Multi-Purpose Cockpit Display of Traffic Information: Overview and Development of Performance Requirements

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This paper describes a Multi-Purpose Cockpit Display of Traffic Information (MPCDTI), which integrates core functional capabilities that can be combined in various ways to perform ADS-B In applications in the NextGen environment. The MPCDTI is different from other CDTIs in that it packages the capability to manage multiple applications within a single piece of equipment. Four key elements of the MPCDTI have been defined: elemental functions, simultaneous enablement, automatic algorithm selection, and output arbitration. These elements allow compatible functions to be enabled and prevent the MPCDTI from outputting infeasible or conflicting guidance to the flight crew. The objectives of this paper are to present the key features of the MPCDTI and also to suggest a functional approach for developing MPCDTI and future application performance requirements.

I. Introduction

Implementation of the Next Generation Air Transportation System (NextGen) is considered a priority by the FAA; a similar concept known as Single European Sky is maturing in Europe. NextGen refers to the modernization of the current US National Airspace System (NAS). A central component of NextGen is Automatic Dependent Surveillance-Broadcast (ADS-B), which is a new technology that broadcasts aircraft identification and state information, such as GPS position and ground speed.[1] The broadcast information can be used by both Air Traffic Control (ATC) and other aircraft, thus enabling new procedures involving aircraft-to-aircraft surveillance that are intended to address NextGen goals through increases in safety, efficiency, and capacity. Several research institutions have investigated the development of a cockpit display of traffic information (CDTI), which displays neighboring aircraft to the flight crew, and in some cases, provides speed or maneuver guidance to the crew. This technology allows some of the tasks and responsibilities traditionally assigned to ATC to be delegated to the flight crew.

ADS-B can provide the necessary surveillance information to drive a CDTI along with additional capabilities needed to enable the envisioned modes of delegation between ATC and the flight crew. Research and development to date have yielded a wide range of potential modes of delegation to the flight crew including spacing relative to another aircraft, merging behind another aircraft at a fixed point, and resolving conflicts with other aircraft.[2,3] Concepts that use ADS-B to give pilots a greater role in traffic management in the air and on the surface to achieve NextGen goals are usually referred to as "ADS-B In applications."

Whereas the air traffic system can expect to enjoy improved capacity and throughput as a result of these new capabilities, each additional delegated task or responsibility adds an incremental cost. Operators are currently reluctant to commit to ADS-B In, as no single application has yet been identified that will offset the full cost of initial equipage. However, a single CDTI, properly designed to enable multiple applications should provide a positive cost benefit case, raising the likelihood that operators will be motivated to equip their fleets.

The MITRE Corporation's Center for Advanced Aviation System Development (CAASD) has conducted research into the requirements for a suitable Multi-Purpose CDTI (MPCDTI). Other researchers have developed CDTIs for NextGen applications; however, few have considered how multiple applications may: 1) be

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managed from a single interface; 2) be used simultaneously to accomplish a single operational goal; 3) interact appropriately with multiple ADS-B In applications; and, 4) interact with other airborne and ground-based systems. MITRE's research has yielded requirements and a sample design and simulation prototype, which integrates thirteen functional capabilities that collectively enable a multitude of NextGen applications.

The objective of this paper is to illustrate the process of developing the requirements for the MPCDTI that are aligned with different operational concepts and their objectives, as well as to demonstrate the feasibility of combining several applications within one single piece of equipment. By demonstrating feasibility and deriving requirements for the MPCDTI based upon a selection of developed operational concepts, the MPCDTI concept should be able to be used to drive the development of future operational concepts and equipment standards, further justifying the use of a single piece of equipment to handle multiple NextGen applications.

The paper is organized as follows: Section II provides a short history of CDTI and application development. An overview of the MPCDTI is presented in Section III, which includes descriptions of the elemental functions that in combination form an operational concept or application. A new approach for developing application standards is presented in Section IV. Challenges and open research topics for a new approach to requirements development are discussed in Section V, and final conclusions are presented in Section VI.

II. Background

Research involving the display of traffic information to pilots has been occurring since the 1940's with the goals of increasing safety, efficiency, and capacity.[4,5] Concepts have been originated by diverse sources including aircraft operators, public and private research organizations, universities, industry associations, aircraft and avionics manufacturers, and sponsoring government agencies. For much of the last half-century, studies have primarily focused on identifying new potential CDTI applications, safety and situation awareness benefits of providing traffic information, speed, and maneuver guidance to pilots, and optimal ways of displaying this information. The specific early application work typically focused on in-trail following, spacing, and merging concepts as well as collision avoidance.

The introduction of TCAS in the 1990s was the first widespread integration of traffic information in the cockpit. Despite its success in reducing and preventing mid-air collisions, it relies on transponder interrogations for position calculations and has neither the accuracy nor a rich enough data set to enable more complex applications - especially those that would provide any guidance for speed changes or maneuvering to achieve a traffic management objective. However, the development of ADS-B in the 1990's provided an enabling surveillance technology that allows for continuing development and a realistic means of implementation.

Application development efforts have been diffused across a large research community and specific concepts have in many cases been developed with little consideration for how they fit into a larger set of capabilities. However in 2001, a joint US and European cooperative research group established a classification framework for what later became known as Aircraft Surveillance Applications (ASAs) in order to aid the development of new applications.[6] Four hierarchical categories were established:

- Airborne Traffic Situation Awareness - Enhancements in flight crew knowledge of surrounding surface and airborne traffic;
- Airborne Spacing - Flight crews ensure an assigned spacing value from a designated aircraft;
- Airborne Separation - Flight crews ensure separation from a designated aircraft, which relieves the controller from the responsibility for separation between these aircraft;
- Airborne Self-Separation - Flight crews ensure separation of their aircraft from all surrounding traffic.

This new framework allowed for better coordination of activities for identifying applications in a systematic way and establishing a time frame for implementation. In the last decade, the FAA Applications Integrated Work Plan, and the joint US/European Action Plan 23 were created to assess levels of maturity of application concepts, and identify candidates for near-, mid-, and far-term implementations. Development efforts have been greatly accelerated and active concepts include (but are not limited to): enhanced situation awareness on the surface and in the air; alerting flight crews to unsafe conditions on the airport surface; interval management with and without delegated separation responsibility to flight crews including crossing and passing; in-trail climb/descent procedures in oceanic airspace; paired approach operations to closely spaced parallel runways; and applications involving the use of CDTIs to supplement and replace out-the-window aircraft acquisition requirements for visual operations. The international Requirements Focus Group (RFG) is in the process of developing operational, technical, and safety requirements for a set of near-term applications called Package 1,[7] although research and development for other applications continues to occur through organizations such as the FAA, MITRE CAASD, NASA, RTCA, and EUROCONTROL.

A. Prior Work on MPCDTIs

Despite the various efforts to coordinate application development, much detailed concept work continues to occur with little consideration for how a flight crew and host avionics system can manage more than a single application that provides guidance to the flight crew. Although some prior work describes systems with combinations of air/ground situation awareness for decision support and collision avoidance applications,[8, 9] none of these application types involve providing guidance to the flight crew beyond simple notifications and alerts (with the exception of a TCAS II Resolution Advisory). As such, operators of these systems do not need to specifically call these applications nor do application outputs need to be arbitrated by the processing system.

This paper considers more complex application management systems under the term MPCDTI. As considered here, an MPCDTI will have the following characteristics: 1) It must be able to host more than one application that remains dormant until: selected, set up, and enabled by the flight crew; and 2) It must provide a capability to host more than one function that provides guidance (e.g. speed and/or lateral or vertical guidance) to the flight crew to assist them in accomplishing a safety or air traffic management objective. More advanced distributed air/ground concepts and associated traffic displays that rely heavily on assisting the flight crew and controllers in coordinating routes and trajectories, such as NASA Ames's Free Flight,[10] are not directly applicable to the goals of an MPCDTI and have not been considered here.

At a minimum, efforts to develop MPCDTI systems should account for: common interface elements, simultaneous enablement, output arbitration, alerting schemes, processing requirements, compatibility of integrity/accuracy requirements, and certification requirements. While many individual application development efforts consider these factors, none to date have attempted to consider these factors across a wide range of application capabilities. There are several reasons for this, including: the continuously evolving state of many applications and associated algorithms, CDTI location uncertainty in forward fit vs. retrofit aircraft installations, and still evolving whole-cockpit concepts, which presume a much tighter integration of ADS-B information and processing into the Flight Management System (FMS) and data-based communications.[11] The compounding effect of these uncertainties has generally made it difficult to realize specific requirements on which to base a design. Also, the generally accepted phased approach to development which results in faster implementation of the simpler applications and later implementation of more complex concepts as time and technology allow, has traditionally not resulted in a strong demand for a “do-everything” system.[6] With the continuing lack of a single ADS-B In application that justifies widespread equipage, however, at least some form of an MPCDTI will be necessary to satisfy business cases that will need to be built on the aggregate benefits of multiple applications.

In spite of the obstacles, some past work does occasionally reference systems that would be used for more than one application. The group developing principles of operation for the use of ASAs noted that aircraft would not be expected to carry more than one set of application-enabling equipment.[6] It also made mention of some human factors considerations for a common human interface:

> *Although specific tasks and responsibilities will be different between various applications, there should be consistency between the procedures used for the different applications to avoid high workload and confusion when more than one application is used on a single flight. Careful procedures to allow transition from one application to another (e. g. from self-separation to spacing) will be essential, as will means of identifying which application is in effect.*

Reference [6] has also hinted at one of the major challenges facing a multiple application integration effort: how to arbitrate between output guidance coming from different sources. In this case, the need for a type of alert arbitration and suppression between ASAs and Airborne Collision Avoidance Systems (ACAS) sharing a common display was identified. But despite these initial considerations, the group did not establish in any further detail how a traffic display system that supported numerous applications may be expected to function.

The Aircraft Surveillance Applications System (ASAS) Minimum Operational Performance Standards (MOPS) document (RTCA DO-317) provides a set of performance standards for processing and display systems that support an initial set of conflict detection and situation awareness applications for enhanced decision making.[9] Although these applications are expected to use common processing and interface systems, and the standards provide useful, baseline CDTI design criteria, the document does not provide specific considerations needed for MPCDTIs that provide active guidance.

Drawing on a series of experiments that evaluated airborne spacing concepts from flight deck and controller perspectives in 2005, CoSpace documented a series of flight deck user requirements for Sequencing and Merging applications and considered Human Machine Interface (HMI) requirements for integrated and standalone CDTIs.[12,13] Although the requirements were focused on airborne spacing operations, they did consider an environment in which multiple options for the spacing task were selectable by the pilot: either REMAIN or MERGE with or without an initial heading. Two major levels of integration were considered: an integrated cockpit and a standalone system. Much of the HMI detail was focused on the integrated cockpit with application setup and control managed through Multi-purpose Control and Display Units (MCDU) and Navigation Display/Primary Flight Display integration for display.[13] However, some high-level requirements for standalone systems were provided, including a suggestion that the active ASAS application should be available on the guidance indicator.[12] The document also proposed algorithms to cover the different sequencing and merging conditions; however, beyond the transition from merge to remain behind, algorithm output arbitration was not applicable.

As part of its overall Distributed Air Ground Traffic Management (DAG-TM) activity, NASA-Ames's Concept Element 11 (CE-11) also assumes both MERGE and SPACE (remain) capabilities for aircraft.[3] However, specific CDTI considerations for application management were not discussed.

Another significant activity that assumed management of multiple applications is the Safe Flight 21 (SF 21) program. Sponsored by the FAA, SF 21 participants conducted two operational evaluations in 1999 and 2000 that were intended to demonstrate the benefits of providing ADS-B traffic information to pilots and improved information for controllers.[14,15] Although the only application tested that provided guidance was airborne (approach) spacing, several non-guidance applications, including departure spacing, Airport Surface Situational Awareness, Final Approach and Runway Occupancy Analysis, were also evaluated. Although these evaluations did not require an MPCDTI as defined for this paper, they did involve procedural application management by the flight crew as they transitioned domains and were an important evolutionary step toward the more capable Aircraft Communication & Surveillance Systems (ACSS) SafeRoute system.

Although still not technically an MPCDTI as defined by this paper, the SafeRoute system is the most advanced CDTI display system that has been certified and fielded for operational use.[16] Developed by ACSS and recently implemented by UPS for late-night, west coast departures into their Louisville, KY hub, it is capable of three ADS-B In applications: Merging and Spacing (M&S), CDTI-Assisted Visual Separation (CAVS), and Surface Area Movement Management (SAMM). Although application management by the crew and processing system is still not as complex as that needed for a true MPCDTI, the SafeRoute system is designed to detect which application is active and then display the appropriate guidance or status information. Of particular interest for MPCDTI development is the transition between M&S and CAVS. In this case, when an aircraft is selected and M&S is inactive, the differential ground speed between ownship and the target is displayed, enabling transition to CAVS. Then, as the aircraft comes within range to the airport, the system displays the SAMM application. These application management features bring it closer to an MPCDTI than any other fielded system.

B. Commonly-Used Terms

Terms commonly used throughout this paper are defined here.

[ADS-B In] Application: A concept that is based on the use of ADS-B-provided traffic information in the cockpit to allow pilots to achieve a *specific* air or surface traffic management goal. An application will include a defined operational objective in a specified domain, a defined set of air and ground procedures and constraints, and a minimum set of safety and equipment performance requirements.

Functional capability (or Function): A cockpit system capability that uses ADS-B-based traffic information to allow pilots to execute an air or surface ADS-B In application. Functions are defined outside of fully-articulated applications, and must provide a satisfactory level of safety and performance in the context of any application.

Ownship: this refers to the aircraft performing an operation and using the MPCDTI for the necessary situational awareness or guidance in order to perform that operation.

Reference aircraft: this refers to the one or more aircraft with which the ownship is performing an operation. The reference aircraft may not be receiving guidance as part of the operation, but the MPCDTI is providing to ownship situational awareness of or guidance relative to the reference aircraft.

III. Overview of the Multi-Purpose CDTI

A. Objectives and Scope of the MPCDTI

Ongoing NextGen-application development will illuminate the expected benefits of equipping flight decks with the necessary equipment to perform those applications. The MPCDTI is intended to address the issue of cost by positioning the flight deck to be able to participate in the widest possible range of ADS-B In applications using a single piece of equipment.

As such, it is important to anticipate the range of possible uses of the MPCDTI. From displaying traffic information to providing speed and maneuver guidance for spacing applications, the requirements for the integration and packaging of these capabilities need to be derived and designed, respectively. Of particular interest are questions of how to develop capabilities that are defined absent a fully-articulated application context and how to validate the performance requirements such that each capability provides a satisfactory level of safety in the context of any application.

The multitude of potential uses of the MPCDTI implies a need for a well-designed human interface. It is possible to find that even after overcoming all technical integration issues in the design of the equipment, flight crews may not be able to use the equipment because they cannot fathom the range of capabilities provided. For this reason, the number of capabilities a pilot needs to access should be kept to a minimum, the motivation for their use be made as intuitive as possible, and the configuration of required input data must be clearly identifiable.

With the aforementioned objectives in mind, the capabilities of the MPCDTI should include:

1. The display of raw traffic information to support situation awareness.
2. The display of processed information (derived from raw information).
3. Guidance and control algorithms to support a wide variety of ADS-B In applications.
4. Interface elements needed to activate guidance and control algorithms to support a wide variety of ADS-B In applications.
5. The presentation of guidance and control information as needed to support a wide variety of ADS-B In applications.
6. The presentation of messages and alerts associated with or produced by the guidance and control algorithms.
7. Appropriate heuristics to govern the activation and interaction of guidance and control algorithms.
8. Optionally, display elements supporting the integration of the MPCDTI with other avionics systems; e.g., traditional guidance and control, navigation, data communication, and weather detection systems.

B. Key Elements of the MPCDTI

There are four key elements that act as the building blocks of the MPCDTI.

1. Elemental Functions
2. Simultaneous Enablement
3. Automatic Algorithm Selection
4. Output Arbitration

1. Elemental Functions

Functions, as defined by this effort, represent the basic building blocks of the MPCDTI. This is a departure from most, if not all, previous CDTI work, in which the MPCDTI's capabilities are organized around individual ADS-B In applications. By defining and developing individual functional capabilities, the CDTI can be used in the context of many applications. This approach limits the number of features the crew accesses, thus reducing complexity.

Industry, government, and academia have proposed and developed, to various levels of maturity, over 200 proposed ADS-B In applications. CAASD conducted a review of these applications and identified the features needed on the CDTI to support each application. The required features of each application provide a notional understanding of the algorithms needed to drive the features. By grouping similar display features and driving algorithms, it is possible to come up with a relatively short list of functional capabilities to support a fairly large subset of the proposed ADS-B In applications.

Figure 1 illustrates the relationship between ADS-B In applications, MPCDTI functions, and display features. The left column represents the range of ADS-B In applications. Clearly, this is not a comprehensive list. The applications shown share a common characteristic in that they might use speed guidance to maintain a desired interval with an aircraft that ownship would be assigned to follow. It is possible to structure a "Space Function" that provides appropriate speed commands for each of the proposed applications it supports. The flight crew interacts with the Space Function in the same way regardless of the application being conducted. There are also multiple elemental functions capable of producing speed guidance for the crew to follow. The speed guidance is presented to the crew in the same manner regardless of the function providing it. Descriptions of the thirteen elemental functions are provided in Appendix A.

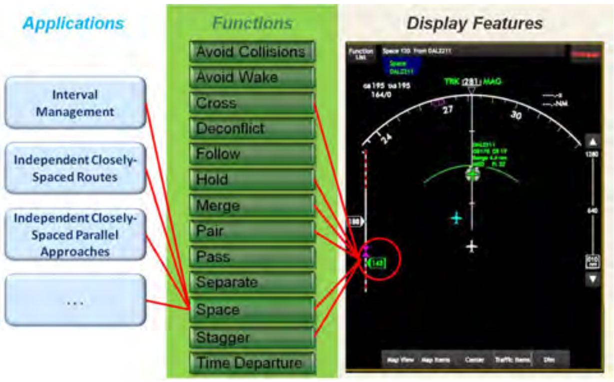


Figure 1. Relationship between Applications, Functions and Display Features.

When the user first attempts to select a foreground function, the MPCDTI creates an instance of that function. The instance will contain all of the data needed to operate the function. During its life-cycle, the function can be placed in one of the following operating modes at any given time:

1. **OFF**: This is a virtual mode and represents the function prior to its instantiation, i.e. when it does not yet exist.

2. **SELECTED**: In this mode, the user can configure all inputs to the function. The function continually validates the inputs and gives feedback. When all of the function's requirements for validity and sufficiency of inputs have been met, the MPCDTI allows the user to attempt to arm the function.

3. **ARMED**: In this state, the function continually checks for the requirements for the computation of guidance to be met. The requirements are in addition to the requirements for validity and sufficiency of inputs needed for arming. If the requirements for engagement are met and the MPCDTI does not detect any conflicting engaged functions, the MPCDTI places the function in the ENGAGED mode.

4. **ENGAGED**: In the ENGAGED mode, the function is operating fully. Although some functions may provide non-guidance outputs in other operating modes, the ENGAGED mode is the only mode in which guidance is provided.

5. **SUSPENDED**: In the SUSPENDED mode, the necessary conditions for the computation of guidance are no longer met. The function continues to operate and may provide non-guidance outputs, which the MPCDTI may display.

6. **DONE**: The DONE mode is a transient mode and serves to mark the function for deletion by the MPCTI.

Figure 2 illuminates the manner in which function mode transitions are achieved in the MPCDTI. By requiring each function to follow a standard convention of operating modes and transitions between those modes, the MPCDTI can encompass a means of exercising control over mode transitions.

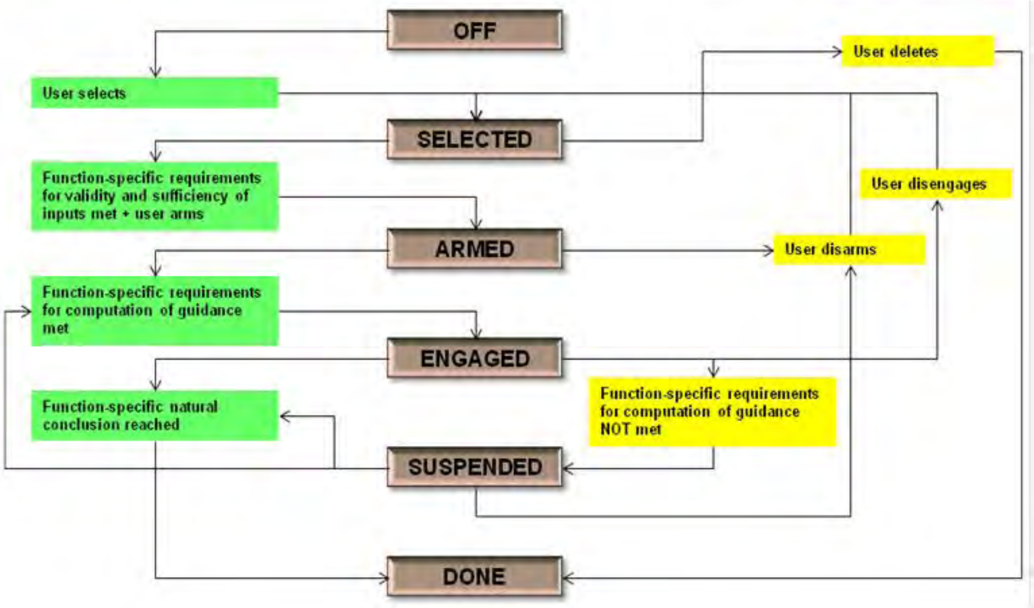


Figure 2. Mode Transitions for Foreground Functions

2. *Simultaneous Enablement*

Some ADS-B In applications will need to access more than one function. The MPCDTI makes this possible, but also applies heuristics to prevent the simultaneous operation of functions whose objectives are incompatible. Each function contains the requisite knowledge to determine that a mode transition would be appropriate or needed from the perspective of that function alone. The MPCDTI uses this information, as well as its understanding of the operating status of other instantiated functions to decide whether or not to allow the mode transition to proceed. In controlling the mode transitions of instantiated functions, the design of the MPCDTI pursues the following objectives.

1. Prevent the simultaneous engagement of functions with incompatible objectives.
2. Prevent the simultaneous engagement of functions for which compatible solutions are not guaranteed in the general case.
3. Prevent the simultaneous engagement of functions whose concurrent engagement, although theoretically capable of producing a solution, is nonetheless deemed operationally undesirable.

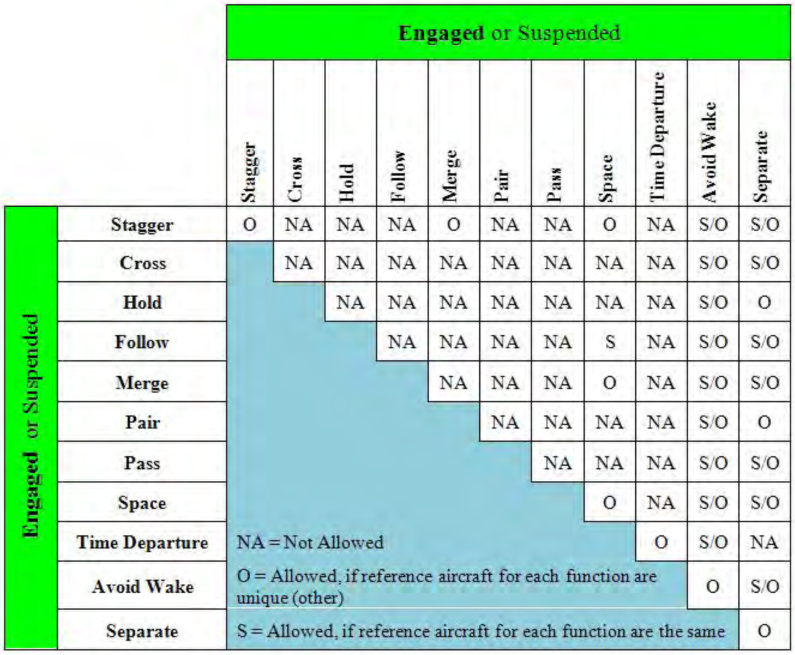
A rule base provides one means of realizing the necessary control of mode transitions. Whereas its specifics can certainly be debated, Figure 3 demonstrates one such rule-base. The MPCDTI uses the following additional rules to govern the simultaneous operation of multiple function instances.

1. The number of functions allowed to exist in the selected mode is limited only by the ability of the user interface to provide the user access to those functions. It may, however, prove desirable from a human-factors perspective to further limit this number.
2. The MPCDTI does not provide the user the means to arm a function until sufficiency and validity of user inputs have been established.
3. The number of functions allowed to exist in the armed mode is limited only by the ability of the user interface to provide the user access to those functions.

4. The MPCDTI places an armed function in the engaged mode, if the function reports that all requirements for the computation of guidance are met and no incompatible engaged or suspended functions exist (Figure 3). By including suspended functions in its consideration, the MPCDTI prevents the displacement of a function that ought to have been operating by a function that may have been intended for engagement at a later point.

5. The MPCDTI suspends any engaged function that reports that one or more requirements for the computation of guidance are no longer met.

6. The MPCDTI engages any suspended function that reports that all requirements for the computation of guidance are once again met.



		Engaged or Suspended										
		Stagger	**Cross**	**Hold**	**Follow**	**Merge**	**Pair**	**Pass**	**Space**	**Time Departure**	**Avoid Wake**	**Separate**
Engaged or Suspended	**Stagger**	O	NA	NA	NA	O	NA	NA	O	NA	S/O	S/O
	Cross		NA	NA	NA	NA	NA	NA	NA	NA	S/O	S/O
	Hold			NA	NA	NA	NA	NA	NA	NA	S/O	O
	Follow				NA	NA	NA	NA	S	NA	S/O	S/O
	Merge					NA	NA	NA	O	NA	S/O	S/O
	Pair						NA	NA	NA	NA	S/O	O
	Pass							NA	NA	NA	S/O	S/O
	Space								O	NA	S/O	S/O
	Time Departure									O	S/O	NA
	Avoid Wake										O	S/O
	Separate											O

NA = Not Allowed

O = Allowed, if reference aircraft for each function are unique (other)

S = Allowed, if reference aircraft for each function are the same

Figure 3. Rule Base for Simultaneous Engagement

3. Automatic Algorithm Selection

The body of research to date has yielded multiple algorithms that can produce the guidance and other outputs expected from the elemental functions.[17,18] Appropriately conceived automation within the MPCDTI can choose the most appropriate algorithm based on a number of factors including crew inputs to or external configuration of the function, relative geometries of the aircraft involved, data available to support the operation, and the configuration of ownship's other automation systems.

In many cases, the objectives of a function can be pursued (to varying degrees of success) by choosing any one from among a number of algorithms that have been developed for relevant functional capabilities. At a high level, two considerations determine the most appropriate algorithm to generate the requested guidance.

1. The availability of input data: Different algorithms may require different types of input data to support their computations. A determination of what input data is available can help to inform the choice of algorithm.

2. The nature of the desired operation: The manner in which the user configures the function, i.e. the objectives the user articulates through the user interface and the context within which the function will operate can favor one algorithm over another.

An example of automatic algorithm selection for a merge operation is provided in Appendix B.

4. Output Arbitration

In cases where multiple functions producing the same type of output have been enabled, the MPCDTI uses heuristics to allow it to choose the most appropriate value to display to the flight crew. For example, eight of the thirteen functions are capable of providing speed guidance and some of those are allowed to operate simultaneously. In the case that at least two functions producing speed commands are enabled, the MPCDTI would choose the most appropriate speed command and display it to the crew. In some instances, the information one function produces may come into conflict with another, and in that case, the most appropriate result of proper arbitration may be suppression of all function outputs.

Functions may provide alerts, ranging from simple status information to cautions and even warnings. Clearly, it would not do to present status information in such a way as to preclude the presentation of an active warning message. The MPCDTI arbitrates the available function outputs using the following rules:

1. Function Priority Rule: The Avoid Collisions function has priority over all other functions. While this function only provides guidance in exceptional cases, when it does provide guidance, any guidance provided by other functions is suppressed in favor of guidance coming from Avoid Collisions. The suppressed guidance includes guidance that may not be in the same dimension as the guidance produced by Avoid Collisions. When Avoid Collisions no longer provides guidance, presumably because the threat of collision has abated, suppressed guidance is once again made available.

2. Lowest Speed Rule: Engagement criteria for functions capable of providing speed commands include a requirement for ownship to be operating, or to be projected, behind the reference aircraft. Therefore, when two functions producing speed guidance are operating simultaneously, the lower speed command can be chosen without an unwanted proximity to one of the reference aircraft developing. This may not allow the performance objective for the function providing the higher speed command to be met.

3. Message Rule: The design for the presentation of conditional messages has not yet been fully considered. A priority system will likely become necessary to ensure that the necessary salience is achieved for critical messages.

C. Design Prototype and Experimental Results

A prototype has been designed and integrated with the flight-deck simulator in CAASD's Air Traffic Management Lab. Using the prototype, a human-in-the-loop (HITL) study was performed. More background on the prototype, the graphical user interface, and the HITL study will be presented in a future paper.

IV. Defining Requirements: The Functional Approach

A. Traditional ADS-B In Applications Requirements Definition

Requirements for the functioning of avionics are developed in order to ensure that applications can meet their operational objectives while maintaining target levels of safety. ADS-B In application maturity currently varies from concept descriptions to certified and fielded operations. The more mature applications have gone to the level of specifying requirements for the quality of the data needed to support them. Where guidance algorithms are needed, either performance requirements, or the specific algorithms, have also been provided.[19]

Two standards organizations, in particular, serve as examples of the process of requirements definition. In the United States, RTCA, Inc. provides a focal point for stakeholders to come to consensus on a host of issues related to aviation applications in general, and, more specifically, ADS-B In applications. The European Organization for Civil Aviation Equipment (EUROCAE) provides a similar function in Europe. For ADS-B related standards, the two bodies frequently interact through a construct called the Requirements Focus Group (RFG), which provides a forum for further refinement of ideas, as well as the harmonization of requirements in an international context.[7] The RFG has published Safety and Performance Requirements (SPR) documents for three ADS-B In applications: (1) ADS-B in Non-Radar Airspace,[20] (2) In-Trail Procedure in Oceanic Airspace,[21] and (3) Enhanced Visual Separation on Approach.[22] Documents articulating the requirements for other applications are currently under development.

RTCA document DO-264/EUROCAE ED-79a, "Guidelines for Approval of the Provision and Use of Air Traffic Services Supported by Data Communications," outlines procedures used to guide the development of data communications applications and the determination of requirements associated with those applications.[23] While the document places special emphasis on performance requirements for communications elements, it has been used by RTCA to provide a context for the development of ADS-B In application requirements.

Before the requirements determination process can be begin, there must be agreement on the ADS-B In applications to be developed. This decision frequently rests with a different group than the one charged with the actual requirements development work. Once an ADS-B In application has been chosen, the RFG uses a consensus-based process to define the exact nature of the application through the crafting of a document called an Operational Services and Environment Definition (OSED). The OSED contains a specific description of the application, including characterizations of the airspace in which the application is applied, air traffic service (ATS) provider and flight deck procedures, and applicable weather conditions. The OSED is accompanied by an Operational Performance Assessment (OPA), which defines performance requirements during nominal operations, and an Operational Safety Assessment (OSA), which identifies hazards and failure modes and articulates operational safety requirements.

The OSED, OPA, and OSA are synthesized in a Safety and Performance Requirements (SPR) Standard which derives, among other things, technical requirements for individual components of the envisioned system. Finally, the Interoperability Standard (INTEROP) provides the necessary framework to ensure that individual components of the envisioned system can act in concert to realize the goals of the envisioned ADS-B In application.

The process of deriving standards and requirements is frequently iterative. Issues discovered during the writing of the OPA and OSA can, for example, inform revisions to the OSED. The goal is to ultimately achieve consensus on technical and operational requirements derived from a fully articulated ADS-B In application.

B. Proposed Functional Approach for Developing MPCDTI Requirements

Whereas the aviation industry as a whole has not yet achieved wide-spread consensus on a time line strategy for fielding ADS-B In applications, some trends in the types of capabilities needed to support future ADS-B In applications have begun to emerge. The elemental functions presented earlier in this paper constitute a proposed set of capabilities that would support a wide range of ADS-B In applications in various stages of development.

As a first step towards developing functional capabilities at the elemental level, the aviation industry would need to achieve a consensus on which capabilities need to be supported. While this paper proposes one potential set of elemental functions, reviews by stakeholders may yield a different set. As an example, recent application development has shown the potential need for a set of measurement and monitoring capabilities not included in the original design presented here.[21] The process of identifying the required capabilities would benefit from the stakeholders' accumulated applications-development experience. The aviation industry is currently much further along in understanding which capabilities will be needed than when the processes for ADS-B In application development were pioneered.

Once the desired functional capabilities have been identified, performance and safety requirements for each capability can be developed. Previously developed SPR documents (including OSEDs and INTEROPs) may be used to drive the performance and safety requirements for the functional capabilities in order to develop overall performance and safety requirements for the MPCDTI. The result of this effort could lead to an entirely new approach to developing ADS-B In applications, as future applications would be built upon MPCDTI functional capabilities and performance and safety requirements. This shift could be considered analogous to when application developers no longer dictated the required performance of GPS for their application, but rather assumed the documented performance of GPS in their analyses.

The broader impact of this shift is the expedited process of fielding new ADS-B In applications. Basing applications on a standard MPCDTI functional framework would eliminate the need for new equipment and additional certification for each new application, which is a major benefit to operators.

V. Function-based Requirements: Challenges and Open Research Topics

Several open research questions are posed to the aviation industry stakeholders. Answers to these questions will provide direction to future research on the MPCDTI and its place in future ADS-B In applications.

What is the minimum set of descriptors that define a function for the purposes of deriving safety and performance requirements?

The traditional ADS-B In applications development process starts with a complete description of the application. The aviation industry will have to come to consensus on a reduced set of descriptors that capture those characteristics of the function that are likely to be relevant to multiple, potential ADS-B In applications.

What is lost by deriving safety and performance requirements outside of the applications context?

Some specificity would be lost as functions will be designed to achieve a more generic goal than would be the case if the needs of an entire application were being considered. For example, ADS-B In application development can provide mitigations for sub-optimal performance of avionics functions through procedural means. Because the procedural means may not be known in a functional approach, there is a risk that mitigations may be developed within the avionics that could be addressed by other, potentially less costly means. Aviation industry stakeholders should clearly understand the impact of pursuing a functional approach for ADS-B In applications development.

What performance do we require of guidance functions in order to ensure safe operations?

The main challenge will be to consider the use of the guidance function in sufficiently general terms to ensure that all of its potential uses remain safe. This is necessary because constraints on the use of the function, traditionally captured in the OSED, will not be available. In addition, the safe functioning of the MPCDTI will need to consider the interaction of its elemental functions.

What performance can be expected of guidance functions in order to realize the envisioned benefits?

There is a subtle, yet important difference between designing guidance functions to be safe and designing those same functions to realize a set of targeted benefits. The targeted benefits would appear to be a characteristic of a specific application and it is not yet clear how a lower bound on performance of a function could be specified without knowledge of the application's needs.

How does the nature of the ADS-B In applications development process change given the functional approach?

Before the functional approach can be applied to the definition of the avionics functions needed to constitute the MPCDTI, stakeholders need to develop the process by which the avionics will be certified. In addition, the path to the approval of ADS-B In applications requiring those avionics, needs to be developed.

Which known requirements can simply be adopted?

The aviation industry has already identified safety and performance requirements for a number of applications. Those requirements do not become any less valid as a result of the functional approach and an appropriate analytic process could show which requirements could simply be incorporated into the MPCDTI as currently articulated. In addition, the derivation of new functional requirements needs to consider whether or not it remains imperative to ensure that requirements already articulated will be met by the MPCDTI.

What happens when it becomes apparent that a function cannot meet a proposed application requirement?

It is conceivable that a function designed and perhaps even fielded cannot meet the requirements of a newly articulated ADS-B In application. The ADS-B In applications development process and the functional approach need to incorporate appropriate means for revisiting safety and performance requirements. In addition, avionics architectures may benefit from adequate provisions for updating and certifying functions as the need arises.

VI. Conclusions

This paper presented an overview of a Multi-Purpose Cockpit Display of Traffic Information (MPCDTI). The MPCDTI has been designed to enable the flight crew to manage multiple applications, thus justifying the cost of equipage through versatility. Elemental functions have been defined based upon a wide range of potential ADS-B In applications. Applications can then be built by simultaneously enabling the requisite elemental functions. An automatic-algorithm-selection element chooses the most appropriate algorithm based upon user inputs amongst other factors, and output arbitration determines the output to the flight crew based upon operational goals, airborne conflicts, and in some cases, conflicting solutions. Feasibility of the MPCDTI concept may promote the development of future applications using a functional approach to develop a common set of safety and performance requirements.

A. Elemental Functions

This appendix presents the elemental functions defined for this MPCDTI. Whereas these functions provide the capabilities needed to support a wide range of ADS-B In applications, it could certainly be possible to identify an alternative set of functions that, in combination, would yield the same ability to support ADS-B In applications. For example, due to their similarities, one may combine the Space, Pair and Stagger functions into a single function.

The names given these functions are in some cases similar to the names of the ADS-B In applications they support. The names were not chosen for that reason, however, but rather because it was thought that a controller instruction that would lead to the use of a function would make use of all or part of the function name. A given function may or may not provide all of the capabilities required by an ADS-B In application of a similar sounding name. In some cases, the need for a function is apparent, but the specifics of its operation are not yet fully developed.

A. Avoid Collisions Function

Avoid Collisions is a background function and is active at all times. This function maintains awareness of the use of other functions and is capable of adjusting its parameters as needed to support other functions in use. For example, with the Pair function engaged, collision avoidance can detect conditions under which ownship's position relative to the reference aircraft guarantees collision avoidance and suppress the collision avoidance functions for that aircraft. When a collision threat is detected, appropriate cautions and warnings are issued and escape guidance is given, if appropriate. This function includes surface operations. Escape guidance suppresses any other guidance provided by the MPCDTI. It may further be possible to expand the volume of protected airspace that the Avoid Collisions function seeks to avoid to include that volume of airspace impacted by wake turbulence.

B. Avoid Wake Function

This is a foreground function, meaning that the flight crew activates it. The MPCDTI provides a display of lateral and vertical track history of the reference aircraft. If sufficient environmental and wake generation data are available, the MPCDTI provides a display of lateral and vertical track history adjusted for expected propagation and dissipation of wake vortices.

C. Cross Function

The Cross function aids ownship in achieving a desired lateral or vertical spacing with another aircraft at a fix. The desired spacing is achieved using speed control alone. The operation terminates when ownship reaches the fix.

D. Deconflict Function

This function comprises conflict detection, conflict resolution and conflict prevention. Potential conflicts are detected and displayed, and resolutions are presented. The resolutions are also conflict-free. Pilots may select a resolution. The function may optionally provide an interface to communicate the selected resolution to onboard navigation systems. It would likely be desirable to deselect (automatically or manually) the Deconflict function in airspaces where air traffic services are provided.

E. Follow Function

The MPCDTI provides guidance or suitable display features to assist ownship in following the lateral, and optionally, the vertical path of the reference aircraft. The user may specify a lateral and/or vertical offset from the reference aircraft's path. If an offset has been specified, the MPCDTI provides guidance for the offset path. Display features intended to assist the lateral and vertical following tasks may include depictions of recorded path data for the reference aircraft. It may be possible to assume some level of history in cases where insufficient track history exists to support the following task.

F. Hold Function

The MPCDTI provides speed guidance to position ownship to exit holding at a specified spacing interval behind either the aircraft holding at the next lower holding altitude or a specified reference aircraft. The MPCDTI may optionally provide lateral guidance so that ownship can match the designated aircraft's holding pattern. In addition, the MPCDTI may provide a cue as to when the next lower altitude has become available. If neither ownship nor the reference aircraft has reached the holding fix, the Hold function will provide speed guidance in a manner similar to the Merge function.

G. Merge Function

The MPCDTI provides speed and/or heading guidance to ownship to achieve a position behind the reference aircraft at a merge fix or point. Both aircraft may or may not be proceeding directly to the same fix. The MPCDTI determines the merge point, if no merge fix is provided. If a merge fix has been provided and ownship is not tracking toward the fix, the MPCDTI computes the point at which ownship should turn toward the merge fix, so that no speed change will be required in order to achieve the desired interval at the merge fix. The Merge function automatically transitions to the Space function after ownship passes the merge fix/point, unless the Hold function is armed at the same fix, in which case it transitions to the Hold function.

H. Pair Function

The MPCDTI provides speed guidance as in the spacing function. However, the target spacing value is computed on the basis of ownship's and the reference aircraft's planned final approach speeds. In addition, forward and aft in-trail boundaries are computed to guarantee collision and wake turbulence protection. These boundaries are displayed on the MPCDTI. Should the aircraft maneuver outside of the boundaries a breakout maneuver is required. It may be desirable to annunciate the need for a breakout in this case.

I. Pass Function

Ownship passes the reference aircraft either in front, behind, above, or below. The MPCDTI provides lateral guidance in the cases of pass in front and pass behind. The MPCDTI provides vertical speed or flight path angle guidance in the cases of pass above and pass below. As the Pass function may require the aircraft to maneuver in either the horizontal or the vertical plane, adherence to a previously defined trajectory cannot be guaranteed. The Pass function terminates after ownship has passed the closest point of approach to the reference aircraft.

J. Separate Function

This function is intended for use in cases where ATC has delegated separation responsibility to ownship's flight crew. The MPCDTI provides features specifically designed to aid in the maintenance of adequate separation, as well as appropriate alerts when separation minima have been or are likely soon to be violated.

K. Space Function

The MPCDTI provides speed guidance to maintain a spacing interval with the reference aircraft. The user may specify an interval in terms of time or distance. The Space function allows the user to specify a lateral offset as an option. Ownship conformance will be checked against the offset. If the Follow function is engaged, the Space function will assume the same offset that the Follow function is using.

L. Stagger Function

The MPCDTI provides speed guidance to ownship to maintain the desired stagger value, or specified diagonal distance, from the reference aircraft operating on a parallel route, approach or departure path. If ownship and the reference aircraft are not operating on parallel tracks, or if the tracks of the two aircraft are offset by more than the stagger value, the Stagger function checks for flight plan data from both aircraft. If the data are available and indicate that a parallel segment with an offset no less than the stagger value exists, then the algorithm attempts to achieve the desired stagger value by the time ownship reaches the parallel segment.

M. Time Departure Function

The MPCDTI detects the start of the reference aircraft's takeoff roll and starts a countdown timer. Ownship must initiate its takeoff roll prior to the expiration of the timer. The governing time interval would be either selected by the crew or retrievable from a database. The countdown timer disappears when ownship begins its takeoff roll. Should ownship not begin its takeoff roll within the allotted time, the crew is alerted.

B. Algorithm Selection for the Merge Function

Guidance to achieve a desired interval, expressed in terms of time or distance, behind the reference aircraft at a fix or point has been developed to support a variety of potential ADS-B In applications.[17,24–26] The details of how and when the desired interval will be achieved vary from application to application and may be subject to the following considerations.

1. Is a specified interval to be achieved at all, or is the only requirement to merge behind the reference aircraft?
2. Do the flight paths of ownship and the reference aircraft converge at a constrained fix?
3. Is the desired interval to be achieved at the first point of convergence of the flight path of ownship and the reference aircraft or at the runway threshold?
4. Will ownship proceed directly to the merge fix or point or will it follow a known, non-direct trajectory?
5. Will the reference aircraft proceed directly to the merge fix or point or will it follow a known, non-direct trajectory?
6. Should ownship begin varying speed immediately to achieve the desired interval or should ownship maintain current speed and a heading that diverges from a direct line to the merge fix - so as to increase the expected interval - until such time as a turn toward the merge fix will yield the desired spacing?

While it is conceivable that one would require the user to answer each of these questions explicitly while configuring the Merge Function, the following clues may be used to determine the required answers.

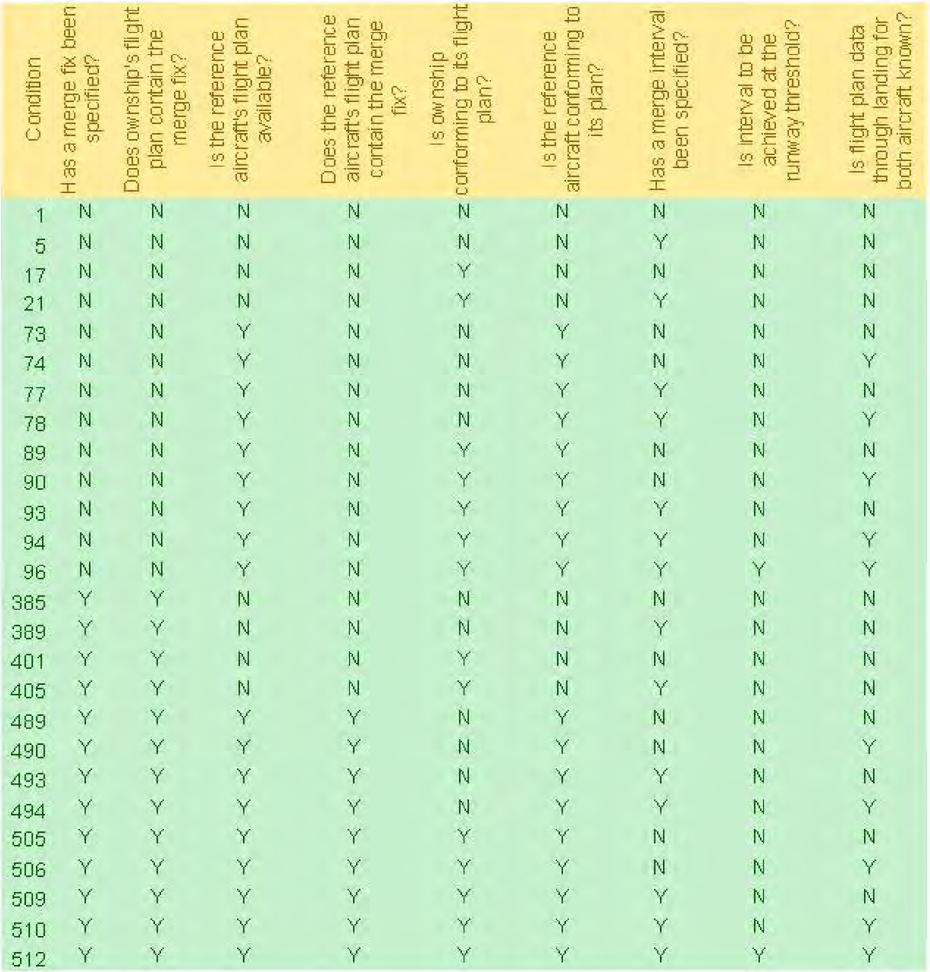
1. Has the user specified a merge fix? In terms of the Merge Function, the merge fix is an optional parameter.
2. Is the flight plan of the reference aircraft available in some form, e.g.: by assumption, transmission of ADS-B intent data, or data communication?
3. If a merge fix has been specified, does ownship's flight plan contain the merge fix?
4. If a merge fix has been specified, does the reference aircraft's flight plan contain the merge fix?
5. Is ownship conforming to its flight plan? This is determined by checking against limiting cross-track and track-angle errors and the configuration of the autoflight system (LNAV mode).
6. Is the reference aircraft conforming to its flight plan?
7. Has the user entered a desired interval?

8. Has the user entered final approach speed data for both ownship and the reference aircraft?
9. Does the available flight plan data specify a satisfactory trajectory from present position to the landing threshold for both aircraft? This list relies on explicit inputs to answer three of the nine questions. The remaining six questions are answered on the basis of context and do not required user intervention.

The nine questions, listed above and shown in Figure 4, if considered to be truly independent, would yield 512 possible combinations. In fact, however, the questions are not independent and many combinations are internally inconsistent. For this reason, the following combinations were eliminated from the set of 512:

1. all combinations that would require that ownship's flight plan contain the merge fix when none has been specified;
2. all combinations that would require the reference aircraft's flight plan to contain the merge fix when none has been specified;
3. all combinations that would require the reference aircraft's flight plan to contain the merge fix when that flight plan is not available;
4. all combinations that would require the reference aircraft to be conforming to its flight plan when that flight plan is not available;
5. all combinations that would require achieving the desired interval at the landing runway threshold when the available flight plan data terminates prior to the landing threshold;
6. all combinations that would require achieving the desired interval at the landing runway threshold when no interval has been specified;
7. all combinations for which a merge fix has been specified, but ownship's flight plan does not contain the merge fix (it may be possible to relax this restriction);
8. all combinations for which a merge fix has been specified, but the reference aircraft's flight plan does not contain the merge fix (it may be possible to relax this restriction);
9. all combinations requiring flight plan data that extends to the landing runway when no flight plan data of any kind is available;
10. all combinations for which the flight plan of the reference aircraft is available and the reference aircraft is not conforming to that flight plan (it may be possible to relax this requirement; however, further work needs to be done to prove that the reference aircraft's intentions can be accurately established through an alternative means);
11. all combinations for which ownship is not conforming to its flight plan and the interval is to be achieved at the landing threshold, since it would not be possible to accurately model the expected trajectory;
12. all combinations for which the reference aircraft is not conforming to its flight plan and the interval is to be achieved at the landing threshold, since it would not be possible to accurately model the expected trajectory; and,
13. all combinations for which the merge interval is to be achieved at the runway threshold and no merge interval has been specified (this has been done to preclude the possibility of the aircraft arriving at the runway with inadequate inter-arrival spacing).

The 26 remaining combinations are each unique and therefore require some level of algorithmic variation in order to satisfy the associated constraints. By examining the questions defining the combinations, the MPCDTI can select the most appropriate algorithm automatically, without the need for an explicit decision from the user.



Condition	Has a merge fix been specified?	Does ownship's flight plan contain the merge fix?	Is the reference aircraft's flight plan available?	Does the reference aircraft's flight plan contain the merge fix?	Is ownship conforming to its flight plan?	Is the reference aircraft conforming to its plan?	Has a merge interval been specified?	Is interval to be achieved at the runway threshold?	Is flight plan data through landing for both aircraft known?
1	N	N	N	N	N	N	N	N	N
5	N	N	N	N	N	N	Y	N	N
17	N	N	N	N	Y	N	N	N	N
21	N	N	N	N	Y	N	Y	N	N
73	N	N	Y	N	N	Y	N	N	N
74	N	N	Y	N	N	Y	N	N	Y
77	N	N	Y	N	N	Y	Y	N	N
78	N	N	Y	N	N	Y	Y	N	Y
89	N	N	Y	N	Y	Y	N	N	N
90	N	N	Y	N	Y	Y	N	N	Y
93	N	N	Y	N	Y	Y	Y	N	N
94	N	N	Y	N	Y	Y	Y	N	Y
96	N	N	Y	N	Y	Y	Y	Y	Y
385	Y	Y	N	N	N	N	N	N	N
389	Y	Y	N	N	N	N	Y	N	N
401	Y	Y	N	N	Y	N	N	N	N
405	Y	Y	N	N	Y	N	Y	N	N
489	Y	Y	Y	Y	N	Y	N	N	N
490	Y	Y	Y	Y	N	Y	N	N	Y
493	Y	Y	Y	Y	N	Y	Y	N	N
494	Y	Y	Y	Y	N	Y	Y	N	Y
505	Y	Y	Y	Y	Y	Y	N	N	N
506	Y	Y	Y	Y	Y	Y	N	N	Y
509	Y	Y	Y	Y	Y	Y	Y	N	N
510	Y	Y	Y	Y	Y	Y	Y	N	Y
512	Y	Y	Y	Y	Y	Y	Y	Y	Y

Figure 4. Rule Base for Simultaneous Engagement

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