Even the reported intrusions of crew 1 and 2 were analyzed, and also those intrusions were not caused by the subject pilots.

11.8.2 Workload

Objective workload can be measured using various techniques. In the 1998 experiment, the subject pilot's eye blink data is analysed, the pupil diameter and the so called scan randomness are measured using Eye-Point-Of-Gaze equipment. The scan randomness proved to be the most reliable measure for workload.

Visual scanning randomness, or *entropy* (as the term is used in thermodynamics, to describe the amount of disorder present in a system) has been used to describe the randomness present in the visual scan of the subject pilots. The rationale behind the use of the entropy measure is that visual scan patterns become more stereotype (less random) with mental loading, so entropy should decrease with task load. The following data are based on entropy rate, which is entropy corrected for dwell time, and which is thought to be a more reliable measure than entropy.

Since indicated workload varies inversely with entropy rate, Y-axis of the figures presented in this section are inversed, so the figures can be "read" as the subjective workload figures ("high bars" mean "high workload").

The digram in figure 11.32 shows the two-way interaction between ATC procedure and equipage, for the protected airways and fully mixed ATC procedures only, but including medium and high traffic densities. The diagram in figure 11.33 shows the same interaction, but now for the medium traffic density only, but now for all three ATC procedures.

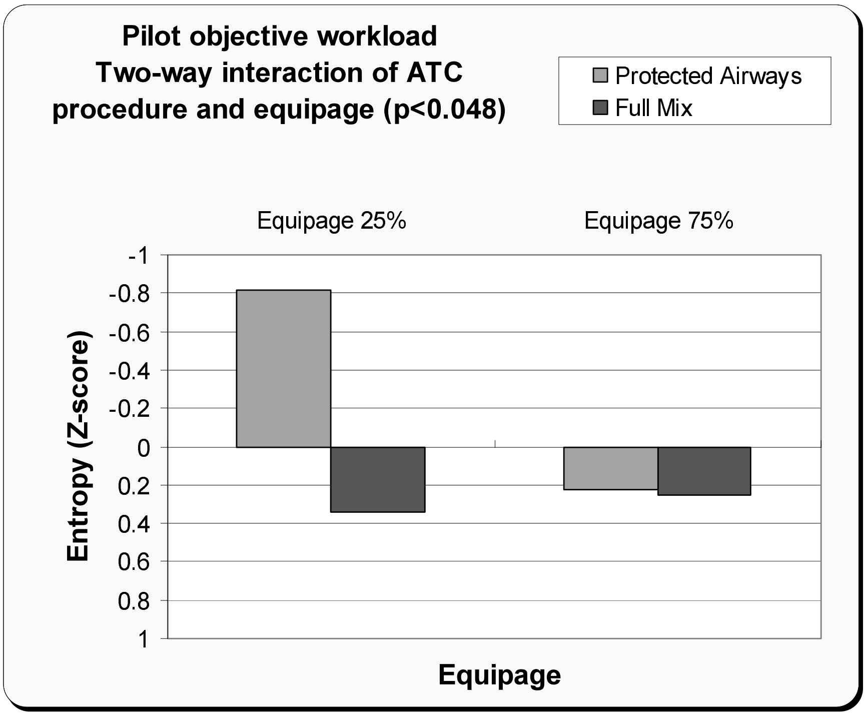


figure 11.32 Two-way interaction between ATC procedure and equipage, protected airways and fully mixed procedures only

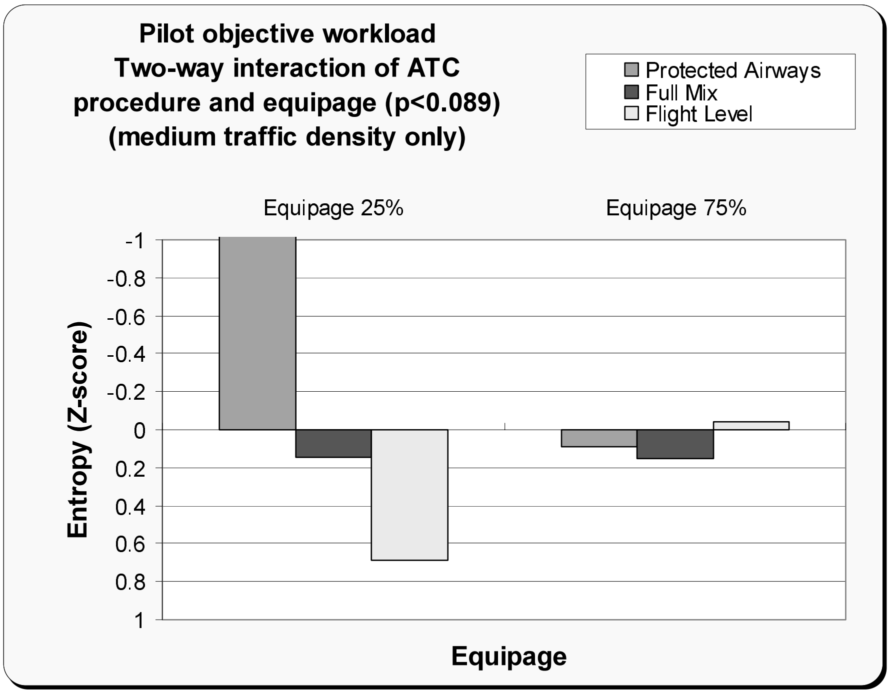


figure 11.33 Two-way interaction between ATC procedure and equipage, medium traffic density only

The results from figure 11.32 and figure 11.33 confirm the subjective workload findings. Higher level of equipage results in lower workload (figure 11.32), similar to the subjective results from figure 11.29. The graph in figure 11.33 confirms the sensitivity for equipage level of the protected airways ATC procedure and also indicates that the flight level ATC procedure follows the initial expectations, i.e. pilots in the equipped subject aircraft (RFS) will have to "handle" more aircraft and will experience more workload under high equipage.

The fully mixed ATC procedure seems not sensitive to the equipage level, and therefore, the conclusion based on the subjective workload findings holds, also after analysing the objective findings.

11.8.2.1 Comparison subjective and objective workload data

The subjective workload data and objective workload data can be compared. The diagrams in figure 11.29 and figure 11.32 present respectively the subjective and objective results. Below figure 11.34 compares these figures. These are the only figures which can be compared since only these two-way interactions reached enough significance in both analysis.

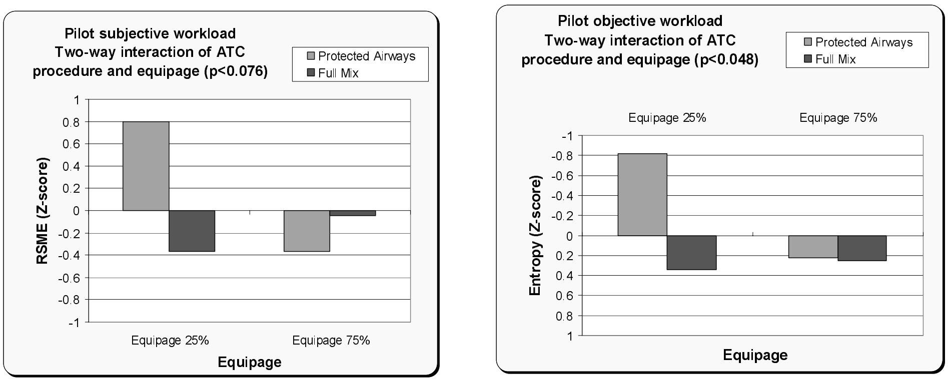


figure 11.34 Comparison of subjective and objective measurements

As can be seen from figure 11.34, subjective and objective measurements are resonably in line with each other, given the fact that data of only four subject pilots was available.

12 Complex conflict geometries study

12.1 Introduction

In this chapter the effect of the resolution algorithm on multi-aircraft conflicts is shown. The conflicts of two aircraft are predictable when the resolution algorithm is understood. The effect of a sequence of conflicts where solving one conflict can trigger a new one shortly can only be described using simulations. The generation of new conflicts by the resolution method is not something that can always be avoided. In the cases where this effect occurs, it is in fact demonstrating a very strong advantage of using the modified voltage potential resolution algorithm.

Two types of conflicts that were regarded as very critical are described in this chapter:

- " superconflicts"
- " the wall"

12.2 Super-conflicts

The name of super-conflicts refer to the type of conflicts where all aircraft involved fly towards the same position, at the same altitude, with the same speed and with an equal distance to that position. A number of these conflicts have been generated with 3, 4, 5, 6, 7, 7, 10, 12 and 16 aircraft. They can be found in the scenario files eby-3scn to eby-16.scn. (Adjusting the resolution strategy is performed by using the 'resonr' command in the traffic manager. See chapter 4)

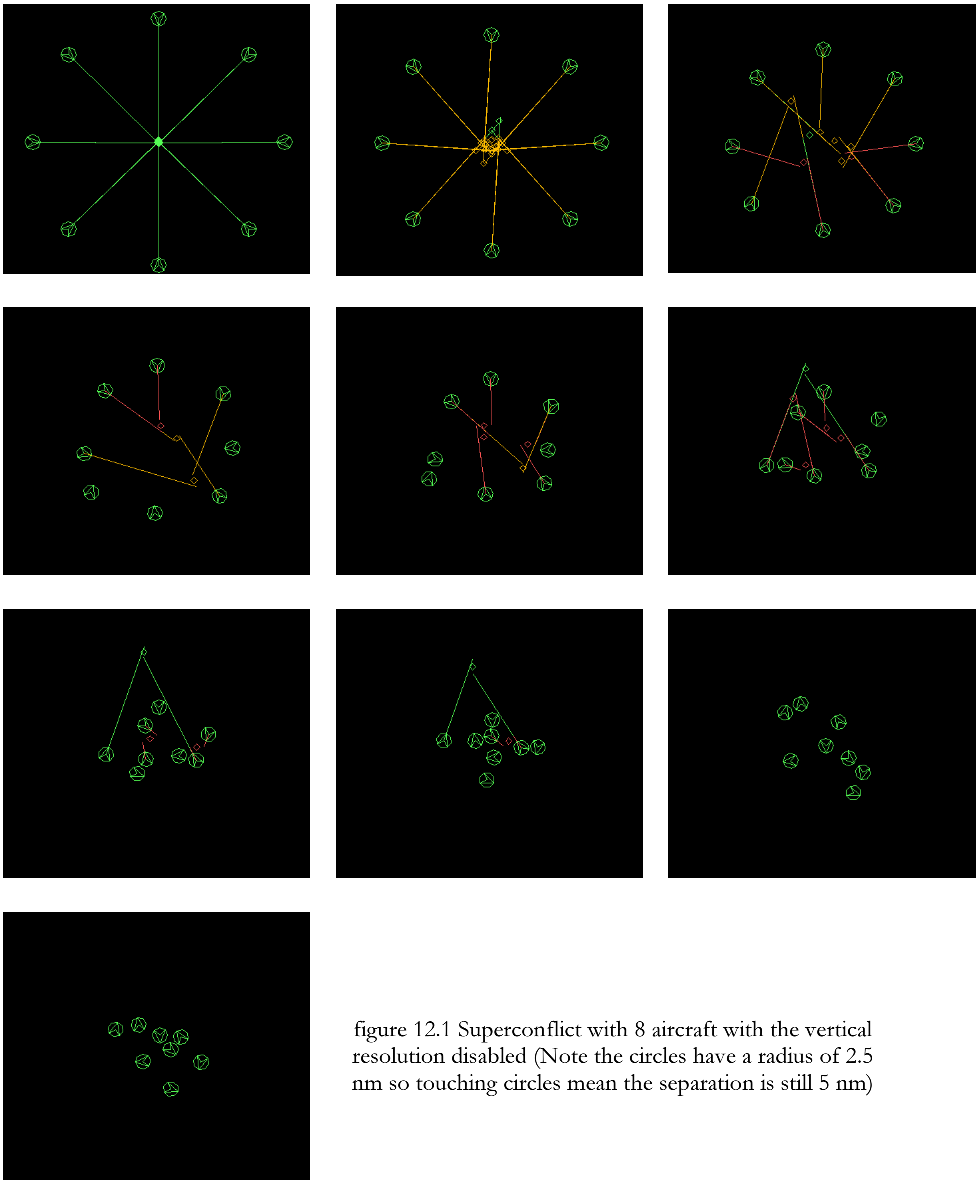


figure 12.1 Superconflict with 8 aircraft with the vertical resolution disabled (Note the circles have a radius of 2.5 nm so touching circles mean the separation is still 5 nm)

The sequence in figure 12.1 shows the traffic manager's screen with a super-conflict with 8 aircraft. Every aircraft is shown using an arrowhead and circle with a 5 nautical mile diameter. When two circles touch, the separation is exactly 5 nautical mile, and the traffic symbol will be red. On the traffic managers' screen a predicted conflict is shown by two lines from the aircraft to the position at the closest point of approach (CPA). A diamond symbol between those two positions indicates the position of the conflict. If this conflict symbology is green, the conflict has not yet been shown to the crew, due to for example filters, if it is red, the conflict will happen within 3 minutes. Amber corresponds to a time to loss of separation of 3 to 5 minutes.

Vertical resolutions have been disabled to add a constraint and make it critical.
In this situation, a lot of conflict revolving action takes place in parallel. After a few minutes miles before reaching the centre, the conflicts are solved.
The interval between the snapshots is 45 seconds.

For a controller it is not possible to simultaneously control all 8 aircraft to solve the conflict. This situation is sometimes used in the training of air traffic controllers. One way to solve this is apparently to for instance request all aircraft to turn left to heading 090, and then deal with each aircraft separately.

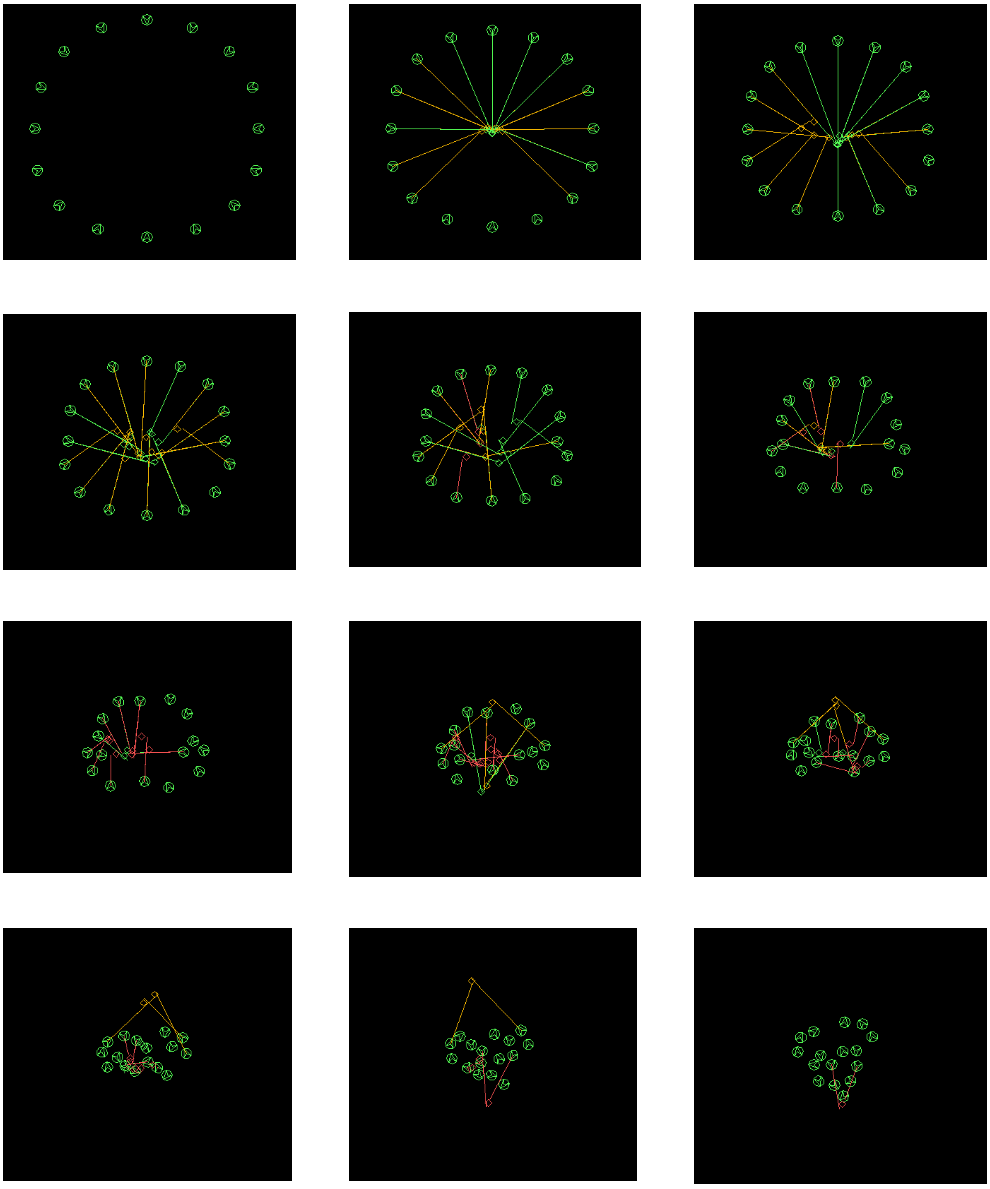


figure 12.2 Superconflict of 16 aircraft with vertical resolution disabled (Note: inall figures the llookahead time is only five minutes)

The sequence in figure 12.2 shows a similar super-conflict with 16 aircraft. Again, the vertical resolution has been disabled to complicate the situation. This takes somewhat longer to resolve but no intrusions occur.

When vertical resolutions are allowed the sequence in

figure 12.3 the next figure occurs.

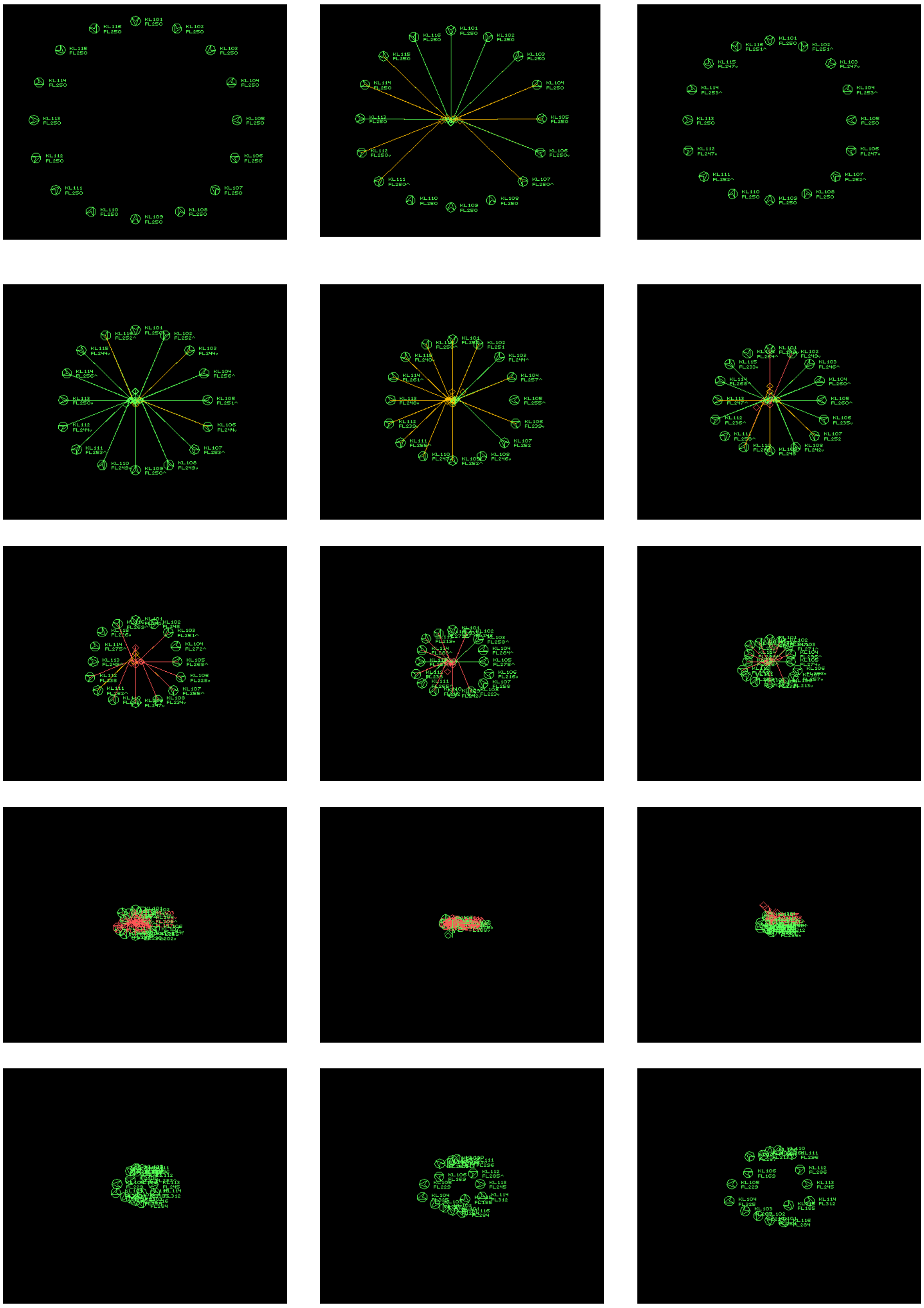


figure 12.3 The same superconflict as in the previous figure, but now horizontal and vertical resolution are allowed. Most aircraft prefer the vertical resolution in this scenario.

Even with 16 aircraft, a vertical resolution is very effective. Every aircraft flies to a different level, using a different vertical speed. Though the number of conflicts detected in these cases seems unacceptably high, per aircraft it is rather low.
With more intelligent crews than the pilot models in the traffic manager (very likely) this could even be reduced.

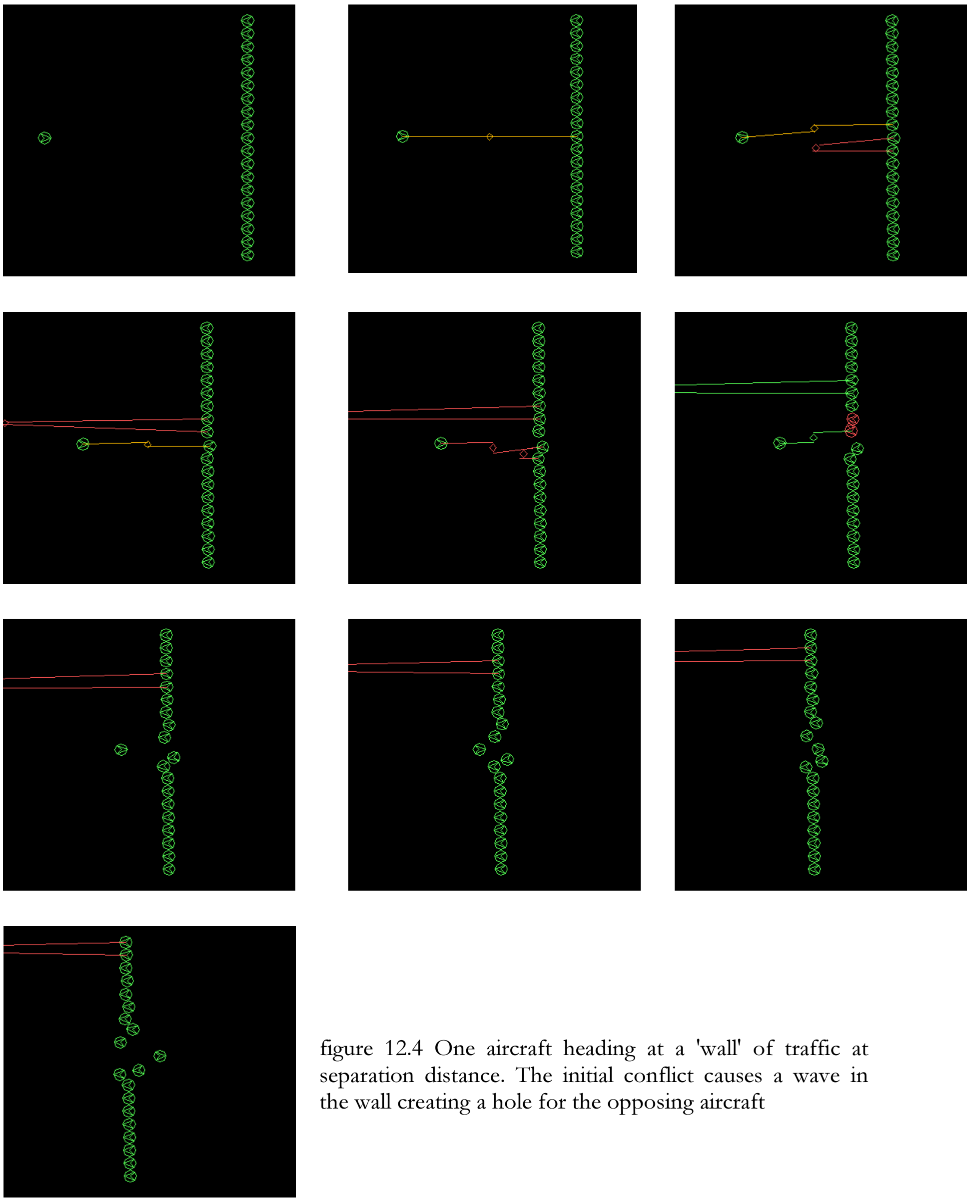


figure 12.4 One aircraft heading at a 'wall' of traffic at separation distance. The initial conflict causes a wave in the wall creating a hole for the opposing aircraft

12.3 Wall scenarios

Several scenarios have been generated, where "walls" of traffic at a distance of the separation minimum fly toward one or more aircraft. They can be found in the wall*.scn, front*.scn and block*.scn files supplied with the traffic manager. This is, just like the super-conflict, a metaphore for a highly congested airspace.

The sequence in figure 12.4 shows a wall of 19 aircraft flying a horizontal distance of nearly 5 nautical miles, as indicated by the 2.5 nm range circles around the aircraft. Vertical resolutions have been disabled. Just like in the super-conflicts, the noise models are disabled. This figure shows the beneficial effect of sequential conflict alerts. The single aircraft at first only has a conflict with the centre aircraft of the wall. Both aircraft then turn left. Apparently, there was already a slight separation in this direction because the exeption handler for head-on conflicts would have triggered a right turn. The result of the heading adjustment to the left is two new pair of conflicting aircraft. The two aircraft in the wall that now also have a conflict will move away from the single opposing aircraft. This is in fact the start of a wave through the wall, resulting in a global solution, which makes sense: All aircraft accelerate or decelerate slightly to be able to move away from the centre of the wall. The wall wrinkles and creates a hole in the centre to fly trough.

The magnitude of the wave decreases when further away from the centre and so do the wrinkles. This is also indicated by the longer conflict lines, meaning the aspect angle is less.

Harder to show in a static 2D figure is the 3D version of the wall. It can be found in the wall.scn scenario file. A special observer aircraft has been created (KL000) whose vertical nav-display shows a full view of the wall ("NAVDISP KL000")

A similar pattern is seen as in the 2D wall in figure 12.4. The speed of the wave is higher in the vertical direction in terms of separation distance (remember the aspect ratio of the protected zone), so the vertical wave creates the final hole, though an oval pattern moves through the complete wall of 190 aircraft.

12.4 Conclusion

The sequences show the power of the algorithm to solve conflicts involving a high number of aircraft in an extremely congested airspace. It provides an insight in the efficiency of a distributed system to deal with constraint situations due to traffic, weather of SUA.

The scenarios used here are examples of dangerous situations which required some effort to develop. These situations contain a dangerously high amount of 'order'. It is an illustration of the contradiction to the intuition that chaos is equivalent to danger.

Though merely testing these cases is not a proof of the overall stability, it is an indication how the capacity, efficiency, robustness and stability compare to today's situation. Just imagine how one controller should solve these conflicts by sequentially addressing all aircraft and waiting for the confirmation before dealing with the next aircraft. Testing these and other scenarios with an air traffic controller might be an exercise worth trying in further research.

13 Costs & Benefits of Airborne Conflict Resolution

13.1 Introduction

This chapter describes a preliminary analyses of the cost aspect of conflict resolutions. This study has been performed as a part of this project by a student of Delft University of Technology, of the aerospace faculty, Mario Valenti Clari. The complete study is described in his thesis[31].

From the man-in-the-loop trials several observations as well as pilot comments were made on the subject of horizontal resolutions, speed changes and the costs of vertical resolutions.

For example it was noticed during the experiments that pilots preferred to resolve conflicts by manoeuvring horizontally; meaning they preferred executing a heading change above executing an altitude or speed change to resolve conflicts with other aircraft.

This is somewhat strange because when using heading in order to resolve a conflict, the aircraft will often need to manoeuvre more than when using an altitude (vertical speed) change. The protected zone can namely be observed as a very flat disc (the width-height ratio is similar to a coin) flying through space. In case of a conflict situation the amount of horizontal intrusion will often be of a much greater order than the vertical intrusion.

In the experiment debriefings, pilots often explained that they avoided vertical manoeuvres because they thought it would have a negative impact on both,

- the fuel efficiency of the flight (economic aspects)
- the passengers perception of the ride quality (passenger comfort aspects)

The option of using speed changes for conflict resolution was even more seldom used, because pilots thought that available (operational) speed window in cruise flight would not allow this kind of resolutions at all.
An extra analysis was needed to give more insight in the costs and benefits of the conflict resolution manoeuvres (heading change, altitude change and speed change) in Free Flight with Airborne Separation Assurance.

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[31] Cost Benefit Analysis of Conflict Resolution Manuoevres in Free Flight, M.S.V. Valenti Clari, M. Sc. Thesis Delft University of Technology, Faculty of Aerospace Engineering, Flight Mechanics group, August 1998

13.2 Cost-Benefit Study of Free Flight with Airborne Separation Assurance

In order to give more insight in the issues raised in the Human-in-the-Loop experiments, NLR started in 1998 a cost-benefit study of Free Flight with Airborne Separation Assurance.
The benefit study can be divided into two major parts. The first part dealt with a study of the costs and benefits of the conflict resolution manoeuvres on a small scale. The second part zoomed out in order to compare a full scale Free Flight environment with an ATC environment like today. This comparison has been done with Monte-Carlo like simulation experiments.

The passenger comfort aspects of Free Flight with Airborne Separation Assurance will briefly be discussed in the last paragraph of this chapter.

13.2.1 One-on-one conflict experiments

As a first step in understanding the economic aspects of conflict resolutions manoeuvring, several one-on-one conflicts were tested on fuel and time efficiency. The one-on-one conflicts were simulated with horizontal (heading change) and vertical resolutions (altitude change) in such a way that results could be compared. This chapter deals with the set-up, results and issues of these experiments.

13.2.2 Modifications to Resolution Module

In order to accommodate “heading-only” conflict resolution manoeuvres (constant speed) the ASAS resolution module has been slightly adapted.

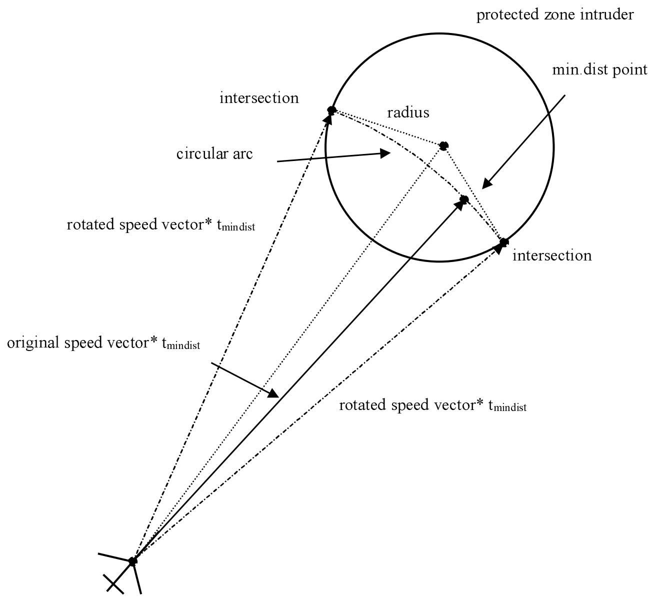


figure 13.1 Heading change only conflict resolution

This was necessary because, when resolving a conflict with constant speed, the speed component of the avoidance vector will have to be compensated with an extra amount of heading as illustrated in figure 13.1.

13.2.3 Experiment set-up

The aim of the experiments was to compare the horizontal conflict resolution (heading change only) with the vertical conflict resolution in several one-on-one conflicts. The method that has been used for the experiments is based on the idea of choosing the position of a large number of experiment points in the protected zone of an intruder aircraft.
Each experiment point represents a minimum distance point for a conflict that will occur during an experiment. The minimum distance point is the important factor for the conflict resolution module because it indicates the amount of intrusion.

The experiment points for the horizontal conflict experiments have been chosen as shown in figure 13.2.

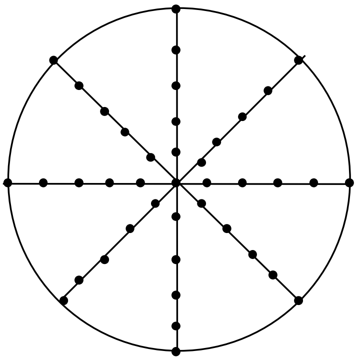


figure 13.2 Predefined experiment points in horizontal plane

The points for the vertical resolution are chosen in the vertical plane as shown in figure 13.3.

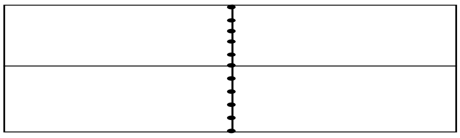


figure 13.3 Predefined experiment points in vertical plane

The points are chosen with various amounts of intrusion with an interval of 200 ft. For the horizontal resolutions the amount of horizontal intrusion is chosen with a 1 nm interval. The experiments have been subdivided like this because for the vertical resolution method only the amount of vertical intrusion will be important and for the horizontal resolution method only the horizontal amount of intrusion. This subdivision makes the task of comparing the two methods much easier.

Horizontal Conflict Experiments

The general experiment set-up has been chosen as follows. Each experiment starts with two aircraft flying with constant speeds and altitudes according a prescribed scenario. One of the two aircraft will be observed as experiment aircraft (own aircraft) the other is the intruder; see for example figure 13.4.

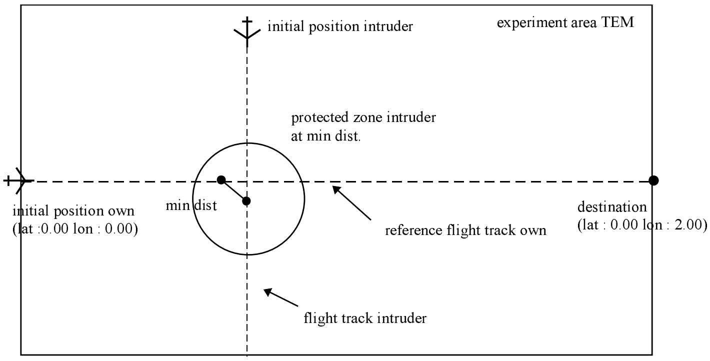


figure 13.4 Example of an experiment situation

The flight path of the own aircraft is a direct flight over 120 nm to a destination at the edge of the experiment area. Each experiment stops when the experiment aircraft exits the experiment area.

The initial position of the intruder is chosen in such a way that when a conflict is detected during flight, the initial point of minimum distance is located at a desired experiment point in the protected zone of the intruder.

For this purpose the horizontal experiments have been arranged in four initial experiment situations. All experiment situations are related to the position of the predefined points in the protected zone of the intruder aircraft. The points are chosen on four lines (a,b,c and d); see figure 13.5.

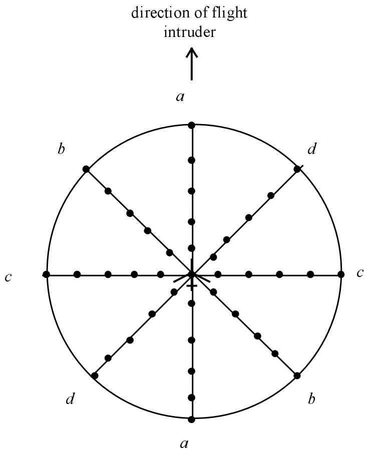


figure 13.5 Situation lines for horizontal experiments

The experiment points on, for example, lines b and d are related to the initial experiment situation b and situation d as illustrated in figure 13.6.

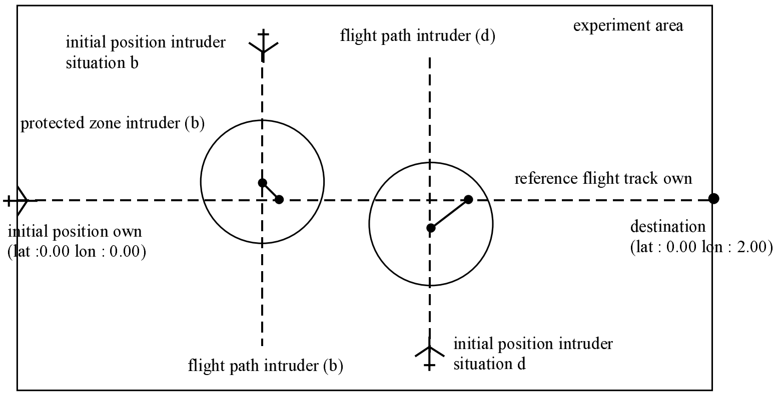


figure 13.6 Example of situation b and situation d experiments

When a conflict is detected the own aircraft will manoeuvre in order to resolve the conflict. The intruder will hold his track without manoeuvring; so the own aircraft will completely have to resolve the conflict (worst case).

When the conflict is resolved the aircraft will remain their flight track until it is time to direct back to the destination; see figure 13.7.

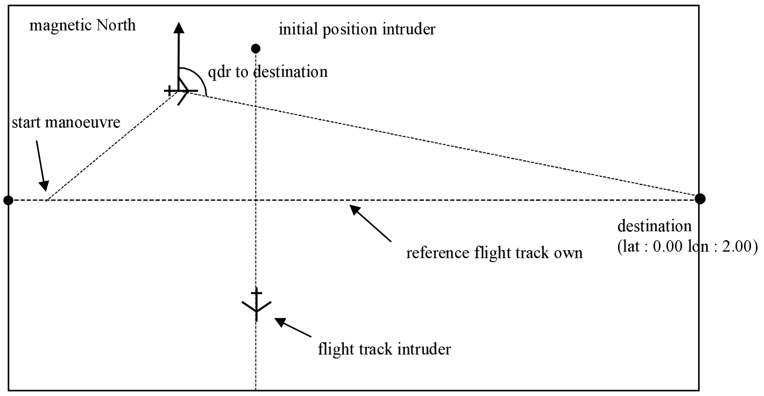


figure 13.7 After resolving the conflict with the ownship follows a direct route to the destination

Vertical Conflict Experiments

Vertical conflict experiments have been executed with a similar set-up as the horizontal conflict experiments. In all the tests the intruder aircraft was on a dead-on collision course with the own, because only the vertical amount of intrusion needed to be varied.

Nevertheless, only the ASAS conflict detection module (not the resolution module) has been used for the execution of the vertical experiments; a standard flight level change procedure has been used for the vertical conflict resolutions. The main reason for this approach is that research is especially interested in the efficiency of manoeuvres, as pilots would execute in Free Flight with airborne separation assurance. The horizontal resolution module results in heading changes similar to those executed by pilots in experiments. The 1997 experiments showed that the vertical conflict resolution, that ASAS can automatically execute, is a very good method of resolving conflicts. Nevertheless, there is a difference between this automatic execution of vertical resolution and the procedures used by pilots for flight level changes.
For the relevance of the study it was decided to implement a more procedural approach of resolving the vertical resolution manoeuvres.

The vertical conflict resolutions have been predefined as follows. The ownship aircraft has been constrained in such a manner that it resolves all conflicts with:

- a climb/descent with constant Mach number
- a level of altitude of 100ft above/below the intruder aircraft
- a fixed vertical speed of 600ft/min

The vertical manoeuvre is illustrated in figure 13.8.

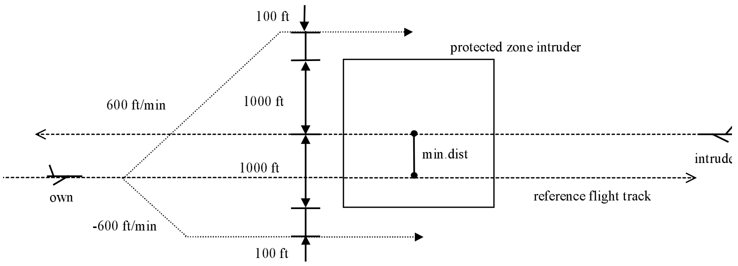


figure 13.8 Vertical conflict resolution manoeuvre

After resolving the conflict the aircraft will return to the original altitude.

Aircraft performance validation

All aircraft models simulated in the TMX are based on BADA aircraft performance data.

All results presented in this chapter have been generated with a medium range twin-engine aircraft of the TMX. The performance of the used BADA aircraft model has been validated by comparing it with the much more sophisticated simulation model of the same aircraft used in NLR's Research Flight Simulator (RFS).

13.2.4 Results

The complete experiment matrix of the one-on-one experiments consisted of

- 44 vertical resolution experiments
  - 11 descents at FL200 & FL300
  - 11 climbs at FL200 & FL300
- 88 horizontal resolution experiments (4 situations of 11 points at FL200 & FL300)
- 2 reference flights (without manoeuvring)

Vertical Conflict Experiments

The results for the climb manoeuvres at FL300 are presented in figure 13.9 and figure 13.10.

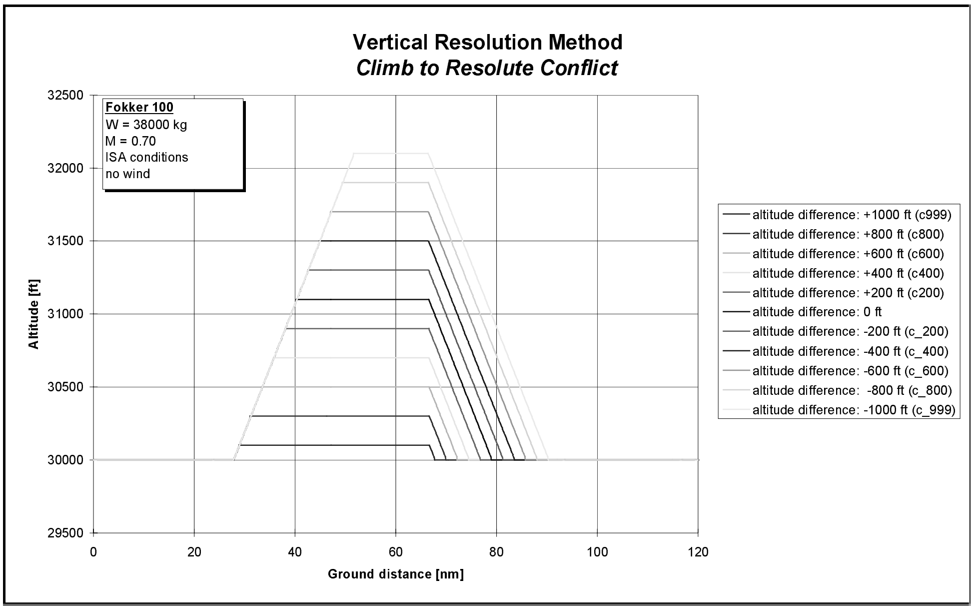


figure 13.9 Flight paths for Climb manoeuvres at FL300

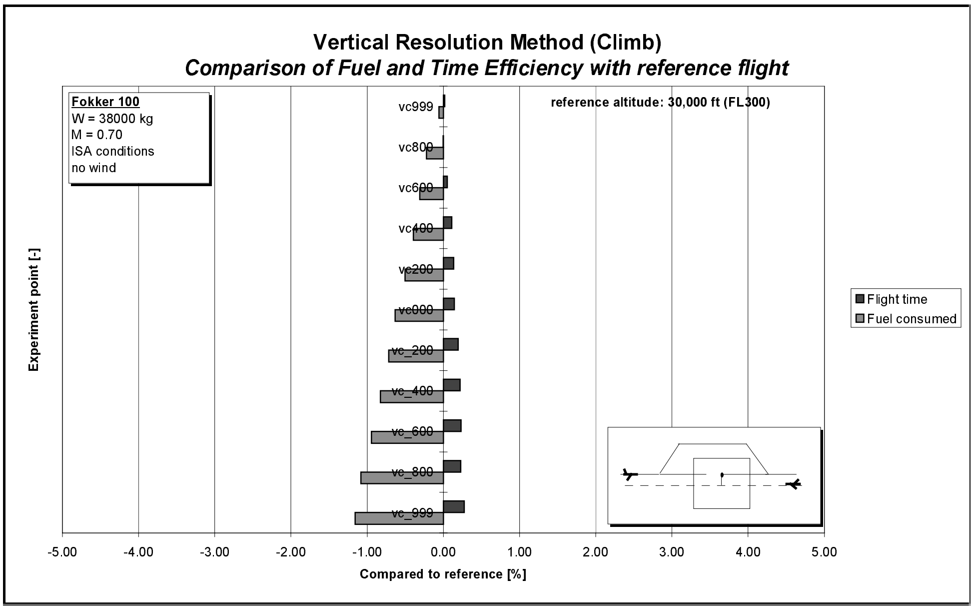


figure 13.10 Fuel burned and time used compared to the reference flight at FL300

Horizontal Conflict Experiments

The results of the situation a and situation c are presented in figure 13.11 - figure 13.14.

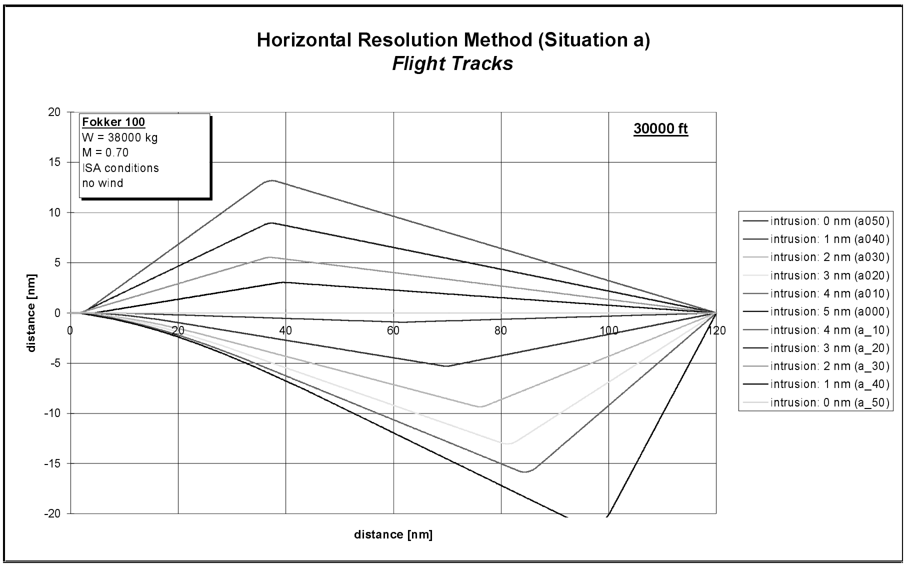


figure 13.11 Flight tracks for situation a at FL300

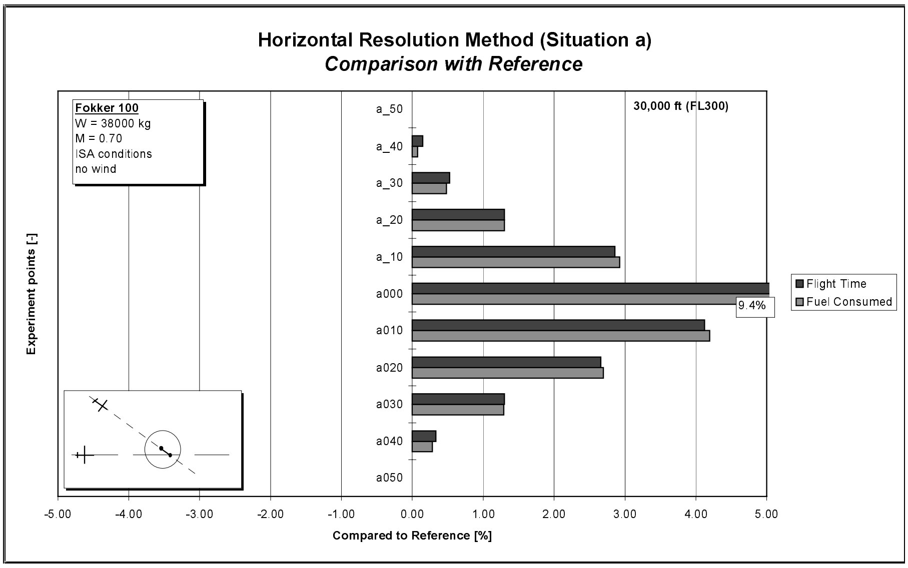


figure 13.12 Fuel burned and time used compared
to the reference flight at FL300 (situation a)

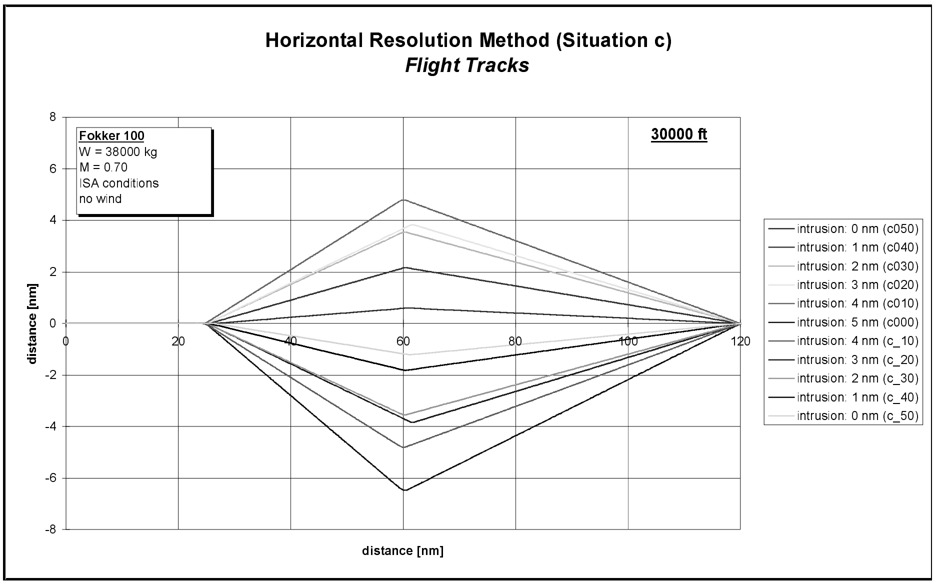


figure 13.13 Flight tracks for situation c at FL300

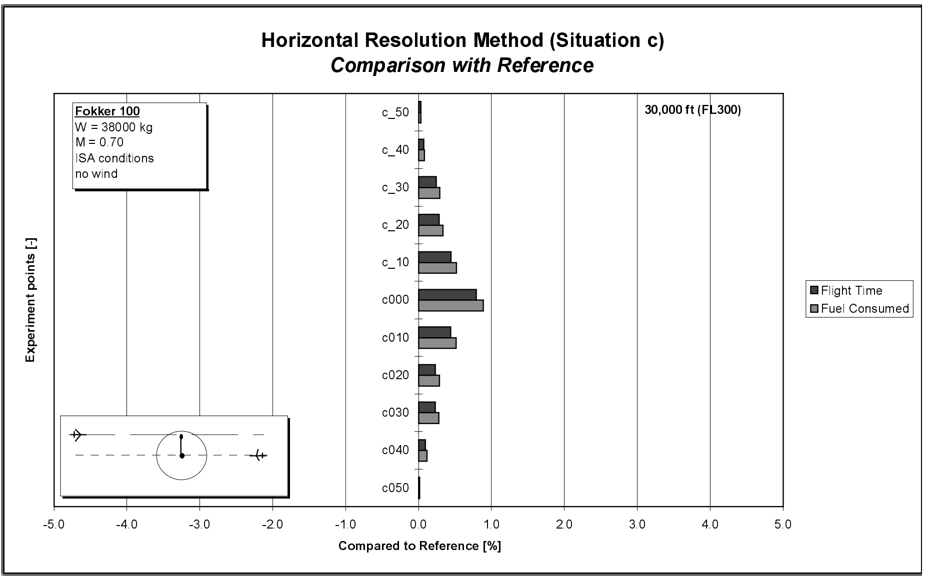


figure 13.14 Fuel burned and time used compared
to the reference flight at FL300 (situation a)

Similar results were obtained from the FL200 runs and the descent runs

13.2.5 Discussion

In the foregoing paragraph the results of the one-on-one simulations have been presented. When analysing these results it should be clear that all experiment were based on some constraining assumptions that implicate a certain level of simplification. The aim of the experiments is to get a better understanding of the economic aspects of the resolution methods.

One of the most determining factors is expected to be the type of aircraft. The experiments have been executed with a simulation model that estimates the behaviour of a medium range twin-engine civil aircraft. Another factor that could drastically influence the performance are the environmental conditions (e.g. wind).

When analysing and comparing the fuel consumption of all the experiments it is clear that in only one case the experiment aircraft saves fuel with respect to the reference flight over the defined trajectory. This is when the aircraft performs a vertical climb to resolute the conflict; see figure 13.10 and figure 13.12. The diagram in figure 13.10 shows that for all experiment points (different intrusions in the protected zone of the intruder) the total fuel consumed is less than the reference value. The low points in the protected zone show the biggest gain. This is not surprising because for these low intrusions the experiment aircraft has to perform a high altitude step; bringing it to a more optimal cruise level. This implicates that after performing the altitude step it would maybe be even more efficient to remain at the higher level. Naturally this decision is also influenced by the distance to destination.
Nevertheless, when assuming a constant Mach number (and flight in the troposphere), the true airspeed will decrease with the increasing altitude. This means that the aircraft will arrive later on its destination, which can also be read from figure 13.10. The amount of time lost is however very small; in the order of a few seconds for the experiment flight over a distance of 120nm. Nevertheless the balance between time costs and fuel costs (cost index) could be, especially on the longer routes, an issue of consideration when choosing between remaining at a higher altitude or returning back to the original cruise level. An even more practical option would be to change speed/Mach number to the value suitable for the higher altitude.

The results from the vertical climb resolution are very promising when regarding the fuel consumption figures. However, there are some issues that could seriously constrain this resolution manoeuvre. It is likely to assume that pilots, when they are given the user-preferred routing possibility, will perform the cruise flight as close as possible to the operational ceiling of the aircraft; especially on the long routes. When the pilot wants to perform a climb in order to avoid a conflict it could well be possible that this is constrained by the ceiling. Other aspects, like the influence of the engine spool-up noises (e.g. when performing climbs near the operational ceiling) on the passenger comfort, could also pose a constraint on the climb manoeuvre.

So, assuming for the moment that the climb manoeuvre is often not an option, this leaves the vertical descent manoeuvre and the horizontal heading change as the possibilities to resolve the conflict. A trade-off can be found between the advantages and disadvantages of all the manoeuvres, which will briefly be presented on a simple decision model in the next paragraph; for use with the Monte-Carlo study.

It can be concluded that the use of the vertical resolution method is not as bad for the fuel consumption as thought by some of the pilots who participated in the Human-in-the-Loop experiments. The vertical climb manoeuvre could even lead to a more efficient flight operation. However, if the climb manoeuvre is not possible the geometry of the conflict (the position of the minimum distance points in the protected zone) can be used to determine what is better: a descent manoeuvre or a heading change.

For the horizontal resolution the "no wind" assumption is a decisive issue. Wind vectors can have positive and negative influences on the efficiency of the horizontal resolution method. Moreover, the optimal flight from an origin to a destination will not necessarily be the shortest route via an earth great-circle. Future research should focus on these more complex influences on the conflict resolution efficiencies. It should be investigated for several aircraft types, and with more sophisticated simulation models, how the fuel consumption for small altitude changes are influenced.

13.3 Decision model for conflict resolution

The results of the one-on-one simulation experiments showed that, depending on the position of the minimum distance point, a decision can be made for a horizontal or a vertical resolution manoeuvre. However, the decision was only applicable for the vertical descent manoeuvre versus a heading change manoeuvre, because in all the experiments it was found that the vertical climb manoeuvre was the best method to resolve a conflict, with respect to fuel consumption.
Assuming that the vertical manoeuvre is not always a possibility, a trade-off position between the horizontal manoeuvre and the vertical manoeuvre was found. The diagram in figure 13.15 illustrates how the decision model was implemented.

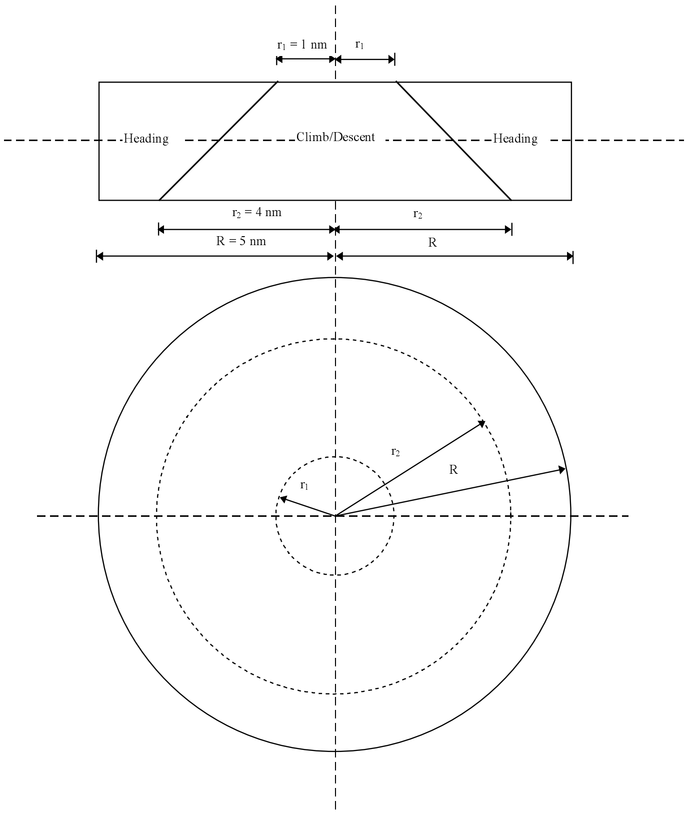


figure 13.15 Decision model for resolution method

13.4 Passenger comfort aspects of conflict resolution

A concern of pilots which caused a preference for horizontal maneuvers was the impact of vertical maneuvers on passenger comfort. In general speed changes and the initiation of a climb and/or descent cause accelerations or noticeable changes in attitude. Today often during the cruise, in the order of once per two hours a so-called 'step-climb' is performed to a level 2000 ft higher. If the conflict resolution also cause climbs or descent several times per hour the concern is this could decrease the passenger comfort.

This is in general probably not the case for a number of reasons:

- **The vertical speed is low.** Vertical conflict resolutions do not require a vertical speed of more than 200 ft/min, which is hardly noticeable. When this vertical speed is used instead of the standard 'level change' causing a 1500 ft/min climb or descent there is no effect on passenger comfort by attitude nor by acceleration.
- **Conflicts are rare.** Conflict resolutions are only required once per hour over busy areas, en-route over the ocean or vast continents this number will probably be even lower
- **Step climbs will disappear.** In a mature free flight environment the fixed flight level have disappeared, so there are no more step climbs. Instead there

will be a contineous shallow climb, in reality probably several climbs of the same order of 100 or 200 ft/min.

This means it is likely that the overall passenger comfort will increase due to the change in operations in a mature Free Flight environment.

13.5 Conclusion and Remaining Issues

The research presented in this chapter was aimed to make a first inquiry into the issues raised in the 1997 Human-in-the-Loop study. This has been done by first observing Free Flight on a very small scale, by conducting one-on-one experiments. Using the knowledge of these simulation, large scale test have been conducted with Free Flight aircraft flying in a so-called "mixed equipped" traffic environment. All experiments have been executed using the Traffic Manager (TMX) for Free Flight environment simulations.

The one-on-one simulation experiments showed some surprising results. The vertical resolution method has always been regarded, especially by the pilots who flew the Man-in-the-Loop experiments, as a less efficient manoeuvre that could also have negative impact on the fuel consumption. The experiments showed that, in all cases the vertical climb manoeuvre would save fuel. The explanation is that when climbing to resolve a conflict the overall fuel consumption will reduce because of the higher altitude.

However, it can be expected that a climb manoeuvre will not always be an option when flying Free Flight. For example, when assuming the voltage potential concept, the vertical component of the resolution advisory could be in the opposite direction.

The horizontal heading change manoeuvre and the vertical descent manoeuvre can therefore be compared on basis of fuel consumption. Dependent on the position of the minimum distance point in the protected zone of the intruder a simplified decision model has been developed that indicates if the conflict should be resolved with a heading change or with an altitude change.

14 Distributed systems vs. central systems

14.1 (Un)Predictability of a Distributed System

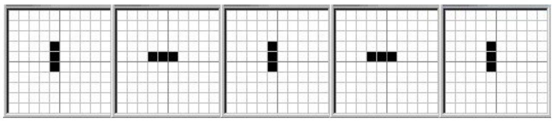
When people, experts or not, are confronted with the Free Flight concept, the first reaction often is that it sounds like a dangerous idea. This probably is a result of the way human nature reacts to the chaotic nature of the traffic flow. Chaos is usually associated with danger. Throughout the NLR study the making of conflicts proved much harder than avoiding conflicts. In other words: a random, chaotic scenario, even using existing route structures was unlikely to have a lot of conflicts. In today's traffic density, applying direct routing (horizontally and vertically) will result in a conflict rate of about once per 50-60 minutes per aircraft. A carefully, precisely constructed scenario was required for complex geometries like 'the wall' or the 'super-conflict' (see chapter on conflict geometries). These scenarios are much more orderly but also much more dangerous. The concentration of traffic at airways is also artificially increasing the local traffic density. Even though this increases the collision probability, this orderly pattern is reassuring to the human observer.

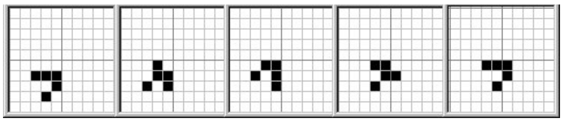
What is the reason for this distrust in chaos? This needs to be understood. The acceptance by aviation authorities, pilots, air traffic controllers and the public is required before the concept can be further developed and gradually introduced. Apart from the conditioned negative association of chaos, there probably is a rationale behind this reaction. This could be the unpredictability of a distributed system with this high level of interaction.

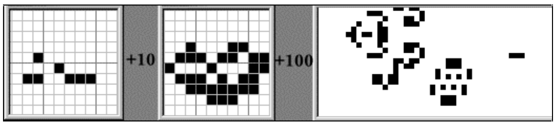
A one-on-one encounter can be analysed with some calculation and the manoeuvres as advised by the resolution algorithm can be derived and understood. To check all one-on-one situations already becomes harder since there are quite a lot of different possibilities with respect to the three dimensional position and three dimensional velocity of the aircraft.

However, the stability of a high-density traffic scenario really is a problem that is of a different order. It is comparable to trying to understand consciousness in terms of the characteristics of a single neuron, the treshold, firing time etc. This touches the field of mathematics called cellular automata, which deals with the maths of interacting units. A famous example of cellular automata is 'Conway's Life'. This is a simulation in which every state is derived from the previous one with a fairly simple, discrete rule. It uses a two-dimensional matrix field consisting of cells. A cell is either dead or alive. By counting the number of living cells in the 8 neighbouring cells, the state of the cell in the next state is determined. If the total is 0 or 1, then the cells dies of 'starvation'. If the number of living cells equals 2, the state of the cells remains the same ('stable'). If the total is 3, then a new cell originates independent of the previous state ('growth') and the total higher, thus 4 to 8, results in the death of the cell due to being 'overcrowded'.

This rule is much simpler than a geometrical conflict resolution rule. However it yields some surprising higher order effects. Some examples are shown in the figures below.


'Windmill'


'Floater'



'Acorn'

figure 14.1 Examples of sequences from the 'Life' program, illustrating the apparent lack of the realtion between the micro-interaction and the macro-effects.

The 'windmill' of three cells is easy to understand. The 'floater' of only 5 cells moves one cell up and one cell left in five steps. This is something that is already a consequence not easily seen from the simple rule above. In fact, most patterns have been discovered in random patterns instead of being designed. The 'acorn' illustrates the effect of a structure of only seven cells after ten and after another hundred iterations.

This Life program that was often used as a screen saver in the old days of computing, is an analogy of how an extremely simple mathematical formula or law of nature can result in fantastic unforeseen effects. It has some philosophical aspects when compared with the laws of nature, which are not relevant here. But the behaviour of these patterns has puzzled mathematicians for decades and still there is no theory available that describes the phenomena shown above. Even logical AND, OR and NOT ports have been built (or discovered) in Life. This means at a large Life-field a complete computer can be built using these cells, while at the low level the simple rule still applies. It is a dramatic illustration of the magnitude of the challenge to analyse the behaviour of a distributed system.

A traffic pattern using a Free Flight conflict resolution algorithm is not a discrete, but a continuous system, with a geometric interaction as well as scheduling and reaction time effects. It is right now and will, for a long time, be impossible to mathematically guarantee the stability or risk associated with the behaviour of a large number of aircraft in any configuration. The characteristics of an aggregation level below the behaviour of the pattern, for example a pre-scripted one-on-one conflict is more predictable. The large-scale effects of traffic patterns can only be studied using simulations. The risks of introducing a distributed system can only be analysed by comparing the effect of the change in structure between a centrally controlled system and a distributed system.

14.2 Safety as a result of distributing separation assurance

In this and the next section, we analyse the effect of distributing the ATM system with some simple mathematics. For this, we use a model sector with some simplifications. We assume all actions of air traffic control are aimed at avoiding future conflicts. In reality, these actions are not simply conflict resolution but also include sorting the traffic in a way that avoids future problems. In addition, the airspace structure adds constraints that affect the number of actions required by both air and ground. The focus of this section however is to investigate the effect of distributing a separation system. Therefore, we assume a model sector with a number of potential conflicts when no action is taken. These conflicts can be prevented by actions either by a central, ground based air traffic control or by a distributed system consisting of airborne crews using an airborne separation assurance system. It is therefore looking at just one aspect of the introduction of Free Flight and not a complete comparison of today's situation with a future Free Flight operation. Still, it provides insight in the benefits of distributing air traffic management. Especially the effect on the safety and (more dramatically) on the capacity of our model sector.

We observe a sector with N aircraft. The general probability of having a conflicting route for any combination of two aircraft is p_2. The probability of failure of the overall ground system is called p_g. This includes human failures and the failure of tools like radar and software. The probability of an overall airborne separation system failure is called p_a. These parameters are listed below:

N	Number of aircraft simultaneously present in a sector
p_2	Probability that two given aircraft have a conflict
p_g	Probability of a failure of overall ground based separation system per conflict
p_a	Probability of a failure of overall airborne separation system per conflict

Let's assume two cases: (1) the centralised '*Ground*' case, in which a ground based air traffic controller is completely responsible for the detection of conflicts and conflict resolution, similar to today's ATM; (2) the distributed '*Air*' case, in which all aircraft in the sector perform airborne separation co-operatively (no priority rules!), similar to the mature Free Flight concept.

We are then able to express the probability of a conflict resolution failure p_f for the complete sector (thus all aircraft) in the above mentioned parameters for both cases '*Ground*' and '*Air*'. Multiply all possible combinations of two aircraft out of N with the probability that they meet. This is the conflict probability. Then multiply this by the failure probability per conflict.

Ground: $$p_{f_g} = \binom{N}{2} \cdot p_2 \cdot p_g$$

Air: $$p_{f_a} = \binom{N}{2} \cdot p_2 \cdot p_a \cdot p_a$$

Because for any conflict two aircraft have an airborne separation assurance system, this provides a fail-safe system. This squares the probability of a failure. In case when both systems have a similar reliability ($p_g = p_a$), this means the safety of a distributed system is a magnitude larger than the safety of the central based system.

For systems that reduce the safety margins significantly probabilities of 10^{-7} times per hour are required and for safety critical (loss of aircraft) systems 10^{-9} times per hour of flight.[32] One could argue the ASAS system fits in one of these two categories depending on whether there is a back-up system like TCAS available.

These numbers can be used in two directions:

- Suppose we use these requirements per aircraft not assuming anything about the reliability of the conflicting aircraft. We then get an extra reduction of the collision probability of 10^{-7} or 10^{-9} due to the squaring of failure probabilities.
- Suppose we do assume a system on-board the other aircraft in the 'equipped only' airspace with a similar required reliability. In this case the squaring effect of the failure probabilities mean we only need a system about 10^{-4} times as good as the ground system!

There is currently no reason to assume that with current mechanisation the airborne avionics would perform less or be less reliable than the current ground based equipment.

On the ground, there is a possibility of having back-up equipment just as well as in the air. The two ASAS of the conflicting aircraft are different in that they are always both actively involved in the separation and are therefore more fail-safe than a back-up system which is only active when the main system fails.

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[32] JAR AWO Subpart 3 – Joint Aviation Authorities Committee

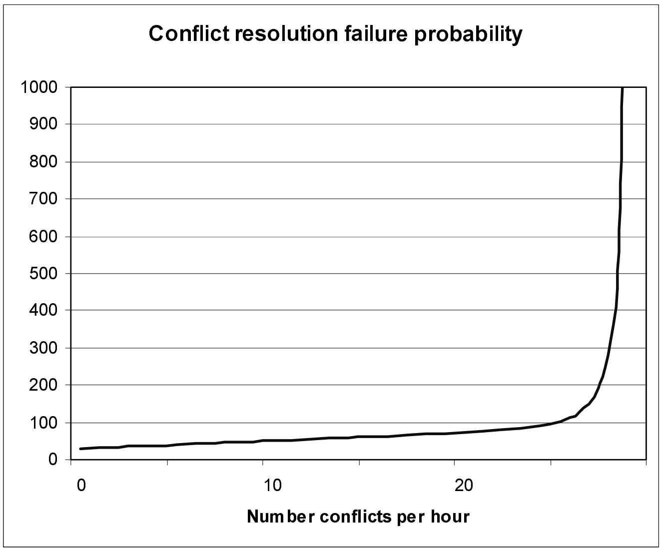


figure 14.2 Example of the effect of an overload situation

For the human element in the separation system there are two opposite effects in the comparison of the safety or capacity: the airborne crew might only be partially available for the separation task but also has only one aircraft to control.

This is where another interesting effect of distributing the effort occurs. Assume both the ground and the airborne systems have a cut-off point for the number of conflicts where the resolution failure probability soars. The effect of this overload on the failure probability looks something like the figure above. This means the overall probabilities p_g and p_a are influenced by the number of aircraft N via the resulting conflict rate. This determines the capacity of the system. As will be shown in the next section this is where the distribution of control is even more beneficial with growing air traffic.

This means that a certain conflict rate (around 27 conflicts per hour in the example figure) caused by a high conflict probability will cause the system to fail due to an overload situation. What is the effect of this on the capacity of the system for both the *'Ground'* and *'Air'* case?

14.3 Capacity as a result of distributing separation assurance

The overall conflict probability p_c is the same for both systems:

Both:

$$p_c = \binom{N}{2} \cdot p_2 = \frac{N \cdot (N-1)}{2} \cdot p_2$$

The experienced conflict probability is substantially different:

Ground: $$p_{c_g} = \tfrac{1}{2}N(N-1)p_2$$

Air: $$p_{c_a} = (N-1)p_2$$

For the ground case, this is a parabolic curve, while for the airborne case this is a relatively shallow straight line. The *'Air'* probability is much less because of all aircraft only 2/N part of the conflicts involve the 'ownship'. The resulting curves are drawn in the figure below:

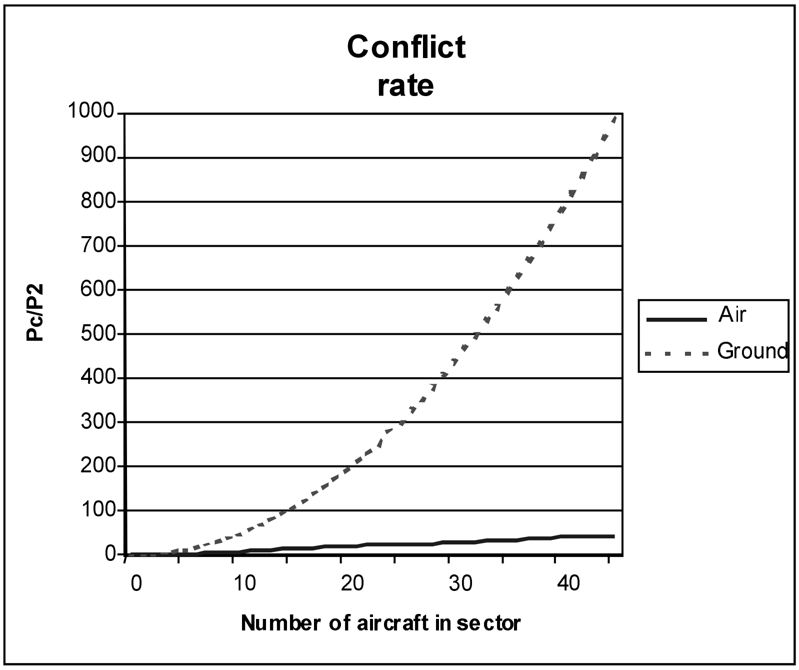


figure 14.3 Comparison of the effect of traffic density on airborne and ground based separation assurance

This figure shows the conflict rate normalised with the probability of two aircraft meeting each other (p_2). This figure shows the conflict rate that is the factor that drives the x-axis of the 'overload' figure above. It is clear that the central 'Ground' system is much earlier overloaded as traffic grows compared to the distributed 'Air' system.

From this picture, it is clear that with an increasing amount of aircraft over the coming few years, the centralised ground system will have to increase its capacity enormously. A distributed system like Free Flight with Airborne Separation is less affected by the growth of the air traffic. Today on average 10 aircraft are present in an en-route sector of 100 nm x 100 nm. Peaks are in the neighbourhood of twenty aircraft (referred to as double density). This is predicted to at least be doubled around 2015. This means that during peaks the air traffic controller will experience more than four times as much conflicts as today!

Adding values to all the parameters could provide some insight to the real effect. These numbers are however highly dependent on the size and structure of the airspace, the air traffic controller, the pilots, the equipment, etc. The numbers as experienced during the various simulations are used here as indications of the order of magnitude.

The following observations form the basis for the parameters:

1) Assume a European en-route sector of 100 x 100 nm
2) Average Western-European traffic density means about 10 aircraft simultaneously present in the sector
3) Peak densities double the amount of aircraft
4) During direct routing average conflict rate per aircraft without separation is once per hour
5) During an experiment with or without airways air traffic controller were not able to handle triple the Western European traffic density
6) During experiments the scenario with three times the Western European average density, was experienced as 'not busy' by the pilots during airborne separation
7) During demonstrations 10 times the WE traffic density was still manageable by an experienced pilot

From these observations the following numbers can be deduced using the hour as a reference time unit:

4) leads to $p_{c_a} = 1.0 \ \frac{1}{hr}$ for an en-route sector of 100 nm x 100 nm in case of direct routing for $N = 10$ (average WE density)

With the earlier derived formulae, this yields the p_2 for this situation.

$$p_2 = \frac{p_{c_a}}{(N-1)} = \frac{1.}{9.} = 0.11 \, \frac{1}{hr}$$

And also the conflict rate for the controller:

$$p_{c_g} = \tfrac{1}{2} N(N-1) p_2 = 5. \, \tfrac{1}{hr}$$

In this case, the controller has to resolve 5 potential conflicts per hour. This is five times as much as the pilots in case of airborne separation. During peak hours $N=20$. With the p_2 being independent of N, we can compare the conflict rate as experienced by the air traffic controller and pilots in our scenario:

Ground: $p_{c_g} = \tfrac{1}{2} N(N-1) p_2 = 21. \, \tfrac{1}{hr}$

Air: $p_{c_a} = (N-1) p_2 = 2.1 \, \tfrac{1}{hr}$

In other words the controller already has ten times as much conflicts to handle. How will this be during a peak in 2015 with an estimated $N=40$?

Ground: $p_{c_g} = \tfrac{1}{2} N(N-1) p_2 = 86. \, \tfrac{1}{hr}$

Air: $p_{c_a} = (N-1)p_2 = 4.3\,\frac{1}{hr}$

This means the controller of this example sector will have to resolve 86 potential conflicts per hour (one every 42 seconds). In the same situations the cockpit would experience one conflict per 14 minutes during the peak. This is assuming the traffic is more evenly distributed over the airspace due to the direct routing. The fact that using airways instead of direct routing increases the potential conflict rate significantly means that the real effect is even worse. It could mean one conflict every 10 to 20 seconds on average.

Decreasing the sector size to solve this problem will also produce more overhead due to the higher number of hand-offs and will therefore only be able to solve this partially. An advantage of decreasing sector size however is that if our square shaped example sector is divided in four squares, on average an aircraft will only cross two squares and not all four. This means the number of aircraft under control will be decreased more significantly than the number of hand-offs will grow. A smaller en-route sector size does pose a problem when a conflict is further ahead than the length of a sector. This might lead to a need for more inter-sector co-ordination: one aircraft could be in sector A, another in sector B and the conflict in sector C. So decreasing the sector size is only a very temporary solution, not a fundamental one.

The numbers in the above conflict rate example are chosen to replicate the situation in the European Airspace, though they might not be completely accurate. Most numbers heavily depend on the local situation and route structure. The real numbers might be worse. The number of 1 conflict per hour is one that is already a few years old and probably should be higher. The doubling of air transport over Europe by 2015 is also quite conservative, the ratio is probably closer to 2.5 or maybe even higher.

Thus this example illustrates that introducing direct routing and airborne separation might be the only viable solution as the air traffic grows.

Doubling or even quadrupling today's air traffic density, raises the question whether there is enough physical airspace for these increasing number of aircraft. Assume we still use the 5 nautical mile, which was based on radar characteristics, not the navigation performance of today's aircraft. In that case, statically there is sufficient space for four hundred (20 x 20) aircraft at one level. Cruising takes place at least 15 levels with a separation of 1000 feet. So in case of a traffic density of 400 aircraft in a square of 100 by 100 nautical mile the airspace is filled about 7% with the (huge) protected zones of 5 nautical miles. Densities of 40, like the 2015 peak density, therefore still refer to a rather empty airspace.

14.4 Conclusion

Though the reality is more complex than the example situation used in the mathematics, the main conclusion holds. The fact remains that the 'conflict pressure' on a central system will increase in the order of N^2 and for the distributed with the order N. This means that with even completely different numbers and a different offset, the effect of the higher power of N can never be beaten by any central system when air traffic is growing.

15 Conclusions & Issues

15.1 Conclusions

From overviewing the results of the substudies that have taken place in the Free Flight project the following conclusions can be drawn. These results are only valid within the limitations of the scope of the study. Three main limitations of this validity is that the study has been limited to the designed operational concept, the cruise phase and the assumed system performance of ASAS, especially the communication via ADS-B.

Within this context, it can be concluded that

- None of the substudies could refute the **feasibility** of airborne separation assurance without co-ordination by a ground based controller. This indicates that airborne separation assurance is feasible in the cruise phase.

- Several substudies indicate the **benefits** of distributing air traffic control in terms of **capacity, safety and efficiciency** for en-route sectors. (chapter 6, 8, 11, 13 and 14)

- Pilot **workload** is not significantly increased due to the added task of airborne separation assurance in the cruise phase (chapters 8 and 11).

- Pilot **acceptability** is high after exposure to the concept of airborne separation assurance (chapters 8 and 11).

- An **operational concept** for airborne separation assurance has been desiged, implemented in simulations and validated in this study. Several **associated tools** like algorithms and display symbology have been implemented, evaluated and succesfully demonstrated in simulations. (chapter 3, 5, 7 and 9)

- As the demand for airspace capacity increases exponentially, airborne separation assurance could provide **a solution for the air traffic management** in the near future, which in its current centralised structure has reached its limits (chapter 14)

Overall, it seems the concept of airborne separation assurance is an option which should be seriously considered and investigated for future Air Traffic Management.

15.2 Open Issues

Several issues need further exploration:

- Other flight phases: airborne separation assurance appears to be feasible in high altitudes, but how low can you go with this concept?

- System performance: will all the components perform sufficiently to meet the required characteristics for the operational concept? Especially the communication function (ADS-B) is critical in terms of bandwidth, update rate and reliability.
- What will be the effect of more humans in the loop than in the simulations so far? The effect on the traffic pattern has to be investigated.
- Competition: what will the effect of this concept be in a commercial environment with sometimes extreme competition between airlines. Ground controllers are often arbiters in these situations, what happens if they are no longer in control and people start 'bending the rules'?
- Man Machine Interface: Though the designed MMI in this study has been evaluated with success, a thorough study of all options might result in a more optimal man machine interface in terms of symbology, alerting etc.
- Transition: the mixed equippage study has shown that ATM procedures which handle the mixed equippage sectors are critical and need further study to avoid problems on the ground or at the flight deck.
- Flight Plan information: If flight plan information of other aircraft is available, how can this be integrated in the ASAS system without destroying all the benefits of a state based system?

15.3 Future work

In the near future several studies will be aimed at the open issues of the last section.

A so-called human interaction experiment will explore the effect of competition and of 'bending the rules' on the operational concept. For this study a high number of participants will 'log on' to the traffic manager and control an aircraft in a scenario using their own PC and a downloaded flight simulation program including the ASAS system. A competitive effect will be introduced in the experimental design, resulting in more insight in the application of the operational concept in a commercial environment.

A simulator study will explore the effect of the operational concept in other flight phases, starting in cruise until final approach. In addition extra constraints like weather, terrain and SUA will be introduced.

System characteristics like ADS-B performance will be evaluated for several options of the ADS-B communications. The effect of bandwidth, update rate and message collisions on the flight deck and ASAS performance will be studied using both off-line and on-line (human in the loop) studies.

In co-operation with the NASA Langley, the effect of the integration of flight plan information in the ASAS will be explored.

ACRONYMS AND ABBREVIATIONS

A/C	Aircraft
ADS-B	Automatic Dependent Surveillance – Broadcast
AIRSIM	Avionics Integration & Research SIMulator (desktop simulation)
ASAS	Airborne Separation Assurance System
ATC	Air Traffic Control
ATCo	Air Traffic Controller
ATM	Air Traffic Management
ATN	Aeronautical Telecommunications Network
BADA	Base of Aircraft Data
BSMI	Beoordelingsschaal voor Mentale Inspanning (Dutch name for RSME)
CAS	Callibrated Airspeed
CD	Conflict Detection
CD&R	Conflcit Detection and Resolution
CDTI	Cockpit Display of Traffic Information
CR	Conflict Resolution
FAA	Federal Aviation Administation
FF	Free Flight
FFAS	Free Flight Airspace
FMS	Flight Management System
GPS	Global Positioning System
HMI	Human Machine Interface
IAS	Indicated Airspeed
ICAO	International Civil Aviation Organisation
IFR	Instrument Flight Rules
IMC	Instrument Meteorological Conditions (when IFR should be applied)
INS	Inertial Navigation System
MAS	Managed Airspace
NASA	National Aeronautics and Space Administration
ND	Navigation Display
NLR	National Aerospace Laboratory, The Netherlands
NRP	National Route Program
PASAS	Predictive ASAS
PFD	Primary Flight Display
PVD	Plan View Display (of a controller)
RFS	Research Flight Simulator
RNP	Required Navigation Performance
RSME	Rating Scale of Mental Effort
RT, R/T	Radiotelephony (voice radio)
RTCA	Radio Technical Commission for Aeronautics
STCA	Short-Term Conflict Alert
SUA	Special Use Airspace
TCAS	Traffic Collision Avoidance System
TCP	Trajectory Change point
TEM	Traffic and Experiment Manager (=TMX)

TLS	Target Level of Safety
TMX	Traffic Manager (=TEM)
TOPAZ	Traffic Organization and Perturbation AnalyZer
UMAS	Unmanaged Airspace
VFR	Visual Flight Rules
VMC	Visual Meteorological Conditions (when VFR can be applied)
VS	Vertical Speed

Appendix A Questionnaires phase I trials

Pilot Experience Questionnaire

Date: **Airborne Free Flight**

Name: PF/PNF

Date of birth:

List the type, approximate flight hours, and your position for the different transport aircraft you have flown.

AIRCRAFT	FLIGHT HOURS	POSITION(Capt., F/O, etc.)

Do you wear glasses or lenses (Yes/No)

If yes, are they bifocal (Yes/No)

Also, please provide the following information (approximate hours):

Total Flight Hours:	
Current Aircraft Flying:	
Current Airline:	
Current Ratings:	
EFIS Experience (hrs.):	
FMS Experience (hrs.):	
Military Jet Experience (hrs.):	
International Experience (hrs.):	
# of research projects as pilot participant:	

BSMI

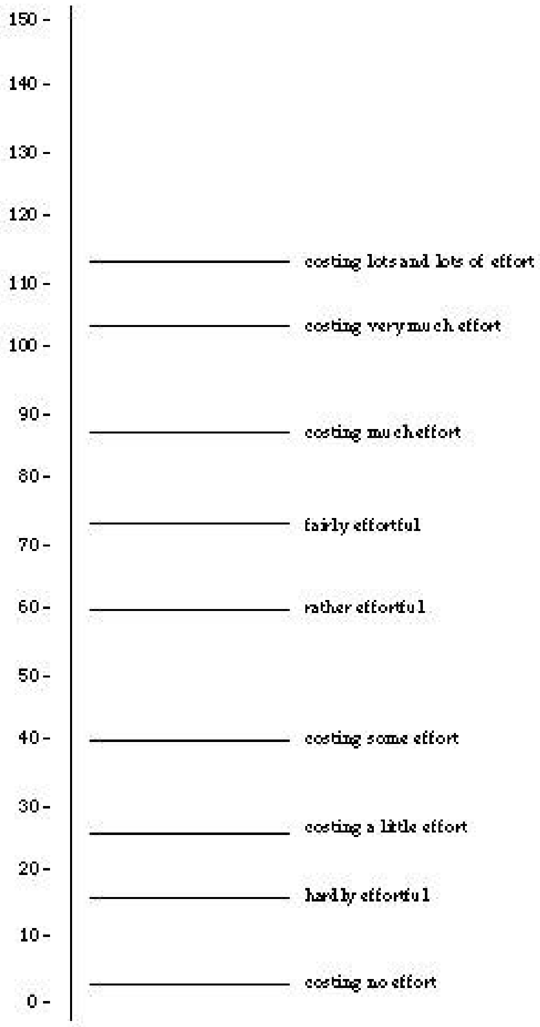
Date: **Airborne Free Flight**

Name: PF/PNF

Condition: ○ Manual ○ Execute combined ○ Execute separately

Runnumber: Density: "XXXX":

Please indicate, with a cross on the vertical line, how much effort it cost to do your work in the above mentioned flight.



Date: **Airborne Free Flight**

Name: PF/PNF

Condition: 0 Manual 0 Execute combined 0 Execute separately

Runnumber: Density: "XXXX":

Please rate the overall acceptability of your last flight..(one tick only)

☐ Perfect in every way
☐ Favorable
☐ Acceptable
☐ Undesirable
☐ Completely unacceptable

Please tick True or False to express your opinion on the statements below.

TRUE	**FALSE**	
☐	☐	I think I could safely guarantee the airborne separation with the set-up just flown
☐	☐	I manoeuvred more than normally
☐	☐	I exceeded passenger comfort levels
☐	☐	I need more information about the traffic situation to guarantee the safety
☐	☐	I need better information about the traffic situation to guarantee the safety
☐	☐	I need more explicit rules of the road to guarantee the safety
☐	☐	I need more explicit on board procedures to guarantee the safety
☐	☐	I need more training to guarantee the safety

How does in your opinion the safety of the set-up just flown compare to modern present day ATC operations? (one tick only)

☐ FF much safer
☐ FF safer
☐ Same
☐ ATC safer
☐ ATC much safer

POST-TRIALQUESTIONNAIRE

Date: **Airborne Free Flight**

Name: PF/PNF

Condition: 0 Manual 0 Execute combined 0 Execute separately

1. On a scale from 1-5 rate the following aspects of the Free Flight concept.
   - 1 - completely unacceptable
   - 2 - undesirable
   - 3 - acceptable
   - 4 - favorable
   - 5 - perfect in every way

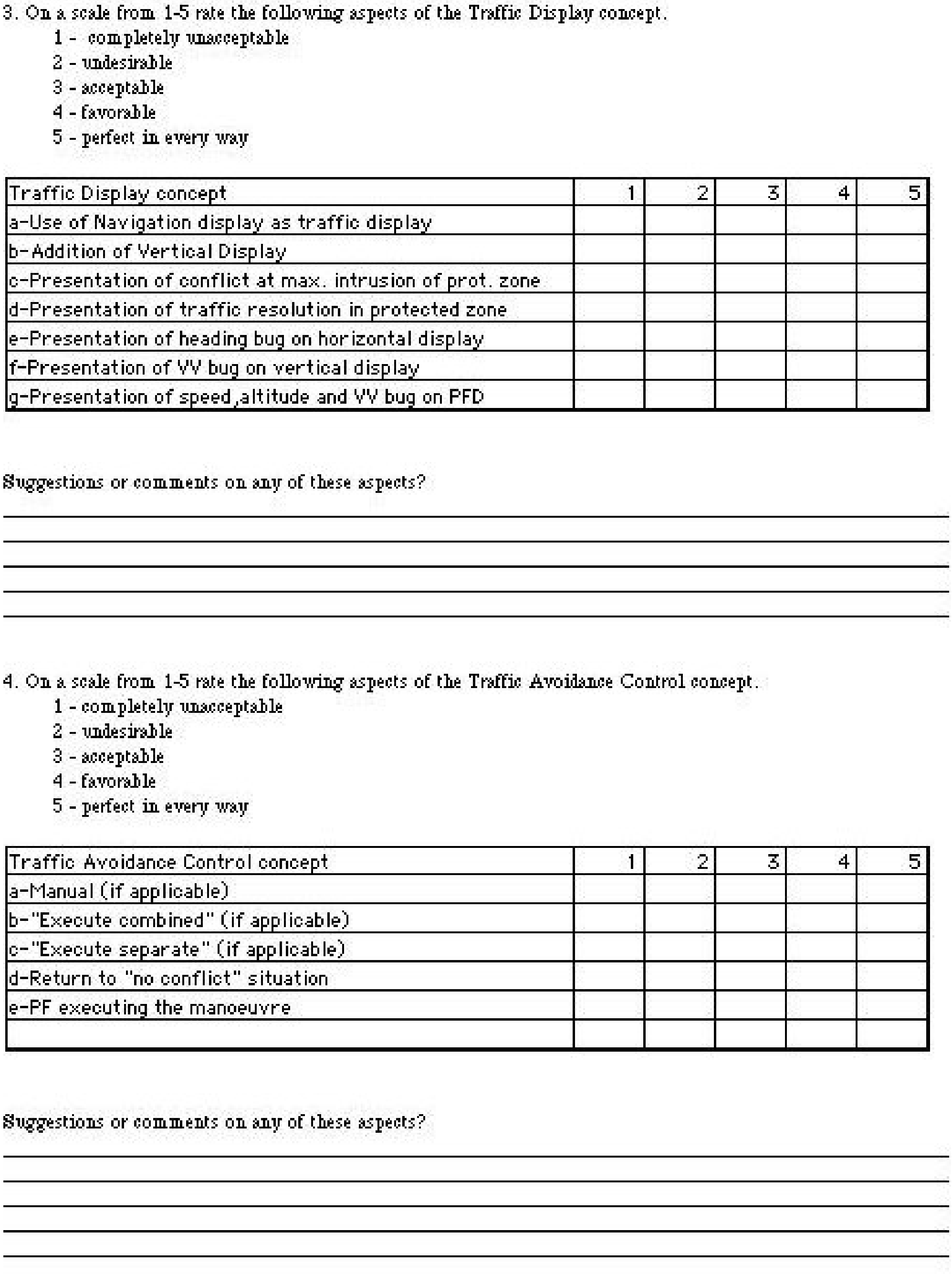
Free Flight concept	1	2	3	4	5
a-No ATC present					
b-No priority rules (but all acft deviate)					
c-Conflict detection based on max. intrusion prot. zone					
d-Times to conflict used (5 min amber, 3 min red)					
d-Voltage potential resolution					
e-Intra flight comms					
f-Ground arbitration					

Suggestions or comments on any of these aspects?

2. On a scale from 1-5 rate the following aspects of the Alerting concept.
   - 1 - completely unacceptable
   - 2 - undesirable
   - 3 - acceptable
   - 4 - favorable
   - 5 - perfect in every way

Traffic alerting	1	2	3	4	5
a-The use of the glareshield indicator					
b-The repetive use of an aural alert (conflict present)					
c-The aural used for "amber" conflict					
d-The aural used for "red" conflict					
e-The functionality of canceling an alert					

Suggestions or comments on any of these aspects?



3. On a scale from 1-5 rate the following aspects of the Traffic Display concept.

1 - completely unacceptable
2 - undesirable
3 - acceptable
4 - favorable
5 - perfect in every way

Traffic Display concept	1	2	3	4	5
a-Use of Navigation display as traffic display					
b-Addition of Vertical Display					
c-Presentation of conflict at max. intrusion of prot. zone					
d-Presentation of traffic resolution in protected zone					
e-Presentation of heading bug on horizontal display					
f-Presentation of VV bug on vertical display					
g-Presentation of speed,altitude and VV bug on PFD					

Suggestions or comments on any of these aspects?

4. On a scale from 1-5 rate the following aspects of the Traffic Avoidance Control concept.

1 - completely unacceptable
2 - undesirable
3 - acceptable
4 - favorable
5 - perfect in every way

Traffic Avoidance Control concept	1	2	3	4	5
a-Manual (if applicable)					
b-"Execute combined" (if applicable)					
c-"Execute separate" (if applicable)					
d-Return to "no conflict" situation					
e-PF executing the manoeuvre					

Suggestions or comments on any of these aspects?

5. On a scale from 1-5 rate the following aspects of the Generic Control Panel.

1 - completely unacceptable

7. On a scale from 1-5 rate the criticallity of the following functional elements for safety.

1 - extremely critical
2 - very critical
3 - critical
4 - not really critical
5 - not at all critical

Functional elements	1	2	3	4	5
a-Traffic Flow Management					
b-Traffic detection					
c-Conflict detection					
d-Resolution computation					
e-TCAS as backup					
f-ATC as backup					

Suggestions or comments on any of these aspects?

a-Perspective display on PFD					
b-Perspective display on lower EICAS					
c-Use of pointing device for selective interrogation of target					

Suggestions or comments on any of these aspects?

BSMI

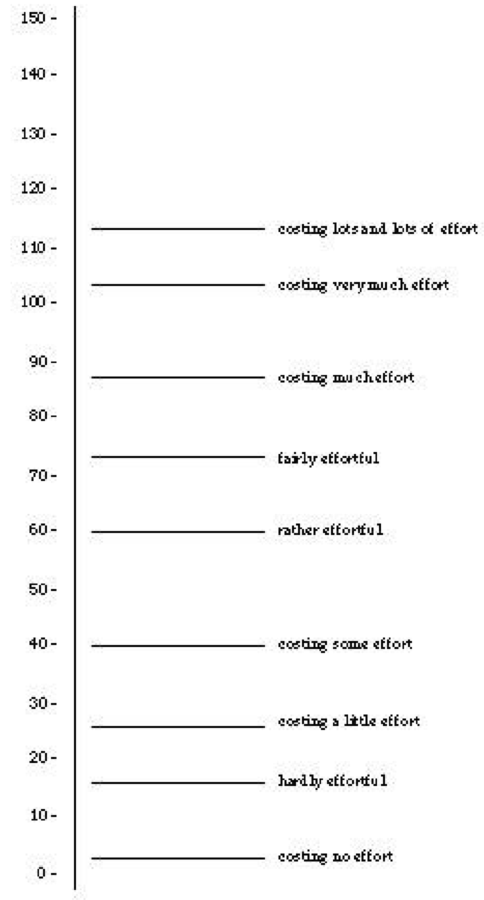
Date: **Airborne Free Flight**

Name:

Condition: 0 Protected Airways 0 Fully Mixed 0 Flight Level

Runnumber: Density: Mixage: "XXXX":

Please indicate, with a cross on the vertical line, how much effort it cost to do your work in the above mentioned flight.



Date: **Airborne Free Flight**

Name:

Condition: 0 Protected Airways 0 Fully Mixed 0 Flight Level

Runnumber: Density: Mixage: "XXXX":

Please rate the overall acceptability of your last flight..(one tick only)

☐ Perfect in every way
☐ Favorable
☐ Acceptable
☐ Undesirable
☐ Completely unacceptable

Please tick True or False to express your opinion on the statements below.

TRUE	**FALSE**	
☐	☐	I think I could safely guarantee the airborne separation with the set-up just flown
☐	☐	I manoeuvred more than normally
☐	☐	I exceeded passenger comfort levels
☐	☐	I flew economically

How does in your opinion the safety of the set-up just flown compare to modern present day ATC operations? (one tick only)

☐ FF much safer
☐ FF safer
☐ Same
☐ ATC safer
☐ ATC much safer

How many conflicts did you encounter during this flight ? ☐

How did you usually resolve them ? Vertical Speed / Heading / Speed
(Please encircle the option(s) used)

Please state the reason why you used the above maneuvre option(s) and/or why you did not use the other(s)?

POST-TRIALQUESTIONNAIRE

Date: **Airborne Free Flight**

Name:

Condition: ○ Protected Airways ○ Fully Mixed ○ Flight Level

1. On a scale from 1-5 rate the following aspects of the Airborne Separation Assurance System ASAS.

1 - completely unacceptable
2 - undesirable
3 - acceptable
4 - favorable
5 - erfect in every way

ASAS	1	2	3	4	5
a-Horizontal Display of traffic					
b-Vertical Display of traffic					
c-Presentation of conflicts (not the Predicitive part)					
d-Presentation of resolution advisory					
e-Presentation of predictive ASAS (on PFD & NAV)					
f-The aural alerts used					
g-The glare shield alert light					

Suggestions or comments on any of these aspects?

2. On a scale from 1-5 rate the criticallity of the above mentioned functional elements. (In other words rate how much they are needed to ensure airborne separation safely)

1 - not at all critical
2 - not really critical
3 - critical
4 - very critical
5 - extremely critical

ASAS	1	2	3	4	5
a-Horizontal Display of traffic					
b-Vertical Display of traffic					
c-Presentation of conflicts (not the Predicitive part)					
d-Presentation of resolution advisory					
e-Presentation of predictive ASAS (on PFD & NAV)					
f-The aural alerts used					
g-The glare shield alert light					

Suggestions or comments on any of these aspects?

Appendix C Traffic Manager Command overview

In this appendix a list of the commands is given to provide insight not only on how to use the traffic manager, but also in the capabilities. All commands shown beolow can be typed in the command window, though in general using the mouse to click on the map window and the buttons is easier. These commands can be recorded in scenario files which consists of time stamped commands. Playing this scenario files has the same effect as if all the commands were typed by the user at the specified time. Tools, like autoscen or multitple create, also generate files with these comands to simulate high density traffic scenarios.

HELP FUNCTION

?	Use ? as (only) in-line argument to read helptext and argument list

TRAFFIC COMMANDS

CRE acid, type, lat, lon, hdg, alt, spd	Create an aircraft at specified position (use mouse)
DEL acid	Deletes an aircraft
MDEL latmin,lonmin,latmax,lonmax	Deletes all aircraft within rectangle (use mouse)
MCRE n,type,alt,spd,dest	Multiple create within current window, use '*' as wildcard
RENAME acid,newname	Rename an aircraft
MOVE acid,lat,lon,alt	Move an aircraft (use mouse)
REPOS acid, origin[,t]	Reposition controlled traffic to FF position
RETYPE acid,type	Set aircraft type to different type

TAKE (acid)	Hand aircraft over to airsim
GIVE	Ask airsim to release control over aircraft

(acid) or **POS acid**	Retrieves position & info on aircraft (double click a/c = POS)
(acid) HDG (hdg)	Heading command
(acid) LEFT/RIGHT (delhdg)	Relative heading command
(acid) SPD (IAS/Mach)	Speed command
(acid) ALT (alt) [,vertspd]	Altitude command (optional with vertical speed)
(acid) VS (vertspd)	Vertical speed (first set commanded altitude)

LNAV acid/*, ON/OFF	Set artificial pilot (navigation & resolution) on/off (*=for all aircraf
VNAV acid/*,ON/OFF	Set vertical navigation on/off (*=all aircraft)
SQ[UAWK] [acid,]code	Set transponder code

NAVDISP/ND (acid)	Show nav display for specified aircraft (TAB to toggle)

acid CHASE targetid, time	Chase target aircraft to meet at time
(acid) DEST (airportid)	Set destination for navigation purposes
(acid) ORIG (airportid)	Set origin for bookkeeping purposes
(acid) ROUTE	Display route for aircraft on/off
acid ADDWPT (name/lat,lon),[alt],[spd],[afterwp]	Add waypoint to route of aircraft
acid ADDTUBE heightm,widthm,lat,lon,alt,iwptype,wpname	Add tube point (AWARD project)
acid AT wpname SPD spd	Set speed at waypoint
acid AT wpname ALT alt	Set altitude at waypoint
(acid) DIRECT[TO]/DIRTO (waypoint)	Set active waypoint
(acid) DELWPT wpname	Delete waypoint from route

(acid) DELRTE	Delete entire route
LISTRTE acid[,pagenr]	List route for a/c (pagenr mainly used internally)
DEFWPT name,lat,lon	Define a waypoint temporary
UNDEFWPT wpname	Undefine waypoint
LISTWPT [pagenr]	List defined waypoints (pagenr not necessary)

FREE FLIGHT COMMANDS

ASAS acid, [ON/OFF/TOGGLE]	Equips a/c with ASAS or not
RESO acid, ON/OFF	Switch on/off ASAS resolution module
RESONR resonr/name	Set conflict resolution method (see conflict.dat)
FFLEVEL altitude	Set level above which Free Flight is allowed
DFFLEVEL deltaaltitude	Set thickness of transition layer below fflevel

DTLOOK time	Set lookahead time
DTNOLOOK	Set lookahead between conflict probings
DTLOOKATC	Set lookahead time for controlled traffic
MANUAL/SEMIAUTO/FULLAUTO	Set resolution execution method for RFS
NORESO acid	Set (one) aircraft not to avoid
PREDASAS/PA acid	Show current values of forbidden bands for given aircraft
PREDASAS/PA ON/OFF	Switch predasas function of navigation display on or off
FILTCONF ON/OFF	Set Conflict Detection time lag filter on/off
FILTTRED	Set time lag for filtering 'RED' urgency conflicts
FILTTAMB	Set time lag for filtering 'AMBER' urgency conflicts

DISPLAY COMMANDS

ZOOM IN/OUT	Set zoom of current display (radar or navigation display)
++++ / -----	Multiple zoom in (+) or zoom out (-)
VERZOOM IN/OUT	Set vertical range of vertical navigation display
V++++/V--------	Multiple vertical zoom in/out
PAN (LEFT / RIGHT / UP / DOWN / RFS / MCS / acid / airport / lat, lon)	Pan radar window
TRACE (acid)/OFF	Keep panning the display on specified aircraft
NAVDISP/ND (acid)	Show nav display for specified aircraft (TAB to toggle)
SWRAD GEO / GRID / APT / VOR / WPT / NDB / LABEL	toggles features on or off
LABEL	Cycles info level of lables
RADAR	Switch back to radar display (TAB toggles)
WPTLABEL ON/OFF	Switch Waypoint labels on/off
SWCOLEQP ON/OFF	Switch colour coding of traffic based on equipage on/off
VERDIST ON/OFF	Use distance or forward looking projection for vertical nav display
LOWALT altitude	Set lower altitude limit for aircraft to be shown in radar window
UPPALT altitude	Set upper altitude limit for aircraft to be shown in radar window
SYMBOL	Switch aircraft symbol in radar display

SIMULATION CONTROL

IC [playfile],[recfile]	Initialize condition
OP	Start or continue running

HOLD	Pause or hold simulation
EXIT	Exit program (or use ESC key)
RTF rtf	Set real-time factor for fast-time simulation
FIXDT ON/OFF	Forces the Traffic and Experiment Manager to use a fixed time step
DT [dt]	Sets time step to the value dt, shows current DT without argument
TAKE (acid)	Hand aircraft over to airsim
GIVE	Ask airsim to release control over aircraft
NOISE ON/OFF	Switch noise on/off
SAVEIC filename	Save current situation as IC
AUTOSCEN [filename]	Opens filename.ASC and filename.RTE for scenario generation
AUTOSTOP [ON/OFF]	Sets start/stop recording FX10 aircraft (see autostop.dat)
DATALOG ON/OFF/filename	Set datalogging on/off
LOG text	Write text timestamped to log file

MISCELLANEOUS COMMANDS

DENS[ITY]	Calculates traffic density of current radar window
DIST lata,lona,latb,lonb	Calculate bearing and distance from A to B
QDRPOS lat,lon,qdr,dist	Calculate lat/lon given bearing and distance [nm]
HDGREF M/T	Set default headings to Magnetic or True, if no M or T is used after
TURB latmin,lonmin,latmax,lonmax,(L/M/S)	Specify light medium or sever turbulence area
DEL TURB	Delete turbulence area
CLOUD lat,lon	Set cloud at specified location
DEL CLOUD	Delete cloud
AREA lata,lona,latb,lonb[,latc,lonc]	Specify experiment area (leaving a/c deleted)
AREA OFF	Switch experiment area off
CLRAREA lata,lona,latb,lonb[,latc,lonc]	Specify area that generates requests for clearances
CLRAREA OFF	Switch clearance area off
EVENT eventcode	Set eventcode
REF acid, fuel,way,time	Set reference values for statistics of efficiency
INSEDIT (txt)	Insert a text as if edited. Meant for use in BUTTONS.DAT
MODE submenu	Set submenu of mouse buttons
ECHO ON/OFF/text	Set echo on/off or display text
GRAB example.pcx	Dump screen in PCX file
FREQ	Displays program update frequency
ETH (device) ON/OFF	Switch communication to device ON or OFF. Devices: RFS, MCS, CMD, GSM, ATC

General command syntax

All command lines start with the command followed by command line arguments if necessary. The arguments are separated by one comma and/or space(s). When the first argument is an aircraft id that exists, it is also allowed to swap command and id. So “ALT KL104, FL250” is equivalent to “KL104 ALT FL250”. This means the user can first select the aircraft with the mouse, then watch the current values at the bottom line in the strip window and then decide what command should be issued. Using the mouse in the radar window and the selection bar a lot of commands can be issued without touching the keyboard.

Mouse clicks

The button strip offers a range of commands to be selected with the mouse. Also the following arguments can be selected with a mouse click in radar window or selection bar:

acid = aircraft identification e.g. NLR001 (max. 8 characters)
(lat, lon)= position (decimal degrees)
hdg = heading by clicking in direction from reference position (true, decimal degrees)
alt = altitude (from selection bar) (xxxxx ft or FLxxx or xxx)
spd = speed (from selection bar) (CAS kts or Mach)
type = aircraft type (from selection bar)
dest = airport closest to click in radar window