Towards Defining Required Interval Management Performance

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Abstract*—Interval Management (IM) is an airborne spacing concept that provides precise inter-aircraft spacing relative to another aircraft. The IM concept is currently being developed by the FAA and in Europe under SESAR through standards and local implementation plans. The IM system is comprised of a ground-based component (GIM) and a flight-deck-based component (FIM). The FIM component involves the use of avionics, called the FIM equipment, which provides speeds to the IM aircraft that will achieve and/or maintain a desired spacing interval relative to a target aircraft. IM operations are expected to provide benefit in a variety of environments with a wide-range of operational objectives, where the performance characteristics of the FIM equipment needed for each IM operation may vary. Such variation leads to the identification of a performance-based approach to ensuring that the overall longitudinal spacing performance, termed the IM tolerance, is met to satisfy operational objectives in the required environments. This paper presents the concept of Required Interval Management Performance (RIMP) to be used in the design, management, and certification of IM operations. RIMP is a categorization scheme, comprised of four components−the IM tolerance, the quality of the IM and target aircraft state data, the performance of the speed control algorithm in the environment, and unique functional capabilities. The combination of these components uniquely identifies the performance required for a given IM operation. Initial analysis and standards development has shown that a few discrete performance levels for each of these components is possible and may sufficiently span the performance needed to support both near-term and longer-term IM operations. The analytical methodology used to determine the RIMP type for an IM operation developed thus far is presented, and further development is proposed. The analysis developed to date is applied to two example IM operations, and direction for future work is provided. Coordination within the user community to further develop and analyze the RIMP concept, in the context of a robust set of IM operations, is the next step.

Keywords*−*Interval Management, Airborne Spacing, NextGen.

I. Introduction

Due to projected increases in air traffic over the next decade, several efforts have been undertaken to improve the efficiency of the National Airspace System (NAS). Traffic Flow Management (TFM) concepts that better utilize NAS resources when controllers are managing traffic flows are being explored. Time-Based Flow Management, for example, broadly describes the use of trajectory prediction on the ground to determine Estimated Times of Arrival (ETAs) and the ability of aircraft to more precisely fly their trajectories determined by the Flight Management System (FMS) in order to meet Scheduled Times of Arrival (STAs) throughout the NAS [1], [2].

Improving the efficiency of operations in the terminal area has received particular attention. Reducing the variability of inter-aircraft spacing in the terminal area leads directly to increases in throughput [3], and decision support tools aiding the controller in sequencing, merging, and spacing aircraft–and the flight-deck avionics that support the flight crew in the same tasks–are being explored as a means to provide this reduction while also reducing controller workload. The division of capability and responsibility for sequencing, merging, and spacing tasks between ground-based and flight-deck-based systems, is an important question and is the topic of past studies [4], [5]. Spacing accuracy is seen to improve when the aircraft are equipped with avionics that aid in spacing when compared to controller tools alone.

Research into airborne spacing concepts, which employ the use of flight-deck avionics to manage the spacing relative to another aircraft, has been ongoing for several decades. EUROCONTROL and NASA Langley Research Center, for example, have evaluated airborne spacing concepts for terminal-area spacing in fast-time simulation environments, human-in-the-loop studies, and field testing [6]–[9]. Additionally, United Parcel Service has certified and field tested avionics for airborne spacing in their arrival operations at Louisville International Airport [10].

Growing out of this and other past research, the concept of Interval Management (IM) is currently being developed by the Federal Aviation Administration (FAA) for near-term implementation supporting NextGen. Similar plans exist in Europe under SESAR. IM provides precise timing within the airborne traffic flow by managing the relative spacing interval between a target (lead) and an IM (trail) aircraft, and thus increases the efficiency of a variety of air traffic operations. The IM system is comprised of an airborne component and a ground component. The airborne component of IM, Flight-deck Interval Management (FIM), includes avionics onboard the IM aircraft, called the FIM equipment, which derives longitudinal speed guidance that will achieve and/or maintain a desired spacing interval relative to the target aircraft assigned by the air traffic controller. A speed control algorithm in the FIM equipment determines the speeds of the IM aircraft as a function of IM and target aircraft states (i.e., horizontal position, vertical position, and horizontal velocity) and possibly other information about the environment. The IM aircraft is defined as being equipped with FIM equipment and, thus, is capable of participating in IM operations. The ground component of IM, Ground-based Interval Management (GIM), makes use of prediction tools on the ground, as well as the increased precision provided by FIM, to efficiently manage the spacing interval between aircraft within multiple environments and operations. In addition, GIM assists controllers in setting up the FIM operation by providing speed updates to meter aircraft to a point where the FIM operation begins. A primary enabler of the IM concept is the expected widespread deployment of ADS-B Out and ADS-B In.

The precise spacing made possible by FIM, and managed by GIM, is expected to enable IM operations with varying operational goals, such as managing a schedule across sectors, enabling Optimized Profile Descents (OPDs), increasing throughput to a runway, and metering to a departure fix. IM operations are unified in concept and procedural design, but the scope of environments in which benefits are expected results in a range of performance. Initial analysis of a set of near-term IM operations confirms these performance differences [11], and the authors believe that further analysis of a broader set of IM operations will reinforce this variation.

A performance-based approach to characterize individual IM operations, termed Required Interval Management Performance (RIMP), enables the development and management of IM operations in the airspace, which have varying operational goals and changing operational environments. The association of a RIMP type to each operation enables the management of the total system performance needed to satisfy operational goals. The total system performance is specified by the 95% longitudinal spacing accuracy, referred to as the IM tolerance. The RIMP type includes the IM tolerance and the performance and functional capabilities of the FIM equipment that ensure that the IM tolerance is met in the operating environment.

The analysis which determines the RIMP type is seen as an important ingredient to the establishment of IM operations in general. It drives FIM equipment requirements, certification standards, and provides guidance in operational design and approval. The analysis is currently under development, with initial results beginning to be established. This paper focuses on both the derivation of overall system performance captured by the IM tolerance, and the lower-level performance of the FIM equipment that ensures that the IM tolerance is met.

In this paper, the methodology and proposals for future direction and development are presented. The main topic of the paper, the RIMP concept and associated methodology, is defined in Section II. The components of the RIMP type are detailed in Section III, including analyses that have been developed to date and the proposed methodology for future analyses. In Section IV, the RIMP concept is applied to two example IM operations. Open issues and conclusions are presented in Sections V and VI, respectively.

II. Required Interval Management Performance

An IM operation requires a longitudinal spacing precision, called the IM tolerance, that satisfies operational goals. The IM tolerance is derived from the system perspective, and is a measure of the allowable deviation from the desired spacing interval. The magnitude of this deviation is based on what is needed to meet operational objectives, but is also limited so that the controller trusts that the IM system is operating within nominal bounds. The IM tolerance represents the bounds on the fault-free spacing precision that is achieved and/or maintained 95% of the time by the IM aircraft implementing the speeds determined by the FIM equipment. The fault-free spacing precision is assumed to be modeled by a Gaussian distribution, which is a reasonable assumption for the analysis, but further validation of this assumption should be performed in future work.

The GIM component relies upon the precision described by the IM tolerance to meet operational goals, and the FIM equipment onboard the IM aircraft makes use of the IM tolerance to manage the spacing interval during the IM operation. As with other performance-based metrics, the analysis and framework that would be provided by RIMP would ensure that the IM tolerance is met in the IM operation.

The IM tolerance and associated allocations of the IM tolerance to state data errors and the performance of the speed control algorithm in the assumed operating environment define the performance metrics for an IM operation and are included in the RIMP type. In addition, it is possible that the level of FIM equipage will be mixed, and that the controller may need to differentiate IM aircraft according to additional functional capabilities (e.g., an ability to handle complex IM and target aircraft route geometries). The RIMP type is comprised of a combination of discrete performance levels for each of the following four components:

- the IM tolerance to be met,
- the required performance of the state data,
- the required performance of the speed control algorithm in the assumed operating environment, and
- additional functional capabilities of the FIM equipment.

To meet the IM tolerance, a sufficiently high performance level of the state data is required by the speed control algorithm for calculating the speed commands. State data performance describes the accuracy and integrity of the IM and target aircraft state data (i.e., horizontal position, vertical position, and horizontal velocity measurements obtained through surveillance reports from the target aircraft and sensors onboard the IM aircraft), including latencies in the use of the state data and update intervals between surveillance reports from the target aircraft. Furthermore, the speed control algorithm must provide speed commands that correct deviations in the spacing interval well enough that the IM tolerance is achieved and/or maintained in the assumed operating environment. Initial analysis indicates that a few discrete performance levels defined for the state data and the speed control algorithm will cover the needed performance of the spectrum of IM operations. Discretization of the IM tolerance value defining the RIMP type is also likely feasible and desirable. The range and number of IM tolerance values will be informed by the analysis of more IM operations.

Furthermore, certain IM operations may require the FIM equipment to have functional capabilities which may not be implemented in all instantiations of FIM equipment. For example, an IM operation may require the knowledge and use of final approach speeds, or to acquire and use complex route geometries for the IM and target aircraft. The RIMP type, and an IM aircraft's certification to support different RIMP types, provides a way that the controller may manage functional differences in FIM equipage when conducting IM operations. Here again, a few discrete levels of functional capabilities are envisioned. The determination of these levels is expected as an outcome of pending benefit and cost decisions to be made by the aviation community.

The RIMP type and associated analysis have the potential to be used in a number of ways.

- The ground domain may use RIMP as a means for the categorization and management of IM operations. RIMP provides a way to assign IM operations appropriately, and to easily adapt to changing environmental conditions or operational goals.
- Pilots may use the RIMP type when initiating and conducting the IM operation and as part of their situation awareness.
- Operational designers establishing the airspace and procedures for an IM operation may work within the defined and available bounds provided by the RIMP types. Fully developed, the RIMP analysis will provide a direct relationship between bounds on the operating environment and fundamental operational objectives.
- Avionics manufacturers may consider the RIMP types in the design of FIM equipment. Final categorization of the RIMP components establishes requirements on the FIM equipment which directly relate to the benefit provided by the supported IM operations.
- Certification authorities may use RIMP for operational approval of an IM operation and certification of the associated FIM equipment to be used.

In collaboration with the user community, the determination of discrete performance levels associated with each of the four components of RIMP–IM tolerance, state data quality, speed control algorithm performance, and functional capabilities–and consequently, the overall set of RIMP types is underway. The determination and specification of RIMP types is expected to continue as the initial set of IM operations and FIM equipment are developed, analyzed, and ultimately fielded. It is proposed that once this set of performance levels is established, FIM equipment is built and certified to perform to them, and there is some experience with their combination in fielded IM operations, they should be systematically applied to the design and certification of future IM operations. In particular, IM operations designed after the approval of FIM equipment standards may leverage the RIMP types and analysis to ensure that previously certified FIM equipment can be used to support new IM operations.

The performance analysis underlying the RIMP concept and the direction for its development are detailed below. In the next section, the four components of RIMP are discussed in greater detail. The methodology for determining the IM tolerance for a given IM operation is provided in Section III.A. In Section III.B, the allocation of the IM tolerance and determination of state data and speed control algorithm performance levels are described. Finally, the determination of the RIMP type resulting from analysis of an IM operation is described in Section III.C. It is important to note that, while the methodology described is based on past research and current standards development, it is intended to be used as a starting point for the development of a certified concept for the NAS. In particular, operational input from controllers, pilots, Air Navigation Service Providers (ANSPs), and other stakeholders is one of the next steps in the maturation of the RIMP concept, and may lead to realignment of the analytical methodology.

III. Components of RIMP

A. Operationally-Required Tolerances

The operationally-required tolerances (ORTs) are used to model the operational objectives for a given IM operation. Two quantities comprise the ORTs: the nominal spacing bounds and the controller intervention threshold. Both of these quantities relate to bounds on the deviation from the desired spacing interval.

The nominal spacing bounds relate the operational goals to a nominal spacing performance curve, assumed to be described by a Gaussian distribution for simplicity. The nominal spacing performance is the actual longitudinal spacing interval that is achieved and/or maintained in the presence of nominal state data errors and environmental effects. The mean and standard deviation of the performance curve are chosen such that the deviation from the desired spacing interval meets the operational goals under fault-free conditions. Generally, faulted conditions correspond to the tails of the error probability distribution; therefore, the standard deviation is specified by an observable bound, typically between 90% and 99.9%.

The controller intervention threshold is a theoretical threshold, which if crossed, will cause the controller to intervene in the IM operation. For spacing operations, where controllers are monitoring for separation, it is proposed that in at least 99.9% of non-faulted IM operations, the deviations from the desired spacing interval do not exceed the bounds defined by the controller intervention threshold. For IM operations where an increased complexity demands greater controller trust in the IM aircraft's ability to negotiate the environment, a more stringent constraint on the likelihood of breaching the controller intervention threshold may be necessary.

Extrapolating the nominal spacing performance to its 99.9% bound may demonstrate that the controller intervention threshold is respected under fault-free conditions. Alternatively, the controller intervention threshold may over-constrain nominal spacing performance and hence drive the IM tolerance. In high-complexity IM operations, monitoring or alerting functions in the FIM equipment may be designed to meet more stringent constraints or to mitigate off-nominal conditions.

Fig. 1 illustrates the ORTs in the context of an IM operation. Whereas performance curves defined by the nominal spacing bounds and the controller intervention threshold may be established independently, a single Gaussian distribution representing the nominal spacing performance in the assumed operating environment is determined to respect both constraints. The IM tolerance is defined to be the 95% bound on the nominal spacing performance.

B. *Allocations of the IM Tolerance*

Uncertainty in the actual states of the IM and target aircraft directly leads to reduced spacing precision. Similarly, increased uncertainty in the operating environment corresponds to increased deviation from the desired spacing interval. The IM tolerance is thus allocated to: 1.) the performance of the IM and target aircraft state data and 2.) the performance of the speed control algorithm in the assumed operating environment. These allocations provide top-down performance budgets for setting FIM equipment requirements, allowing the two effects to be managed independently.

The allocation process is iterative meaning that an initial conservative allocation is made to the most stressing and uncertain component: the speed control algorithm in the operating environment. The resulting allocation left for the state data performance is used as a top-down budget for those performance requirements. Any budget left after setting the state data performance is re-allocated to the speed performance in the environment.

1) IM Tolerance Allocation to State Data Performance: Uncertainties in the IM and target aircraft positions and velocities arising from latencies and measurement errors result in errors in the calculated spacing interval that the IM aircraft is acting upon. A conservative model of the uncertainty in the spacing interval determined by the FIM Equipment as a result of errors in the state data has been established [11]. The model is independent of the particular implementation of speed control algorithm. From the top-down budget of the IM tolerance allocation to state data errors, requirements may be set on the individual parameters (e.g., horizontal position accuracy and horizontal velocity accuracy) that satisfy the allocation.

The application of this model to provide a measure of the spacing interval uncertainty attributable to state data errors depends only on the expected ground speeds of the IM aircraft. In reference [11], this model for state data errors has been applied to an initial set of IM operations, and two discrete state data performance levels were found to be sufficient for the initial set of operations. These two performance levels are expected to support most near-term IM operations. Whereas the first two performance levels differ only in horizontal position accuracy, additional performance levels may arise from future analysis and may further constrain other parameters, such as horizontal velocity accuracy, vertical position accuracy, or latency.

2) IM Tolerance Allocation to Speed Performance in the Assumed Operating Environment: Operational uncertainties such as winds, turns, descents, and varying aircraft performance characteristics lead to deviations in the longitudinal spacing interval from the desired spacing interval. The fundamental concept behind FIM is the provision of speed commands derived by the speed control algorithm to counteract these environmental effects. As the environment increases in severity or complexity, it is expected that the performance of the speed control algorithm in the environment will be reduced resulting in a less precise spacing interval. In the same environment, a higher performing speed control algorithm will provide a more precise spacing interval. In this way, the assumed operating environment for an IM operation is related to the performance of the speed control algorithm, and an allocation of the IM tolerance is ascribed to this factor.

As has been partly established for the state data performance, it is expected that a set of discrete performance levels for the speed control algorithm will emerge in the initial set of IM operations. Higher performance levels will provide greater precision in the spacing in the presence of operational uncertainties. It is proposed that the performance levels be differentiated by bounds on the closed-loop performance of the IM aircraft when following speeds determined by the speed control algorithm.

Whereas the allocation to the speed control algorithm performance in the assumed operating environment specifies the accuracy within which the spacing interval must be achieved and/or maintained, there are other considerations when specifying the speed performance levels. In some IM operations, strings of aircraft will be formed, where each IM aircraft is spacing relative to its preceding aircraft in the string while also acting as a target aircraft for its trailing aircraft in the string. When strings of IM aircraft are formed, a disturbance, arising from an operational uncertainty, to one IM aircraft may propagate along the string such that the deviations in the spacing intervals and the magnitudes of speed commands to correct these deviations increase along the string. Therefore, to provide efficient performance in these types of IM operations, the string performance of the speed control algorithm must also be considered when establishing the speed performance levels.

In references [11] and [12], the closed-loop response of the IM aircraft to speed commands is related to a second-order system, which is parameterized by damping ratio and the aircraft's response to a new speed. Upper and lower bounds on these parameters are a promising metric for the performance levels associated with the speed control algorithm, as they are easily testable and constrain the system both in terms

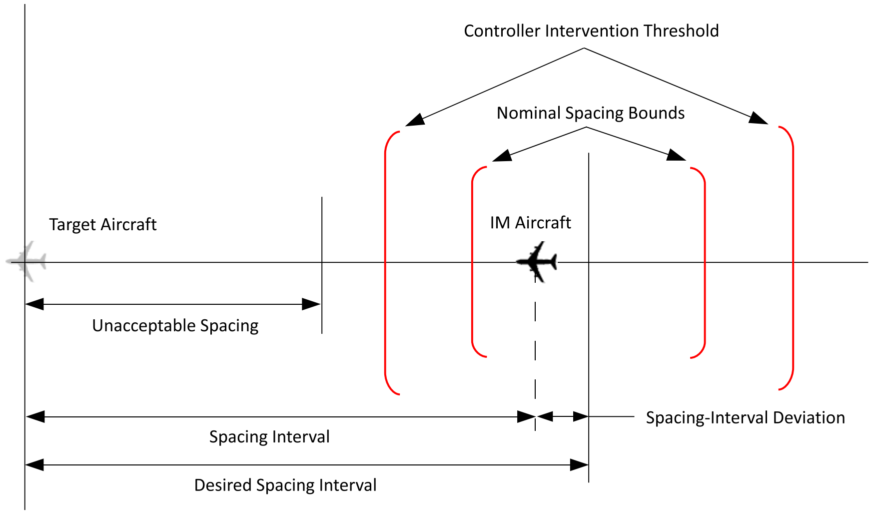

Fig. 1. Depiction of the Nominal Spacing Bounds and Controller Intervention Threshold in an IM Operation.

of meeting the allocation of the IM tolerance and ensuring efficient string behavior.

Analysis has shown that acceptable string behavior can be achieved by increasing the damping ratio such that the system is over-damped, which limits the propagation of disturbances along the string. A lower bound ensures good string behavior, where IM aircraft cannot correct deviations in the spacing interval more quickly than the lower bound.

An upper bound prevents the IM aircraft from correcting deviations from the desired spacing interval too slowly. There are two considerations in specifying an upper bound: the upper bound ensures that the desired spacing interval is achieved and/or maintained within the IM tolerance in the assumed operating environment, and the closeness between the upper and lower bounds promotes interoperability between different speed control algorithm implementations.

Fig. 2 illustrates the upper and lower bounds on the correction of the deviation from the desired spacing interval; the evolution of the deviation is shown when correcting a 5-second initial spacing-interval deviation relative to a target aircraft flying at a constant speed. In the figure, each bound is characterized by a damping ratio and an aircraft response to a new speed. The lower bound is less damped than the upper bound and assumes a faster aircraft response.

Characterizing the assumed operating environment by the operational uncertainties that are expected in the IM operation is one approach towards establishing the different speed performance levels. For a fixed performance level (i.e., upper and lower bounds on damping ratio and aircraft response), the response curves can be generated for each operational uncertainty expected in an IM operation and used to predict the ability to achieve the IM tolerance at that performance level.

The specific means for relating the assumed operating environment and the speed performance level in the establishment of the RIMP type requires further research and validation.

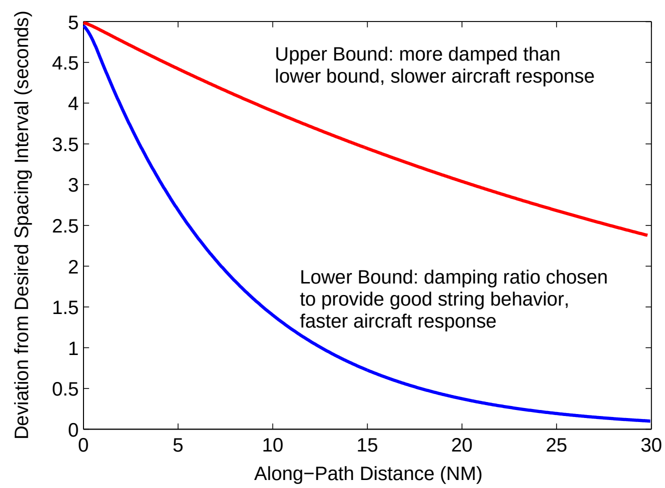

Fig. 2. Upper and lower bounds on the correction of a deviation in the spacing interval from the desired spacing interval. The IM aircraft is correcting an initial five-second deviation relative to a target aircraft flying a constant speed.

Validation of the speed performance levels in assumed operating environments, for example, by fast-time simulation, is an important step in establishing the relationships between the performance levels and the operating environments.

The variation found in the environment and IM tolerance requirements of the IM operations studied to date is noteworthy. This variation indicates that requiring all FIM equipment to perform at the most stringent speed performance levels only would lead to inefficient performance as the IM aircraft would in some cases be unnecessarily working towards a tighter IM tolerance than that specified by the ORTs. The most flexible FIM equipment would be certified for all defined speed performance levels, which would provide the most efficient performance in all IM operations. Further research on the interoperability of FIM equipment using dissimilar speed performance levels is needed and is discussed in Section V.

As in the case of state data performance, a closed-form analysis of the spacing uncertainty that results from the combination of operating environment and speed control algorithm with a given performance level is seen as a useful ingredient in the RIMP methodology. This would provide an analysis that is independent of a specific speed control algorithm implementation. Furthermore, an analytical process for relating the speed performance level to the assumed operating environment provides a flexible framework for determining the performance level needed for a new IM operation without extensive validation.

Further development is necessary to establish certifiable performance metrics that provide a guarantee of achieving the IM tolerance. Depending upon how the assumed operating environment is defined in conjunction with the performance levels, a set of bench tests can be expected to be the mechanism for certifying FIM equipment to a given speed performance level. It is likely that these bench tests will be exhaustive, ranging from verification of simple input responses to required performance in simulated environments.

C. Establishing the RIMP Type

The RIMP type for an IM operation is comprised of the IM tolerance, the performance levels of the state data and the speed control algorithm that guarantee the IM tolerance in the assumed operating environment, and any special functionality required by the FIM equipment. Fig. 3 depicts the process involved in establishing the RIMP type. A feedback loop is included, as indicated by the dashed lines, to allow the IM tolerance or the IM tolerance allocations to be adjusted should it be found that the IM operation is not viable during the validation step.

IV. RIMP Methodology Applied to Example IM Operations

The RIMP methodology is applied to two example operations to illustrate the derivation of the IM tolerance and the allocation process to the state data errors and the performance of the speed control algorithm in the assumed operating environment. These are notional examples intended to show the application of the ORT metrics in the derivation of the IM tolerance, as well as the allocation process.

The required FIM equipment performance would be determined from the established performance levels, described in Sections III.B.1 and III.B.2 such that the performance levels respect the IM tolerance allocations.

A. Example 1

The first example is an IM operation used to achieve the desired inter-aircraft spacing at a waypoint in the terminal area. Given a sequence and scheduled times of arrival at the waypoint, the controller determines the desired spacing intervals needed between each aircraft at the waypoint. The operational goal is to limit drift in the schedule to ± 2 minutes,

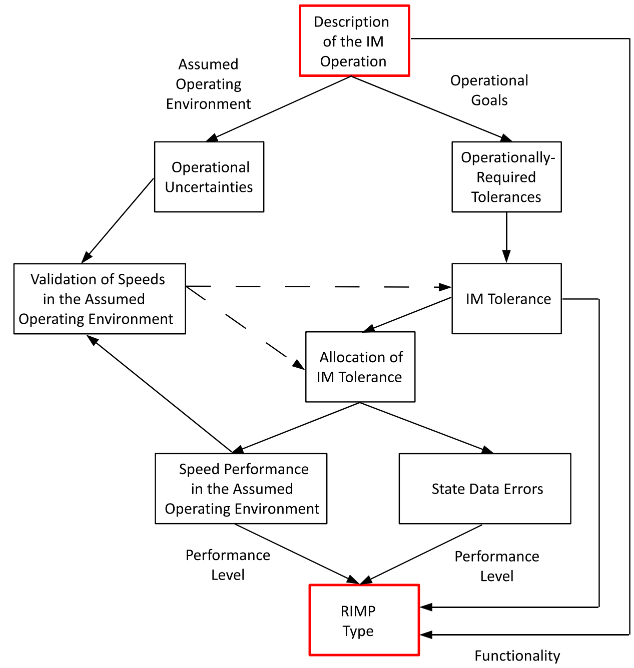

Fig. 3. Determination of the RIMP type from the description of the IM operation.

95%, per hour of operation, and the controller intervention threshold is modeled to be one-third of the desired spacing interval.

1) IM Tolerance: Assume that N aircraft are scheduled to arrive over the next hour. The time for N aircraft to cross the terminal-area waypoint in an hour is described by the random variable Y in eq. 1, where Δ_i is the desired spacing interval of the ith aircraft relative to its target aircraft, and X_i is a Gaussian-distributed random variable with standard deviation σ representing the deviation in the actual spacing interval from the desired spacing interval at the waypoint. The X_is are assumed to be independent, identically-distributed random variables.

$$\begin{aligned} Y &= (\Delta_1 + X_1) + (\Delta_2 + X_2) + ... + (\Delta_N + X_N) \\ &= \sum_{i=1}^{N} \Delta_i + \sum_{i=1}^{N} X_i \\ &= 3600 \text{ seconds} + \sum_{i=1}^{N} X_i \end{aligned} \tag{1}$$

The random variable Y is also Gaussian distributed with a mean of 3600 seconds and a standard deviation of $\sqrt{N}\sigma$.

The standard deviation corresponding to the nominal spacing bounds on the individual aircraft spacing precision that satisfies the operational goal of limiting the variation of Y to 120 seconds, 95%, is determined by the following expression.

$$\sigma = \frac{120 \text{ seconds}}{1.96\sqrt{N}} \tag{2}$$

To reconcile the 99.9% bound on performance defined by the nominal spacing bound with the controller intervention threshold, the following inequality is verified for each desired spacing interval Δ_i.

$$3.29\sigma < \frac{\Delta_i}{3} \tag{3}$$

Assume that the desired spacing interval between aircraft is 120 seconds, resulting in an average of 30 aircraft crossing the waypoint per hour. The resulting value of σ from eq. 2 is 11.2 seconds, which respects the controller intervention threshold, as per the inequality in eq. 3.

However, in the case of 40 aircraft scheduled to cross the waypoint in an hour and a desired spacing interval of 90 seconds along the string, the controller intervention threshold drives the performance needed. The standard deviation that satisfies the operational goal is 9.7 seconds from eq. 2, but a value of σ equal to 9.1 seconds is required to satisfy eq. 3. The resulting IM tolerance of 17.9 seconds is used for the rest of example 1.

2) IM Tolerance Allocations: An initial allocation is made to the speed performance in the assumed operating environment. Because the relationship between the IM operation and the assumed operating environment has not yet been established, the initial allocation to the speed performance is determined based on previous IM-related studies in the literature. Speed control algorithms for IM-related concepts have been tested in fast-time simulation environments, human-in-the-loop experiments, and field testing with different environments of varying complexity. References [7] and [8] found that the spacing precision ranged from 6.0 to 10.0 seconds, 95%, using fast-time simulations.

An initial conservative allocation of 13.0 seconds is made to the speed performance in the assumed operating environment, from which the state data error budget is then determined.

$$\text{State Data Error Budget} = \sqrt{(\text{IM Tolerance})^2 - (\text{Speed Performance Budget})^2}$$

$$\text{State Data Error Budget} = \sqrt{(17.9\text{ sec})^2 - (13.0\text{ sec})^2} = 12.3\text{ sec}$$

The state data error budget is met for Performance Level 1, as defined in reference [11], where state data for the IM and target aircraft have a horizontal position accuracy of 0.3 NM and a horizontal velocity accuracy of 10 m/s; update rates and latencies in the target aircraft state data are assumed for the expected surveillance source (e.g., ADS-B, ADS-R, or TIS-B). For a target aircraft equipped with ADS-R, the bound on the spacing interval uncertainty is 6.6 seconds. This value is found using the conservative model of the spacing interval uncertainty resulting from state-data errors described in reference [11]. The remainder of the state data error budget is re-allocated to the speed performance resulting in a 16.6-second budget for the speeds in the environment.

The speed performance in the assumed operating environment must be validated to show that the 16.6-second budget is met. Initially, fast-time simulations of a baseline implementation will be performed to demonstrate viability of the IM operation.

3) RIMP Type: This example is used to illustrate the process of determining the performance needed for the IM operation described. The RIMP type for this IM operation will be comprised of an IM tolerance of 18 seconds, state data performance level 1, the appropriate speed performance level, and no additional airborne functionality above the baseline functionality.

B. Example 2

The second example is an IM operation for arrival spacing to achieve a desired throughput of 30 aircraft per hour at the runway threshold. This is a more complex IM operation to analyze than the IM operation in example 1, and this example is intended to show the applicability of the ORT metrics and RIMP analysis to IM operations with different operational objectives. This type of operation is planned for near-term implementation.

1) IM Tolerance: The IM tolerance for an arrival operation is determined in order to achieve the desired throughput at the runway threshold. The IM operation is terminated at the final approach fix (FAF) when the aircraft begins its deceleration to its final approach speed; therefore, the IM tolerance is determined at the FAF such that the operational goal is achieved at the runway threshold.

Throughput at the runway threshold is a function of the mean inter-aircraft spacing, or the average desired spacing interval, set during a sequence of consecutive IM operations. In this operation, the desired spacing intervals are set such that wake vortex minimum separation is respected in 99.9% of operations, under fault-free conditions. The nominal spacing bounds for each individual IM operation in the sequence are modeled by a Gaussian distribution with mean equal to the desired spacing interval and standard deviation equal to $\sigma_{threshold}$.

The controller intervention threshold is modeled to be at the wake vortex minimum separation. The modeling of the nominal spacing bounds already ensures that this threshold is appropriately respected under the assumption that nominal spacing performance is Gaussian. Additional measures such as alerting may be required for robustness, for example, if the IM operation involves particularly volatile wind conditions.

It is assumed that the arrival operation is comprised of a mix of aircraft categories, and the minimum (time-based) spacing intervals between aircraft pairs are shown in Table I. The spacing intervals are derived based upon wake-vortex separation standards and representative final approach speeds for the different aircraft categories.

The desired spacing interval is set so that one side of the two-sided 99.9% bound, or 3.29 times $\sigma_{threshold}$, is the wake vortex minimum separation. The matrix w is a representation of the spacing intervals in Table I, where the column index represents the target aircraft category in the pair, and the row

TABLE I
TIME-BASED WAKE VORTEX MINIMUM SEPARATION (SECONDS)

		Target Aircraft		
		Heavy	B757	Large
IM Aircraft	Heavy	110	110	84
	B757	126	78	78
	Large	136	113	86

index represents the IM aircraft category in the pair.

$$Spacing\ Interval_{threshold} = w + 3.29\sigma_{threshold}, \text{ where}$$

$$w = \begin{bmatrix} 110 & 110 & 84 \\ 126 & 78 & 78 \\ 136 & 113 & 86 \end{bmatrix}$$

For an assumed aircraft-type mix, the average spacing interval $\bar{t}_{threshold}$ at the runway threshold can be determined.

$$\bar{t}_{threshold} = \sum_{i=1}^{3}\sum_{j=1}^{3} Spacing\ Interval_{threshold}(i,j)p(i)p(j)$$

Here, $p(i)$ for i = 1,2,3, is the probability of a heavy, a B757, or a large aircraft, respectively, in the sequence. The throughput at the runway threshold is determined from the average spacing interval.

$$throughput_{threshold} \text{ (aircraft/hour)} = \frac{3600}{\bar{t}_{threshold}}$$

To determine the throughput at the runway threshold, the following aircraft-type mix is assumed: $p(1)$ = 0.10, $p(2)$ = 0.70, $p(3)$ = 0.20; e.g., there is a 70% probability that a B757 is next in the sequence. Fig. 4 shows the throughput at the runway threshold for different values of the standard deviation $\sigma_{threshold}$. The intersection of the curve and the 30 aircraft per hour throughput shows that a standard deviation of 9.0 seconds meets the operational goal.

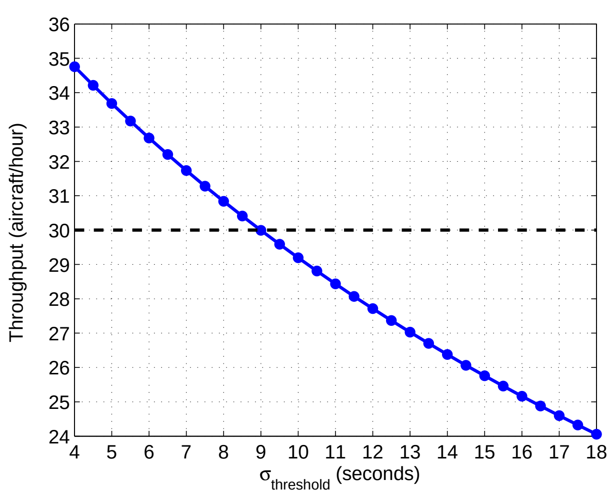

Fig. 4. Throughput at the runway threshold given different values of the standard deviation $\sigma_{threshold}$.

Because the IM operation is terminated at the FAF, the controller provides the IM aircraft with the desired spacing interval to be achieved at the FAF such that the spacing interval needed at the threshold is achieved. The desired spacing interval at the FAF is a function of the times that it takes for the IM and target aircraft to fly from the FAF to the threshold, where the times are computed assuming planned final approach speeds, decelerations to the final approach speeds, and wind speeds between the FAF and the threshold. Therefore, the IM tolerance needed at the FAF is a function of the 95% bound on the spacing at the runway threshold and the 95% bound on the uncertainties in the times for the IM and target aircraft to fly from the FAF to the threshold, modeled by a Gaussian distribution with standard deviation σ_T.

$$\text{IM Tolerance} = \sqrt{(1.96\sigma_{threshold})^2 - (1.96\sigma_T)^2}$$

These uncertainties are a result of errors in the planned final approach speeds, decelerations to the final approach speeds, and winds used to determine the desired spacing interval at the FAF. To determine σ_T, the flight times for the IM and target aircraft from the FAF to the threshold, T_{IM} and T_{target}, respectively, are modeled as independent, identically-distributed random variables. Monte-Carlo analysis is used to determine the standard deviations of T_{IM} and T_{target}, where the final approach speeds are assumed known within 5 knots, 95%, the decelerations are assumed known within 0.15 knots/second, 95%, and the wind is assumed known within 10 knots, 95%. The standard deviations of T_{IM} and T_{target} are 5.2 seconds from which σ_T is determined [11].

$$\sigma_T = \sqrt{\sigma_{T_{IM}}^2 + \sigma_{T_{target}}^2} = 7.4 \text{ sec}$$

Therefore, an IM tolerance of 10.2 seconds is needed at the FAF.

2) IM Tolerance Allocations: As described in the first example, an initial allocation is made to the speed performance in the assumed operating environment. References [8] and [13] found that the spacing precision at the runway threshold ranged from 7.5 to 10.0 seconds, 95%, determined from fast-time simulations and human-in-the-loop experiments. An initial allocation of 8.0 seconds is made to the speed performance in the assumed operating environment, from which the state data error budget is determined to be 6.3 seconds.

The state data error budget is met for Performance Level 2, as defined in reference [11], where state data for the IM and target aircraft have a horizontal position accuracy of 0.1 NM and a horizontal velocity accuracy of 10 m/s; update rates and latencies in the target aircraft state data are assumed for the expected surveillance source. For a target aircraft equipped with ADS-B, the bound on the spacing interval uncertainty is 4.8 seconds [11]. The remainder of the state data error budget is re-allocated to the speed performance budget resulting in an 9.0-second budget for the speeds in the environment.

Again, the speed performance in the assumed operating environment must be validated to show that the allocated 9.0-second budget is respected.

3) RIMP Type: The RIMP type for this IM operation will be comprised of an IM tolerance of 10 seconds, state data performance level 2, the appropriate speed control performance level, and no additional airborne functionality above the baseline functionality.

If the IM operation had higher throughput goals at the runway threshold, the FIM equipment may require knowledge of the IM and target aircraft final approach speeds in order to better predict trajectories from the FAF to the runway threshold. In this case, the added functionality to know and use final approach speeds would be included in the RIMP type along with the appropriate IM tolerance and performance levels to support the tighter IM tolerance.

V. Open Issues and Future Work

Through a motivation of the RIMP concept, and an account of its definition at present, this paper provides a framework for determining the performance needed for an IM operation. This framework has been built upon technical developments; however, further development and backing within the community is needed. A program for completing the development begins with the analysis of an initial set of IM operations. A broad set of IM operations should be chosen to populate RIMP types from which the discrete breakdown of the four components may be identified.

Specifically, the determination of speed performance levels and their interaction with the operational environment needs the most development and validation. The authors believe that the following program of study will be fruitful:

- Complete the analysis of operational uncertainties, initiated in reference [11]. The list is not currently exhaustive (e.g., the inter-aircraft precision provided by GIM in the set-up of the FIM operation has not been studied).
- Analyze IM aircraft response to operational uncertainties as a function of algorithmic performance parameters (e.g., the performance bounds defined by damping ratio and aircraft responsiveness).
- Characterize the assumed operating environment of the IM operation by its operational uncertainties.
- Combine the above into an analysis which translates the assumed operating environment to the achievable precision for a given performance of the speed control algorithm.

To mirror the analysis that is developed for the allocation of the IM tolerance to state data performance, this would yield an analytical tool that relates the allocation of the IM tolerance to a performance level of the speed control algorithm and a parameterized assumed operating environment. The proposed analysis should be conducted in the context of a set of expected IM operations, and fast-time simulations should be conducted for validation.

The determination of performance levels for the other three components of RIMP will be more straightforward. As stated previously, the closed-form analysis for the state data performance is established and application to a set of IM operations, beyond what has already been done, will complete the delineation of performance levels. Similarly, different levels for the IM tolerance will become apparent as the IM operations are analyzed as described. Finally, groupings of functional performance levels are an implementation decision, and will be based on the community's consideration of a set of beneficial IM operations.

In addition to determining the RIMP types from analysis of a set of IM operations, the question of efficient string behavior in the context of performance levels of the speed control algorithm should be answered. In particular, it is to be determined whether different speed performance levels are inter-operable along the string in the same IM operation. If not, then it may be a further restriction for the FIM equipment to be operating strictly at the specified performance level, rather than at or above.

VI. Conclusions

A methodology was proposed for determining the Required Interval Management Performance (RIMP) needed to satisfy operational goals, and from which FIM equipment performance requirements are derived, given a specific IM operation and an assumed operating environment. From the proposed methodology, RIMP types are derived which are comprised of the following four components:

- the spacing precision needed in the IM operation to meet operational goals,
- the required performance of the state data provided by the IM and target aircraft and used by the FIM equipment to calculate speeds,
- the required performance of the speed control algorithm in the assumed operating environment, and
- additional functional capabilities of the FIM equipment.

The RIMP types describe the performance needed for an IM operation, and this categorization framework may be leveraged by, for example, air traffic controllers managing IM operations with changing operational goals and operating environments and by FIM equipment designers to provide efficient performance as a function of RIMP type. It is expected that discrete performance levels of the state data and the speed performance will be revealed in subsequent derivations of the RIMP types leading to equipment-level testing and certification procedures.

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