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Novel Air Traffic Procedures: Investigation of Off-Nominal Scenarios and Potential Hazards

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The paper demonstrates the development of simulation-based models through which off-nominal conditions in air traffic can be investigated and the corresponding potential hazards can be assessed quantitatively. Primarily, those hazards are studied as they arise due to the introduction of new types of vehicles and novel operational procedures within the Next Generation Air Transportation System; the focus is on the combined effect of new vehicles and new procedures that specifically accommodate those new vehicles. These models are intended to complement any hazard assessment of air traffic that may be conducted qualitatively or via simplified or reduced-order analysis due to limited knowledge at the early stages of research. Such models can provide inputs into the system-level quantitative safety and risk analyses that facilitate developing recommendations for any appropriate new regulatory guidance and standards for vehicles and procedures to be adopted for future air traffic implementation. Two specific scenarios are explored in detail: a helix descent in the presence of failed autopilot, and a steep-descent approach of a slower vehicle sandwiched between two regular approaches with vertical navigation failing during the descent.

Nomenclature

D_H and D_V = horizontal and vertical distance between two aircraft
$L(\mu_L, \sigma_L)$ = lognormal distribution with mean μ_L and standard deviation σ_L
$N(\mu, \sigma)$ = normal distribution
n = load factor
$P(E)$ or P_E = probability of occurrence for event E
$P(E|F)$ or $P_{E|F}$ = conditional probability of occurrence for event E given event F
R = turn radius
$R_{\min}$ = minimum allowed turn radius
$U(u_{\mathrm{LB}}, u_{\mathrm{UB}})$ = uniform distribution with lower bound u_{LB} and upper bound u_{UB}
V = true airspeed
V_C = calibrated airspeed
V_I = inertial speed
$\hat{\mathbf{W}}$ = measured wind velocity vector
$\mathbf{W}$ = wind velocity vector
W_N, W_E, W_D = wind velocity components in the north–east-down reference frame
z = altitude
γ = flight-path angle
$\Gamma(\mu_\Gamma, \sigma_\Gamma)$ = Gamma distribution with mean μ_Γ and standard deviation σ_Γ
Δt_i^s = execution time for the i-th task in the s-th flight segment
Δz^b = altitude measurement bias
θ = wind direction in the north–east reference plane
κ = amplification factor for wind speed
$\lambda(p)$ = time-saving factor due to workload sharing among p pilots
τ = pilot's response time delay
ϕ = bank angle
ψ = heading

I. Introduction

THE National Airspace System (NAS) is a very complex and dynamic system composed of numerous entities: the airspace, airports, air traffic control, vehicles, and other elements. Varying degrees of human and automated processes have roles in the operation of the NAS, both in flying and controlling the individual aircraft as well as in planning and managing traffic flows to ensure an acceptable level of safety and efficiency. The NAS is also subject to an operational environment that is itself dynamic, and any scheduled operational plan may suddenly be altered with little or no decision lead time as a result of changing weather, varying human performance, system degradation, or other uncontrollable or unpredictable factors.

The Joint Planning and Development Office (JPDO) [1], a multi-agency organization chartered to plan and coordinate the transformation of the NAS into a Next Generation Air Transportation System (NextGen) capable of efficiently supporting the expected growth in traffic while ensuring safe and environmentally friendly operations, is proposing many operational and technological changes to the existing air transportation system to satisfy the increased demand as well as meet new engineering challenges. The introduction of novel-concept vehicles and procedures (e.g.,

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continuous-descent approach [2]) within the airspace system poses significant challenges in terms of assessing safety risk due to system degradation, as well as the occurrence of unforeseen problems, human errors, and/or malfunctions arising at a system or subsystem level (e.g., loss of communication with an aircraft, degraded surveillance capabilities, faulty measurement sensors, or others), all of which can lead to deviation from "nominal" operations.

New technologies introduced into the current NAS generally result in incremental changes to the system's operation; their impact on safety is relatively well understood and documented, especially at the vehicle level [3]. Most of the changes can be characterized as a replacement of a component/subsystem with a new one providing the same or superior functionality, and the safety implications of this replacement can be assessed in a modular fashion (effectively, by relating it to the reliability of the replacement without the need to evaluate the safety of the system as a whole). For instance, when hydraulic engine controls were replaced with electronic ones (ultimately leading to full authority digital engine controls [FADEC]), their reliability was required to be at least as good as the original hydraulics implementation, which was ensured by means of redundancy.

In contrast, the NextGen safety assessment provides formidable challenges due to uncertainties about the fundamental systemic changes affecting classes of vehicles, procedures, and the architecture of the national airspace itself. The relative-comparison approaches that are at the core of the current certification procedures are not directly applicable when attempting to demonstrate that new configurations are as safe as the existing one. NextGen is intended to operate under circumstances that would overwhelm the current airspace: in addition to a significantly higher density of operations, considerable growth in flexibility is envisioned, where an increasingly heterogeneous population of vehicles is accommodated while taking advantage of each vehicle's individual characteristics. This leads to amplified safety risks that are especially difficult to quantify. From a qualitative perspective, it is clear that both of the critical parameters of a system that influence safety, complexity and level of coupling [4], will increase. The relationship between those two parameters on the one hand, and safety on the other, as advocated by Perrow [4], stirred a significant controversy, primarily because of lack of clarity in their definition. In the context of NAS safety, both factors can, however, be interpreted in the following fashion:

1) Complexity of a system is related to the amount of information needed to describe it (following a general definition of Kolmogorov complexity expressed as entropy [5]) and, specifically, to the size of the state space representing the system's distinct states pertinent to making decisions that impact safety. This general concept of complexity is closely related but not necessarily identical to the definitions used in the context of air traffic complexity and dynamic density [6] due to the presence of more phenomenological metrics for air traffic complexity. From this perspective, 4-D trajectories tailored to the vehicles' individual properties (e.g., even as simple of a differentiation among aircraft as enabling steeper approaches by slower vehicles) inevitably translate into an increase in complexity.

2) Coupling is often described as the number of links characterizing the dependence of an entity to other units within a system. From a safety perspective, coupling can be interpreted as the time required for disturbances to propagate along those links (effectively their strength) rather than simply the number of links, since the propagation time is related to the time available for mitigation purposes. As a result, any decreased spacing between aircraft directly influences the degree of coupling.

Quantifying the impact of those trends on safety requires an extensive reliance on simulation and a significant overhaul of traditional risk-assessment tools, while relying on their strength when appropriate. At the vehicle level, methods employing fault trees and similar techniques combined with functional-hazard assessment [3] rely on mappings between functional requirements and their physical embodiment, thus facilitating the identification of a vehicle's failure modes. Suchlike methods were used for the vehicle separation safety assessment of the current NAS in the work of Hemm and Busick [7]. Relevant risks that account for the performance characteristics of aircraft and air traffic controllers as well as the environment, both natural (weather and terrain) and pertaining to the air traffic density, can be described using this approach.

However, given the complexity intrinsic in the current NAS as well as the envisioned NextGen framework, a large-scale hazard assessment is a multifaceted problem that requires thorough understanding of the interactions among the various entities comprising the NAS, where reductionist techniques are not deemed sufficient to throughly assess its inherent safety [5]. Those interactions are inevitably time-dependent, so fault trees and similar static tools that rely on Boolean algebra to evaluate overall system risk are not always appropriate for adequately capturing them, which has been recognized as a drawback of existing methods for probabilistic risk assessment [8]. To this end, the use of stochastic petri nets (SPN) and similar discrete-event simulation frameworks [9,10] can provide the needed resolution, but they require quantitative characterization of the timing of relevant basic events as inputs as opposed to the simple cumulative probabilities of events' occurrence that are sufficient as inputs into static tools. An additional challenge stems from the fact that the novel NextGen concepts are at low technology-readiness level and thus are affected by a great amount of uncertainty regarding their performance characteristics, which further complicates the investigation of their impact on a large and multifarious system. This paper is focused on specific hazardous scenarios that were identified as credible in the process of evaluating the proposed novel vehicles or concepts of operation. Those scenarios are implemented using agent-based simulation, where such physics-based simulations of specific off-nominal scenarios can provide a means for establishing appropriate performance requirements for the components of NextGen that are necessary to ensure the desired overall safety levels, provided that a consistent risk allocation has been implemented throughout the system. Furthermore, these requirements would include the reliability and performance characteristics of the individual components.

This study is aimed at providing quantitative insights into the safety of certain new technologies, which can ultimately be transferred upstream into the analysis and design process of NextGen. The paper is organized in five main sections, including this introduction and the conclusion. The second section provides a high-level description of the simulation approach and environment adopted in this research, whereas the third and fourth sections introduce two air traffic scenarios, for each of which a quantitative safety assessment was conducted and statistical results collected. The investigated scenarios examine a cruise efficient short takeoff and landing (CESTOL) aircraft in a helix approach, previously proposed as a potential noise-abatement maneuver [11], and a mixed-operation descent procedure involving three aircraft with distinct performance characteristics, which is being considered as a possible way to increase traffic volume on a particular runway.

II. Analytical Approach

The complex dynamics and level of interactions taking place within such an environment as the NAS makes it difficult to capture the behavior of every single entity (e.g., pilots, air traffic controllers, and others) using classical approaches (e.g., differential equations or centralized control architectures). To this end, the agent-based models provide a means to shift attention from individual systems and entities to their inherent interactions and the environment in which they operate. Many systems are intrinsically, or have further evolved into, large and complex architectures of interoperable parts and players, examples of which can be found in many domains, from complex ecosystems [12] or virtual societies [13,14] to the global economy[¶] [15], or from airlines' economic strategies [16] to the system-of-systems concept [17]. Some characteristics of these types of networks are the presence of open boundaries evolving in time, internal heterogeneity, and high quantitative dimensionality. As a

[¶]Data available online at http://www.icosystem.com [Accessed August 2009].

consequence, unified or centralized approaches may not be appropriate, as they are better suited to describe closed and well structured systems. As an alternative, agent-based techniques exploit the idea of distribution by focusing on system constituents and their behavioral rules at the microscopic level, thus allowing the network's dynamics and the components' integration to emerge at the macroscopic level. Improved system-level robustness, adaptability, and self-organization are some of the resulting features that make agents appealing to engineering integration and management of complex infrastructures. To accomplish its objective, an agent interacts with other agents and the environment by exhibiting a host of qualities such as reactiveness, proactiveness, sociability, learning, in-time evolution, and others. Interactions and heterogeneity within a system generate the need for communication protocols and schemes to optimally resolve conflicts and/or enhance interagent coordination, for which various solutions have been proposed in the literature.

The NAS modeling is characterized by the interaction of various heterogeneous entities, such as aircraft, control towers, or various personnel, spatially distributed. The use of agent-based simulations to assess systemic risks was advocated by Stroeve et al. [18] in the case of a particular runway incursion scenario which considers an aircraft taxiing towards the crossing of an active runway while its crew has inappropriate situation awareness. Besides the intrinsic complexity of such large systems, an interesting point being raised at the simulation phase is the difference in time scale among the various entities: a physics-based model may require a fine time step to guarantee adequate accuracy as it is continuous in time, while a discrete-event model will need to be updated less frequently. As observed by Lee et al. [19], this issue of different time granularity works against the possibility of asynchronous simulation and forces synchronization, especially in the presence of stochastic events for which event times are not known a priori. As an alternative, to guarantee consistency of results, asynchronous simulation with partial resynchronization is suggested, where information and data updates are predicted and occur when necessary.

Disruptions or unforeseen events can cause a series of cascading effects which call for time-critical decisions. Decisions may, however, be hard to agree upon when many competing players are involved. An attempt at modeling such circumstances is offered by Campbell et al. [20] who employed the agent-based model IMPACT (intelligent agent-based model for policy analysis of collaborative traffic flow management) to simulate the decision-making process involving airlines and traffic control authorities in response to weather-due schedule changes. Harper et al. [21] have also conducted similar studies with a focus on the human element in the context of decision making. Pilots, airline dispatchers, and traffic controllers are all modeled using the same agent structure, made up of three units: air traffic situation assessor, collaborative decision-making element, and plan executor, respectively, in charge of collecting and processing current data, resolving traffic issues, and performing plan changes. The SAMPLE (situation assessment model of pilot-in-the-loop evaluation) agent-based architecture for modeling human behavior has been integrated in the FACET (future air traffic management concepts evaluation tool) environment, and principled negotiation has been employed as a means to provide coordination and resolve conflicts between aircraft [21], where a solution is sought by providing communal advantages for all the interested parties. The goal of the study was to establish the need, if any, for negotiation in a complex environment where responsibilities and decisions were decentralized and distributed among the parties, approach which would be needed for the implementation of the free-flight concept.

In light of the aforementioned capabilities, agent-based models provide a means for representing portions of the NAS by realistically modeling four-dimensional aircraft trajectories as well as the actions of pilots and air traffic controllers, oftentimes associated with the presence of trigger-based events and interactions. Therefore, they have been adopted as the natural platform for this type of hazard investigation, where small sections of the overall system of "air traffic" were considered in the modeling environment so as to focus on hazard generators at the aircraft level. The impact upon safety of the uncertainty embedded in the agents, their environment of operation, and their interactions (when modeled) was assessed statistically via Monte–Carlo simulations. The process was applied to two distinct off-nominal scenarios, which are presented next.

III. First Scenario: CESTOL Aircraft on a Helical Descent

This scenario considers the impact of realistic steady-state wind conditions on the ability of the flight crew to revert to manual control. Pilot intervention may occur as a result of the following: wind conditions that exceed the limitations of the flight management system (FMS); a generator or electrical failure in which the equipment providing input to the FMS is lost; a failure of navigational inputs to the FMS; or a degraded state of the FMS itself. While this list of possible avionics-related failures is not exhaustive, the end result is a degradation of control functionality, which ought to be compensated via other means entailing a human intervention. As the state of the art in avionics improves, the root causes of a malfunction may differ, but the consequences in terms of traffic hazards might still be characterized in similar ways.

The constantly changing relative wind to which the aircraft is exposed during the helical descent makes maintaining the planned trajectory under manual control a challenge to the pilots. This is further exacerbated by the CESTOL aircraft's low wing loading relative to the one of conventional jet transports, which causes the vehicle to be more susceptible to wind disturbances. The flight crew's and vehicle's abilities to maintain adequate control necessary for a safe landing and for retaining adequate separation from other traffic flows are evaluated. Specifically, attention is given to the assessment of the likelihood of a hazardous drift of the helical trajectory towards a neighboring path of vehicles operating from adjacent runways and airspace.

CESTOL vehicles are designed to both take off and land in a relatively short distance, while also being able to climb quickly and cruise efficiently. Their capability to operate from shorter runways than required by the current similarly sized aircraft would allow operators to take advantage of currently underused runways and airports. This, in turn, may help alleviate congestion at the larger airports, either by diverting traffic or by decoupling operations.

The CESTOL vehicle under consideration is sized for 100 passengers, and is designed to operate from runways as short as 3000 ft, as well as cruise at Mach 0.78 over a range of 600–2000 nautical miles (depending on whether short takeoff and landing capabilities are used or not). To achieve the 3000 ft landing, this CESTOL design relies on low wing loading ($66\ \mathrm{lb/ft^2}$ versus $129\ \mathrm{lb/ft^2}$ for the Boeing 737–800), advanced airfoil design (e.g., high-speed slotted wing and mission-compliant adaptive wing), and a steep approach (5.5° versus the standard 3° glideslope).

Spiral or helical descents are being evaluated by certain research groups as a noise-abatement procedure and a means for alleviating the high-density airspace surrounding the airport. This sort of approach may contain speed restrictions, crossing-height restrictions, or lateral constraints, depending on the airport configuration. Concerns with these types of descents are associated with maintaining trajectory both vertically and laterally, as well as with the impact of wind conditions, equipment limitations and/or failures, and crew situational awareness in a high-workload environment. Illustrated in Fig. 1 are the redesigned arrival and departure routes for four airports in the New York metroplex [11], including the helical arrivals. This airspace redesign assumes that all traffic is capable of required navigation performance (RNP) 0.3 nautical miles, that vectoring is minimized with adequate metering, and that slower traffic is segregated from nominal flows. As noise-abatement maneuvers, spiral descents were originally designed with constant bank angle (decreasing radius) in the presence of no wind, and were located over the airport to minimize the impact on surrounding communities. Then, they were relocated away from the airspace above the airport to allow for missed approaches and avoid interference with other traffic. Their redesign consisted of a varying

Fig. 1 Decoupled arrival and departure routes for four New York metroplex airports [11].

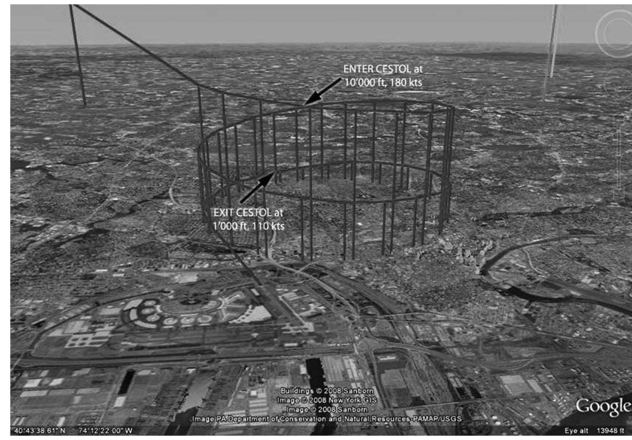


Fig. 2 Helix approach [11].

bank angle and a constant radius to better accommodate engine-out conditions and other failure modes. Consideration is now being given to the specification of only the exit criteria to permit the flight crew and FMS more flexibility.

A. Modeling Assumptions and Analysis

As previously mentioned, the agent-based simulation approach has demonstrated its efficacy and easy implementation in modeling diverse complex systems. In the context of the modeled scenario, the benefits of agent-based modeling have been exploited only to a limited extent, effectively representing a degenerate case that could be modeled without introducing agents. However, the modeling was still conducted in an agent-oriented fashion to allow future expandability and easy integration of other elements of the air traffic framework. The landing procedure has been developed and modeled using the freeware multi-agent simulation environment NETLOGO** [22] (version *3D Preview 5*) from Northwestern University.

In helical-landing mode, the CESTOL aircraft is scheduled to descend with a flight-path angle of $-5.5°$ and a calibrated airspeed that decreases linearly with altitude. In the case of a spiral descent, the turn radius is a function of load factor, flight-path angle, and the vehicle's ground speed, and becomes a dependent performance parameter, whereas it is treated as a requirement and kept constant for a helical descent. Furthermore, assuming the 1.5 nm constant-radius spiral (or helix), the CESTOL aircraft enters the descent trajectory at 10,000 ft above the airport elevation, with a calibrated speed of 180 kt and with a 25° bank angle, and exits the spiral at 1000 ft above the airport elevation, at 110 kt and with a bank angle of $\sim 4°$, at a distance of 1.5–3 nm from the runway threshold (Fig. 2). This additional space from the runway threshold is to permit vehicle stabilization on the glidepath as well as on the localizer. Finally, the aircraft is expected to be in full landing configuration by the time it exits the helix.

With regard to hazard identification, two extreme possible situations can be identified in terms of safety for the surrounding air traffic. In the first case, the flight management system is assumed to be fully functional and capable of compensating for any external disturbance (e.g., wind) in order for the aircraft to land safely and as expected along its designated flight path. In the second situation, a failure in the flight management system forces the pilot to perform the landing procedure manually; hence his/her qualifications, training, recent experience, level of fatigue, and overall ability to compensate for disturbances and anomalies may become critical in terms of safely landing the aircraft in accordance with the regulations and without creating an unstabilized approach or causing a conflict with any approaching traffic. This second circumstance is the basis for the safety assessment of plausible hazards associated with the CESTOL helical-landing procedure.

**Data available online at http://ccl.northwestern.edu/netlogo [Accessed February 2010].

The modeling and simulation environment developed for this traffic scenario, as well as the assumptions feeding into it, are described next in an agent-oriented format.

Agent Definition

An agent is defined as a vehicle plus its corresponding pilot. Two types of agents exist: the CESTOL aircraft performing the helical approach, and conventional aircraft descending along a straight line. Two modules may be thought of as comprising each agent, namely the vehicle and the pilot module.

1) Vehicle module: solely based on kinematics, where the vehicle's state vector includes only its inertial position, flight-path angle γ, bank angle ϕ, and heading ψ. The vehicle's motion is obtained via a time-marching-based integration scheme applied to the inertial velocity vector.

The trajectory of the CESTOL aircraft is divided in three segments:

a) Helical trajectory at $\gamma = -5.5°$, constant turn radius $R = 1.5$ nm, linear V_C profile and consequently varying bank angle ϕ ($V_C = 180$ kts, $\phi = 25°$ at 10,000 ft, $V_C = 110$ kts, $\phi \sim 4°$ at 1000 ft); furthermore, the vehicle will exit at the established altitude regardless of its position and orientation with respect to the runway;

b) Stabilization/transition phase: γ around $-1°$ with path decided by the pilot based on vehicle's location and orientation when exiting the helix;

c) Conventional landing where the flight-path angle γ is not to drop below $-3°$.

The aircraft's kinematics is subject to the following constraints:

a) The load factor $n = \cos(\gamma)/\cos(\phi)$ is not to exceed the limit of 1.15 while descending along the helix;

b) During the transition phase, the bank angle ϕ is not to exceed $\pm 20°$ and the turn radius R must be equal to or greater than $1.5R_{\min}$.

2) Pilot module: it is characterized by a single parameter, namely the time delay τ associated with a pilot's response to a discrete event (an equipment failure in this analysis). The pilot module of conventional vehicles is inactive as they are unperturbed. Regarding the CESTOL vehicles, to account for the time delay τ in the pilot's response to the anomaly and quantify the impact on safety of his/her action, the true airspeed V at any given altitude z is adjusted to compensate for the wind velocity $\mathbf{W}$ measured at the altitude $z - \tau \sin(\gamma) V_I$. During the spiraling phase, the flight-path angle γ is, however, never allowed to drop below $-6.5°$ in response to uncompensated wind, as it is assumed that the pilot would have become aware of such a steep descent and would have responded more promptly. Furthermore, for the results presented herein, no compensation of cumulative velocity drift has been included. At low altitudes, however, it may be hypothesized that visual cues may become available to the pilots to alert them of large incurring drifts in the trajectory.

Environment Definition

The environment consists of the airspace surrounding an hypothetical airport, where wind is present. The wind velocity $\mathbf{W}$ is modeled via a time-invariant profile assumed to depend only on the altitude z. For each simulation, a representative wind profile is constructed using a weighted sum of measured wind data, i.e. $\mathbf{W} = \Sigma_j c_j \hat{\mathbf{W}}_j$. In an uncorrelated fashion, the time-varying nature of the wind could be modeled assuming distinct random weights c_j for each of the vehicles.

Agent-to-Agent and Agent-to-Environment Interaction

The agent-to-agent interaction is not considered in this first scenario. Since only the probability of intrusion into the airspace allotted for the neighboring approaches is estimated, no attention was given to the actual separation violation between two given vehicles; hence, the two traffic streams (for conventional and helical approach) were treated independently of one another, and no interaction in the form of evasive maneuvers by the aircraft whose airspace is invaded was modeled.

The agent-to-environment interaction is void until triggered by the occurrence of a discrete event, namely the degradation of the FMS. At that time, the presence of the wind is no longer compensated by the agent/vehicle, and the impact on its kinematic behavior will depend on its human-operator-based response time.

B. Results for the Helical Procedure

To assess the risk level associated with vehicle-separation violation in the presence of a helix landing, two sources of uncertainty have been modeled and their effects investigated. The first one consists of the wind forecast error, modeled via rescaling and rotation of nominal wind profiles according to Gaussian distributions $N(\mu, \sigma)$. Illustrated in Fig. 3 is the nominal wind velocity profile used as baseline for this study, and obtained through linear interpolation of measurement data. The information on the wind velocity $\mathbf{W} = [W_N, W_E, W_D]^T$ has been expressed in a north-east-down (NED) reference frame with its local-north direction parallel to the runway, with the additional assumption that W_D is equal to zero. The second source of error relates to the pilot's response time delay τ, which was characterized by means of a lognormal distribution $L(\mu_L, \sigma_L)$.

The airport environment is composed of two parallel runways, one of which is used for conventional landings, whereas the other is dedicated to those vehicles performing helical approaches. Under the assumption of independent events, the probability $P_{\text{violation}}$ that two approaching/landing airplanes will violate the minimum-separation safety requirement can be expressed in general terms as follows:

$$P_{\text{violation}} = P_{\text{FMS failure}} \times P_{\text{helix drift}} \times P_{\text{other aircraft}} \tag{1}$$

where $P_{\text{FMS failure}}$ is the probability of an FMS failure, $P_{\text{helix drift}}$ is the probability that the spiraling aircraft will drift away from its nominal course and invade other vehicles' airspace, and $P_{\text{other aircraft}}$ is the probability that another airplane will be in its vicinity. Given the particular layout of the considered landing site, depicted in Fig. 4, attention was given to the term $P_{\text{helix drift}}$ within Eq. (1), in essence the probability that a vehicle on a drifting helix will invade the airspace reserved to other incoming aircraft by crossing the centerline in between the two runways, which was used as the divider between the two airspace regions.

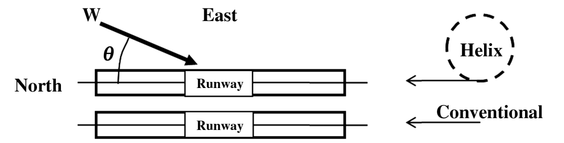


Fig. 4 Planar layout of the landing site.

The hazard scenarios for CESTOL aircraft have been investigated by means of a Monte–Carlo representation of the disturbances associated with the wind conditions and corresponding pilot reactions in the presence of a degraded FMS, where both sources of uncertainty were treated as independent random inputs. The wind nominal profile of Fig. 3 was randomized for each vehicle by assuming a wind-intensity amplification factor $\kappa \sim N(\mu = 1, \sigma = 0.1)$, and a forecast error on the wind direction sampled through $N(\mu = 0°, \sigma = 5°)$. In regard to the pilot's response, the time delay $\tau \sim L(\mu_L = 10\ \text{s}, \sigma_L = 10\ \text{s})$ with a constraint on its maximum allowed sampled value set equal to 20 s to avoid unrealistic lags. The statistical characterization of 10 s for both mean and standard deviation was motivated by a lumped-delay approach, where a pilot's engagement in various tasks was not explicitly modeled in this scenario. Rantanen et al. [23] make reference of a communication-based pilot delay with mean and standard deviation of 2.68 and 4.6 s (following Cardosi's approach [24]). There, the definition of pilot delay is the time elapsed between the first call from ATC and the pilot's first reaction (which could be followed by other interactions) under the assumption that the vehicle is already in the terminal area, hence smaller delays were supposedly expected. In this first scenario, no interaction with the ATC is considered, and drifting due to wind could occur even before any intervention is planned, hence a lumped mean delay of 10 s (with a skewed lognormal distribution that privileges lower values representing more responsive pilots) and a threshold that enables resampling was deemed acceptable, especially since it has to encompass pilot's awareness, reaction, and initiation of any corrective maneuver. Illustrated in Fig. 5 is a screenshot of the simulation environment highlighting both conventional and helical landing procedures. All aircraft enter their respective landing approach at the same location, but each of them experiences a different wind, which ultimately leads to a different response from the pilot and, in the case of helical descents, to a unique stabilization trajectory. Shown in Figs. 6–8 are the results for three wind scenarios, namely southwest, cross-, and tail winds. It can be observed that even in the presence of mild winds with intensity on the order of ~20 kts, significant drift of the helix may occur, as in the presence of a cross wind. In case of wind and aircraft speed of the same order of magnitude, a very quick response from the pilot is needed to contain

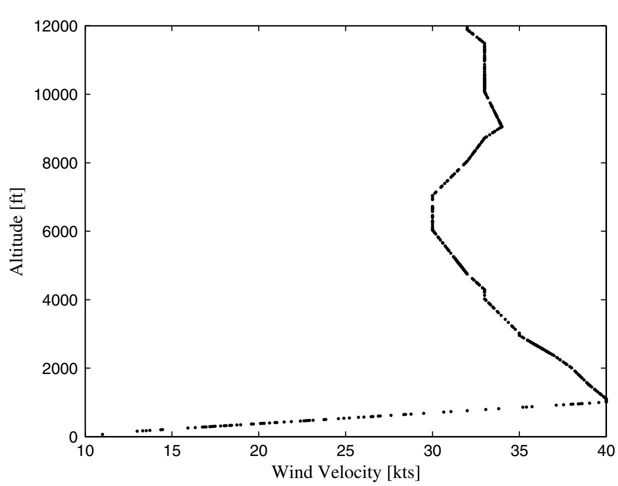


Fig. 3 Nominal wind profile.

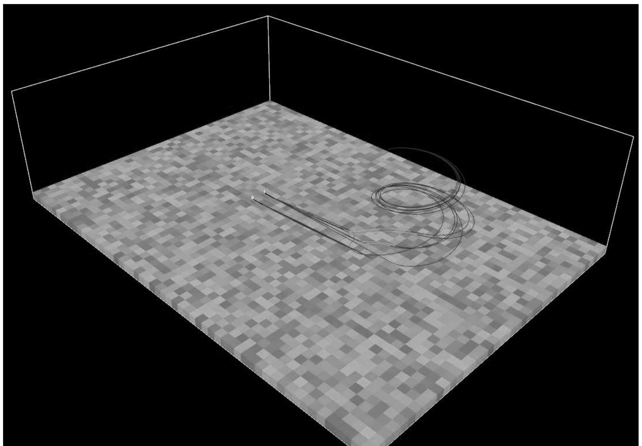
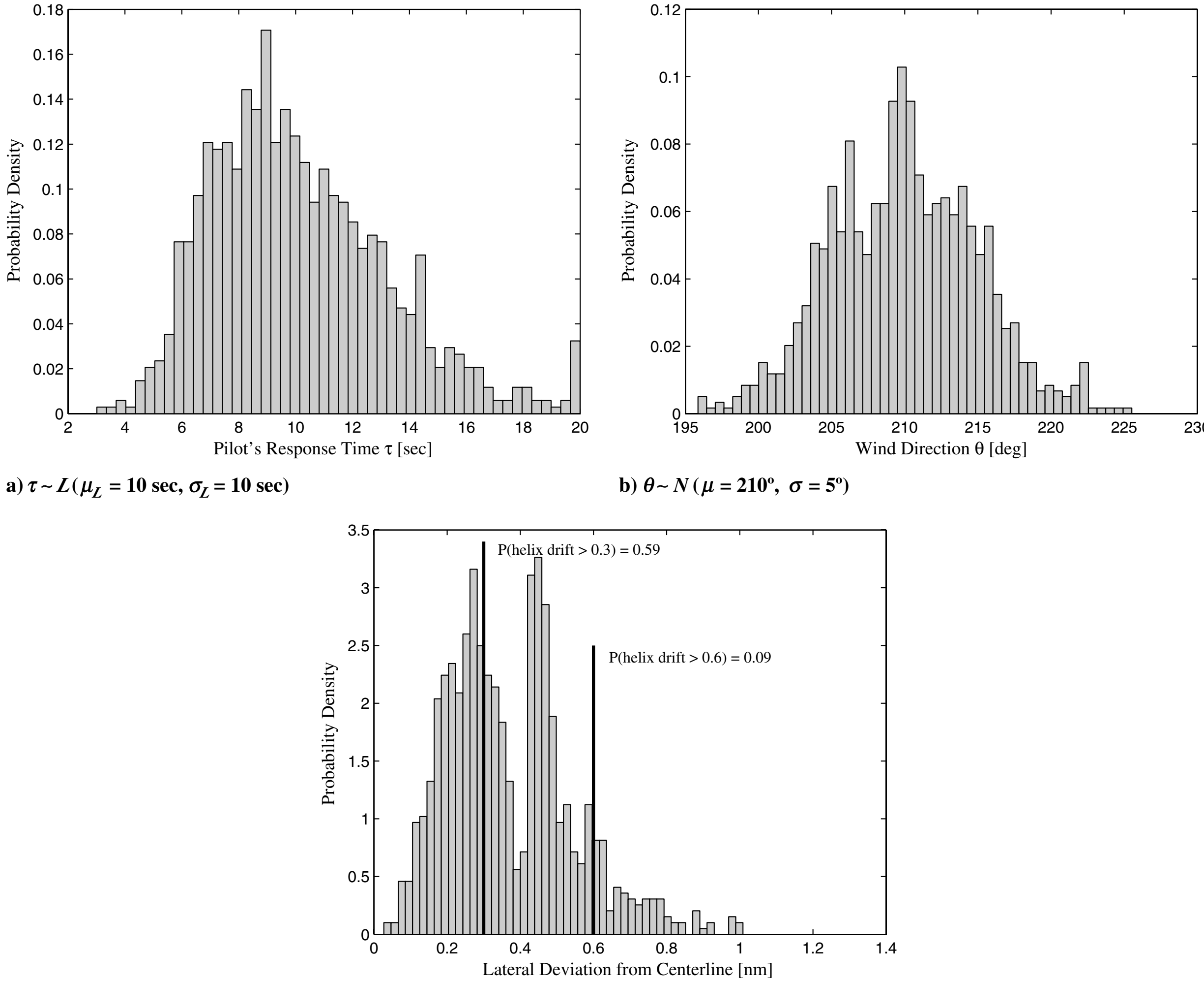


Fig. 5 Conventional and helical landing trajectories in the presence of wind varying conditions.



a) $\tau \sim L(\mu_L = 10\ \text{sec}, \sigma_L = 10\ \text{sec})$ **b)** $\theta \sim N(\mu = 210^{\circ}, \sigma = 5^{\circ})$

c) $P_{helix\ drift}$

Fig. 6 Separation violation hazard in the presence of a southwest wind.

the helix drift, which may otherwise lead to impractical landing scenarios. Accumulated drift without pilot intervention, however, may become unrealistic, as the pilot will eventually realize being off course.

Since the model did not include any logics to compensate for cumulative effects, the aforementioned scenarios were discarded in the postprocessing of the simulation results. Of course, the amount of "invasion" of the adjacent air space will also depend on the position at which an aircraft enters and exits the helix. Relaxing the exit condition by allowing the aircraft to abandon the helix at an altitude other than 1000 ft in favor of a better alignment with the runway may help the pilot better assess his/her position through visual cues and thus control the drift more successfully. In some of the investigated scenarios, the effect of wind exhibited rather minor sensitivity with respect to the response delay. This was the case for tail as well as head winds in which conditions the flight-path angle was the aircraft's parameter affected the most.

IV. Second Scenario: Mixed-Operation Landing for a Very Light Jet

In this scenario, a very light jet (VLJ) is assumed to approach the terminal area of the White Plains airport (HPN) and land using a steep descent. During this maneuver the vehicle experiences a loss of capability in computing correctly its current altitude. More specifically, this off-nominal air traffic situation can be described by the following sequence of events:

1) The VLJ descends on a -5.5° straight glidepath and operates in between two regular aircraft (effectively being "sandwiched" between two conventional approaches). The VLJ loses the capability to evaluate its altitude (e.g., due to a Pitot tube obstruction resulting in a corruption of the air data) and starts to descend with a speed different from the intended one, thus potentially leading to vertical space violation with the leading or the trailing aircraft.

2) The Air Traffic Control (ATC) notices the (impending) loss of separation and orders a corrective maneuver, namely a change in speed, to the appropriate vehicle(s).

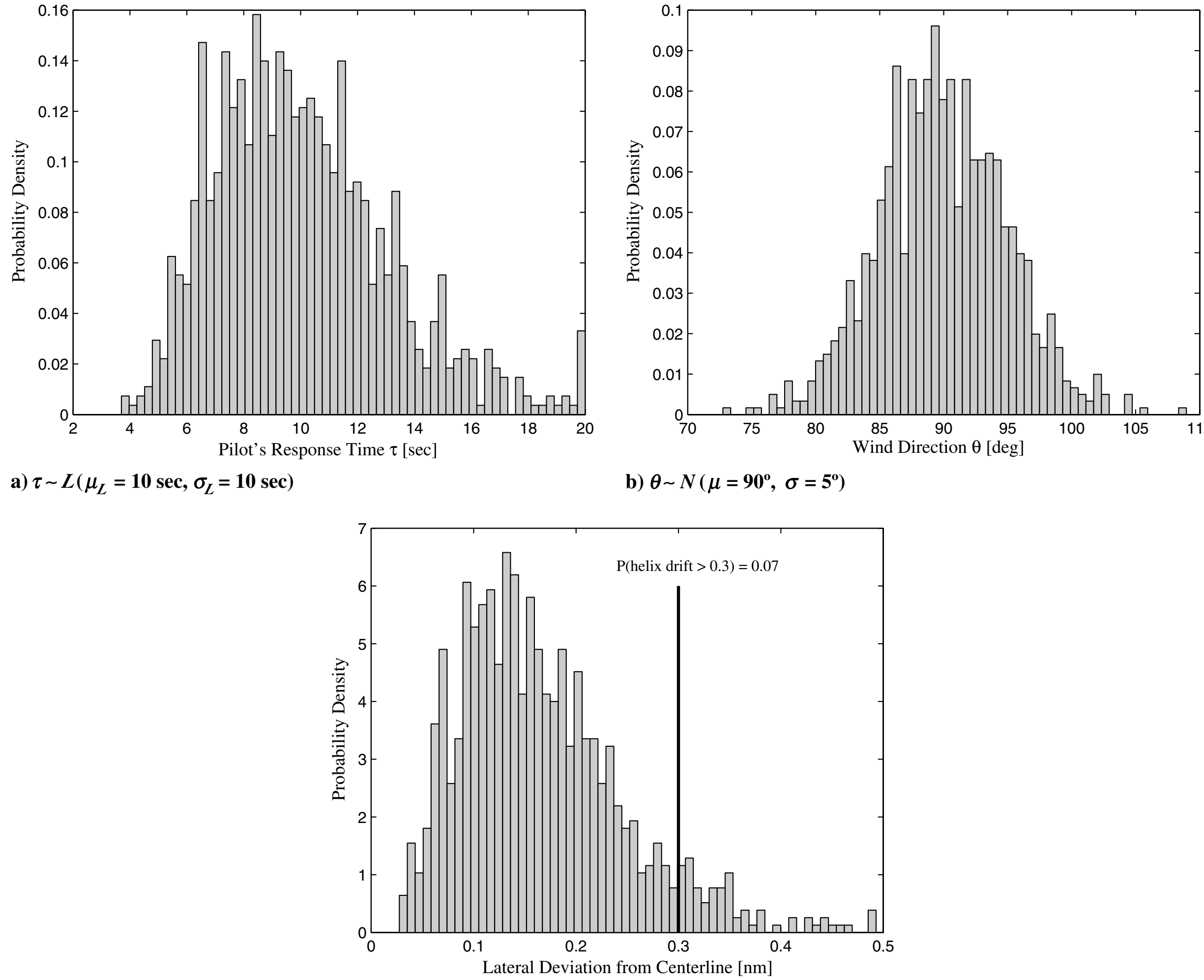
3) Each vehicle's flight crew which is being asked to execute an order will do so according to its own schedule and certain human delays.

Two distinct subscenarios were considered:

1) The VLJ has only one pilot who has to single-handedly perform all the tasks.

2) In addition to the single pilot on board of the VLJ, a copilot on the ground is introduced who has the same capabilities as the main airborne one.

This possible scenario is motivated by the worthiness of accommodating within NextGen mixed approaches, characterized by various descent speeds and glide slopes, by means of vertical separation, as well as the importance of investigating the viability of a backup pilot on the ground. It must be noted that the standard load sharing by pilots, where in the case of emergency one pilot flies the aircraft while the other troubleshoots the problem and communicates with ATC, is not applicable when the copilot is on the ground. While further research is required to investigate the realistic load sharing between the airborne pilot and the copilot on the ground, for the purpose of this study both pilots are assumed to have the same capabilities and share the workload, thus conducting tasks faster (up



a) $\tau \sim L(\mu_L = 10\ \mathrm{sec}, \sigma_L = 10\ \mathrm{sec})$

b) $\theta \sim N(\mu = 90^{\circ}, \sigma = 5^{\circ})$

c) $P_{helix\ drift}$

Fig. 7 Separation violation hazard in the presence of a cross wind.

to twice as fast). Illustrated in Fig. 9 are snapshots of the NetLogo model for these mixed-operation approaches.

A. Modeling Assumptions and Analysis

In contrast to the first scenario discussed in the previous section, three main elements necessary to investigate the hazards associated with this type of mixed operation can be identified: the pilot and ATC (together with their consequent interactions), and the conflict resolution logic, all of which were developed and integrated following a more consonant agent-based modeling paradigm. The agents and the modeling environment are presented next together with their underlying hypotheses.

Agent Definition

Two types of agents were introduced, namely the aircraft and the air traffic controller.

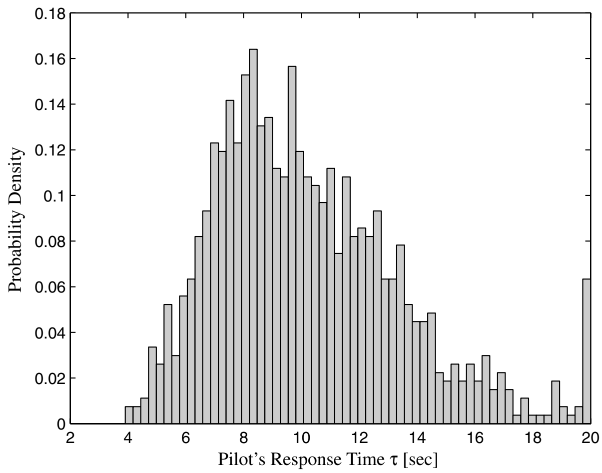
1) Aircraft Agent: it is composed of the vehicle/pilot(s) pair, hence it was broken down into two modules corresponding to the machine and human elements:

a) Vehicle module: it encompasses the kinematics of the airplane, whose motion is defined by an assigned velocity profile as a function of altitude.

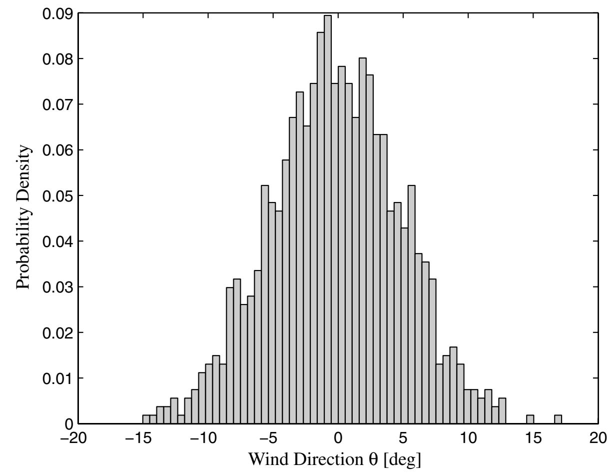
b) Pilot module: it mimics a pilot's response associated with the execution of an ATC-issued command, where such response is modeled to be a function of only workload and current task engagement. Throughout the various segments of a flight, pilots have to perform a certain number of tasks, some of which consist in the monitoring of the aircraft status (e.g., instrumentation and/or flow of data), whereas others involve communication with the ATC for the purpose of requesting information or executing given instructions. In the descent investigated herein, the tasks related to two main flight segments were deemed important, namely from the top of descent (TOP) to the final approach fix (FAF), and from FAF to the runway. Listed in Table 1 are the tasks which have been considered together with their representative statistical characterization used in the simulation. This task representation should not be considered exhaustive, but it provides a valid starting point for a top-level assessment of ATC/pilot interactions.

According to current procedures, if a conflict arises, the ATC issues a command to the pertaining aircraft to perform a corrective maneuver aimed at resolving the problem. The time interval between the appearing of the conflict itself and its proactive acknowledgment by the pilot will depend on his/her workload at that moment. Depending on whether or not the pilot is busy performing a task, the ATC's request might either be put temporarily on hold or it might be attended to right away based on its severity and priority. Given the time t_s necessary to fly through a particular flight segment s, let N_s be the number of routine tasks to be executed within that segment, and let the i-th task in it have a duration $\lambda(p) \cdot \Delta t_i^s$ $(i = 1, \ldots, N_s)$, where Δt_i^s is the time per single pilot and $\lambda(p)$ ($\lambda(p) = 1$ if $p = 1$, $\lambda(p) \leq 1$ if $p > 1$) represents the time-saving factor due to the p pilots sharing the workload, with $\lambda(2)$ herein assumed to equal 0.7 for two pilots. Ideally, assuming that the pilot performs one task at a time, the cumulative amount of free time while flying segment s can be computed as follows:

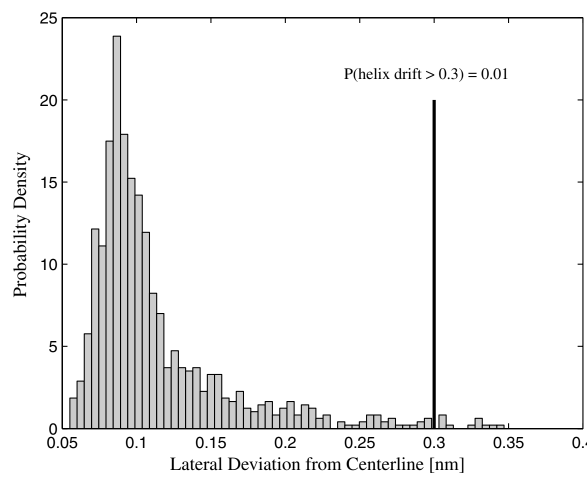
$$\Delta t_{\mathrm{free}}^s = t_s - \sum_{i=1}^{N_s} \Delta t_i^s \cdot \lambda(p) \tag{2}$$



a) $\tau \sim L(\mu_L = 10\text{ sec}, \sigma_L = 10\text{ sec})$



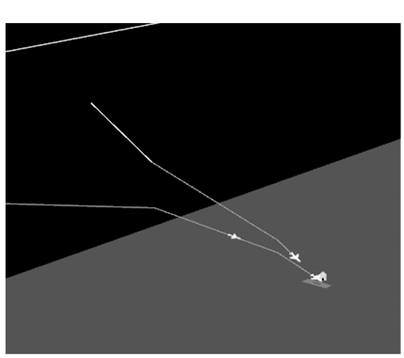
b) $\theta \sim N(\mu = 0°, \sigma = 5°)$



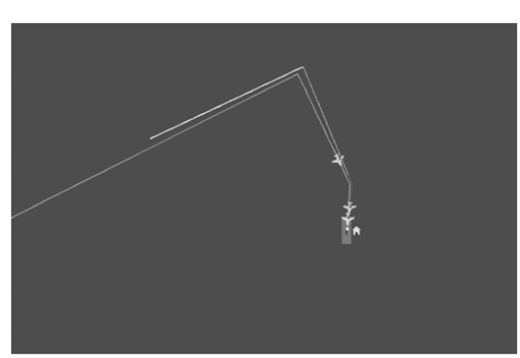
c) $P_{helix\ drift}$

Fig. 8 Separation violation hazard in the presence of a tail wind.

To account for a pilot's idle times, which effectively would result in an overestimation of the free time and a more optimistic performance by the pilots themselves, the segment time t_s is constantly being tracked and the available time updated according to Eq. (2) and the tasks still to be executed. For the particular flight segments listed in Table 1, the quantities Δt_i^s may be obtained for each aircraft/pilots pair through sampling in accordance with the adopted statistical representation. For the tasks that are repeated every so often, the number of their realizations is to be computed as a function of the segment time t_s. Furthermore, if for a particular realization of the execution times the pilot is left with "negative" free time, rescaling of those quantities is performed, meaning that the pilot has to operate at a faster pace. Finally, given the coarse representation of the tasks and the lack of knowledge associated with their actual sequence within the flight segment, their queue is randomly shuffled for each aircraft, thus accounting for the additional uncertainty. Once all the task-execution times and the cumulative free time are computed for the s-th flight segment, tasks (including the special task "be free") are randomly picked by means of a uniformly distributed parameter, executed and removed from the queue, except for the special task. In



a) Perspective view



b) Top view

Fig. 9 NetLogo model of the scenario with VLJ on steep approach and two other aircraft on regular approach.

Table 1 Breakdown of a pilot's descent tasks and execution times

Flight segment	Task	Execution time, min
Before top of descent	Check weather	$L(2.5, 0.65)$
	Check fuel state	$L(0.5, 0.158)$
	Check altimeter setting	$L(0.5, 0.149)$
	Check FMS programming	$L(1, 0.3)$
	Select radio frequencies	$L(0.5, 0.176)$
	Review approach plate	$L(1, 0.25)$
	Receive approach clearance (communicate with ATC)	It varies depending on clearance
	Set DH or MDA into radar altimeter	$L(0.25, 0.017)$
	Select landing gear down	Instantaneous
Top of descent	Monitor descent progress	Every 1 min
	Instrument scan (throughout approach)	Every 0.16 min
	Monitor aircraft systems (throughout flight)	Every 1 min
	Frequency change	$L(0.25, 0.015)$
	Check RAIM	$L(0.25, 0.027)$
	Check aircraft configuration	$L(0.25, 0.046)$
Final approach fix	Report FAF (contact ATC)	$L(0.25, 0.037)$
	Scan for runway environment	Intermittent from FAF to landing
	Verify landing clearance (contact ATC)	$L(0.1, 0.056)$
	Wind check (contact ATC)	$L(0.25, 0.025)$

this investigation, it was assumed that the pilot receiving a command from the ATC while performing a given task would attend to it only after completing what he/she was already engaged in.

2) Air Traffic Control Agent: the model of the ATC is relatively simpler as compared with the pilot's one. Only two primary tasks were taken into consideration:

a) Checking periodically for conflicts between pairs of aircraft;

b) Monitoring of the air traffic conditions to make sure that any previously detected and acted upon conflict has been solved; as part of this task, the ATC makes sure that any aircraft which had to undergo a change in its flight profile due to conflicts resumes it once acceptable traffic conditions have been reestablished.

The execution of the tasks was considered instantaneous, whereas their frequency was modeled by means of random idle times (Table 2). Furthermore, because of delays in the pilots' responses, it was assumed that commands are issued to pilots one at a time, and only after the previous communication has been attended to. It is to be noted that the specific choices for the statistical representation were partly encouraged by other similar research efforts [7,25], as well as dictated by trial-and-error considerations (hence, for instance, the 12 s constraint imposed on the monitoring idle time) aimed at obtaining realistic time lags between events. Finally, in certain cases, the ATC's response time may assume a large numerical value as dictated by its statistical sampling; these cases, however, were not discarded as they could indeed represent actual operating conditions in the presence of a traffic volume greater than the three vehicles modeled herein.

Environment Definition

A portion of the airspace of White Plains airport was modeled in no-wind conditions (i.e., its effect on vehicles' dynamics is fully compensated).

Agent-to-Agent and Agent-to-Environment Interaction

Assuming an agent's environment as defined by its surroundings regardless of other agents' presence, the agent-to-environment interaction becomes null in this traffic scenario since no wind-induced perturbation was taken into account.

In modeling the agent-to-agent interactions, each aircraft interacts exclusively with the ATC, but it does not directly act upon other vehicles' impact on the airspace, herein quantified in terms of space violation. The interaction between the ATC and the aircraft is enabled by the loss of adequate spatial separation between any two vehicles.

Table 2 ATC's tasks and idle times

Task	Idle time before next execution, s
Checking for conflict	$\Gamma(17.6, 8.5)$
Monitoring air traffic	$L(5, 3) \leq 12$

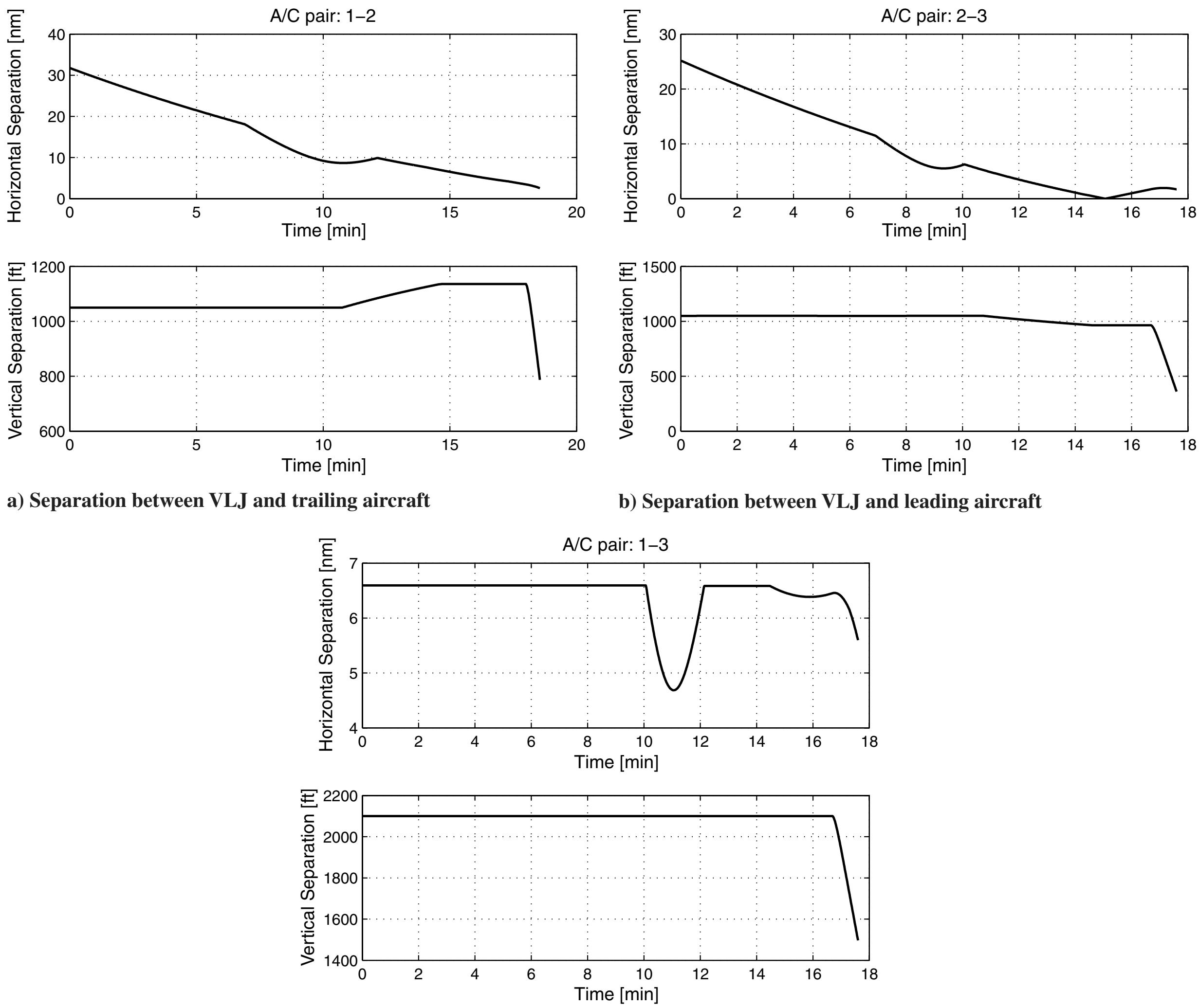
For the mitigation of conflicts, only commands requesting an initial velocity change of ± 15 kt were considered with additional changes (each in the amount of 10% of the previously requested speed variation) allowed if follow-up commands were issued to an aircraft already engaged in a maneuver. Commands were then reverted once separation had been safely reestablished with some additional margin (e.g., 110% of the vertical separation limit of 1000 ft). When requesting a maneuver, the controller gives a reduce-speed command to the aircraft in the given pair that is at a higher altitude if both airplanes were (or neither one was) already in a maneuver. A conflict between a vehicle already maneuvering and one which was not was tackled by asking the latter to speed up or slow down if at a lower or higher altitude, respectively. Finally, to account for the delay in the pilots' response, only one conflict at a time was considered (i.e., the most critical), whereas any other conflict was given consideration only after the ordered maneuvers have been implemented or were in progress. Furthermore, given the fact that the aircraft were modeled without inertia, the time needed for them to change their state or configuration was incorporated within the time needed by the pilot to execute a given command.

B. Results for the VLJ Mixed-Operation Scenario

The safety and success of the mixed operation explored herein relies strongly on the ability of the VLJ to maintain adequate separation from the leading and trailing aircraft. As shown in Fig. 9b, the L-shape descent at the White Plains airport together with the different aircraft velocity profiles is such that the horizontal separation cannot be maintained at all times. Hence, an accidental loss of vertical separation may result in hazardous conditions whose impact clearly varies depending on when it occurs along the descent. In nominal conditions, under perfect compensation of the wind, the velocity profiles $V_I(z)$ of the three aircraft were generated in such a way to maintain the initial vertical separation constant throughout the descent. Hence, the effect of a separation loss was investigated by introducing a bias Δz^b in the altitude used to compute the scheduled velocity profile of the VLJ. Such altitude bias was considered to be uniformly distributed:

$$\Delta z^b \sim \pm U(200\ \text{ft}, 300\ \text{ft}) \tag{3}$$

whereas the instrumentation failure, though random in nature, was treated as an explicit input parameter of the simulation and therefore assumed to happen at given points along the descent path, thus enabling a sensitivity study with respect to it. For instance, shown in Fig. 9b is the effect upon separation of a loss of sensor data accuracy in the vicinity of the waypoint where a $\sim 90°$ change in the aircraft's headings occurs, hence characterized by the most significant



a) Separation between VLJ and trailing aircraft

b) Separation between VLJ and leading aircraft

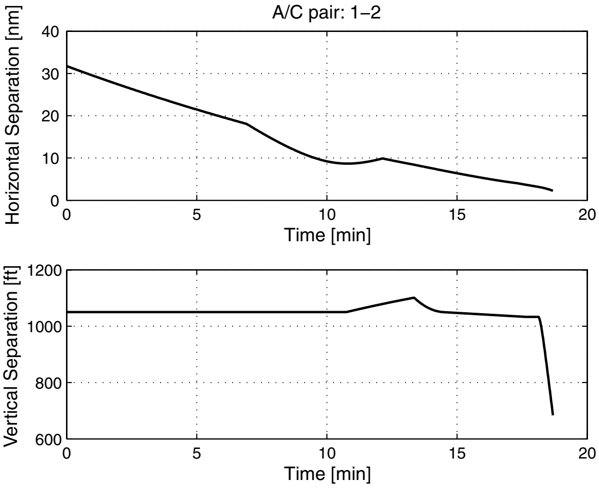
c) Separation between leading and trailing aircraft

Fig. 10 Horizontal and vertical separation in the presence of an uncompensated altitude bias.

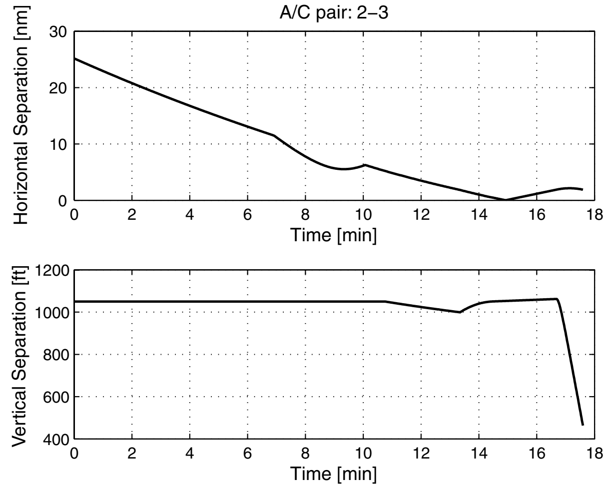
reduction in horizontal distance between the VLJ and the leading aircraft.

At a high level of analysis, the main sources of uncertainty embedded in this type of agent-based simulation can be summarized as a set of events, random or deterministic in nature (e.g., the loss of measurement capabilities or the change in scheduled velocity), taking place at times that can be also either randomly or deterministically distributed. More specifically, these events encompass an instrumentation faulty behavior and random action/reaction times by the various agents. Presented in Figs. 10 and 11 are two single sets of results. In nominal conditions, at the beginning of the simulation, the airplanes are placed at positions along their descent path which result in relative vertical separations equal to 1050 ft. A conflict between two aircraft exists if their vertical separation falls below 1000 ft in the presence of a horizontal distance less than 3 nm. Depicted in Fig. 10 are the horizontal and vertical separations for the three pairs of aircraft, where conflict resolution and consequent interaction between ATC and pilots have been disabled in this particular case. These results indicate a positive altitude bias because of which the speed of VLJ (aircraft #2) at a given altitude is higher than its scheduled value. As a consequence of that, its vertical separation from the trailing (aircraft #1) and leading vehicle (aircraft #3) increases and decreases, respectively. The difference in speed between the VLJ and the leading and trailing aircraft is, instead, such that the other two aircraft eventually reduce their horizontal distance from the VLJ. Moreover, the leading aircraft on the 3° glideslope will be the first to land despite the VLJ's initial shortest horizontal distance from the runway. In fact, as demonstrated by Fig. 10b, at some point the VLJ will be directly above the leading aircraft and in conflict with it because of the instrumentation bias. In the case of a negative altitude bias in the VLJ's instrumentation and no change in the other aircraft's velocity profiles, there will be no conflict between the leading aircraft and VLJ, whereas a conflict might arise with the trailing vehicle depending on how fast their horizontal separation reaches the 3 nm threshold. Additionally, it is worth noting that the accentuated curvilinear trends in the horizontal separation correspond to the situation in which one of the vehicle is going through the ~90° change in heading, while the drastic drops in vertical separation indicate that one of the two airplanes in the given pair has landed. Depicted in Fig. 11 is a similar set of results, corresponding to another randomly-generated positive altitude bias for the VLJ. Contrary to the previous scenario, in this case the separation violation was identified by the ATC, tackled and properly cleared, as illustrated in Fig. 11b.

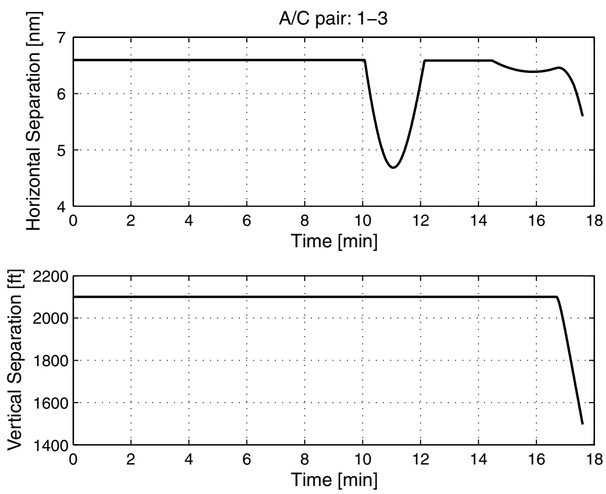
To assess the hazards probabilistically, a set of 5000-run Monte–Carlo simulations was conducted to investigate the effect on safety of the combined uncertainty associated with human performance and instrument failure at four distinct altitudes. Results are summarized in Table 3, where negative and positive altitude biases were treated separately since they led to somewhat dissimilar situations. In fact, a positive bias would cause a conflict between the VLJ and leading aircraft, whereas a negative one would affect, at first at least, the trailing vehicle and VLJ. To constrain the system further and generate more meaningful cases, a 5 nm horizontal separation requirement was imposed for this analysis. The level of conflict was assessed by distinguishing between horizontal and vertical separation and by



a) Separation between VLJ and trailing aircraft



b) Separation between VLJ and leading aircraft



c) Separation between leading and trailing aircraft

Fig. 11 Horizontal and vertical separation in the presence of a compensated altitude bias.

computing two conditional probabilities, $P(D_V|D_H^{\min})$ and $P(D_H|D_V^{\min})$. $P(D_V|D_H^{\min})$ is the probability that the vertical distance D_V between a given pair of vehicles falls below the safety limit of 1000 ft when their horizontal separation is below the 5 nm limit and at its minimum $D_H^{\min}$. Likewise, $P(D_H|D_V^{\min})$ represents the probability that the two aircraft's horizontal distance D_H drops below the 5 nm limit when their vertical separation has reached its minimum value below the 1000 ft threshold. Of course, should the condition not be satisfied for any of these conditional probabilities in the various combinations of vehicle pairs and failures, they would be undefined (as indicated by the "N/O" entries in Table 3).

In terms of vertical separation, the tabulated results show that the probability of a vertical space violation in the presence of a horizontal conflict can be rather significant with peak values above ~0.89. It is important to note, however, that the lack of mandated horizontal separation is primarily embedded in the L-shape structure of the

Table 3 Probabilities of vertical/horizontal separation violation at minimum horizontal/vertical distance between vehicles' pairs

		Positive bias ($\Delta z^b > 0$)		Negative bias ($\Delta z^b < 0$)	
Failure altitude, ft	A/C pair	$P(D_H\|D_V^{\min})$	$P(D_V\|D_H^{\min})$	$P(D_H\|D_V^{\min})$	$P(D_V\|D_H^{\min})$
4000	1–2	N/O [a]	0	N/O	0
	1–3	N/O	0	N/O	0
	2–3	N/O	0	N/O	0
5000	1–2	N/O	0	0	0.24
	1–3	N/O	0	N/O	0
	2–3	1	0.12	N/O	0
8000	1–2	0.014	0.016	0	0.89
	1–3	N/O	0	0	N/O
	2–3	1	0	0	N/O
12000	1–2	0	0	0	0.95
	1–3	N/O	0	0	N/O
	2–3	1	0	0	N/O

[a]N/O = No Occurrence

descent paths and their relative position with one another. Therefore, when the instrumentation malfunction occurs at higher altitudes, the vehicles may experience a greater occurrence of unsafe conditions because their failure-induced loss of vertical buffer is further exacerbated by approaching the waypoint at the corner of their L-shape trajectory. At lower altitudes, this may no longer be a source of high risk, because the vehicles may have already cleared that waypoint by the time vertical separation is compromised.

The probability of a horizontal conflict at the point of minimum vertical separation below the compulsory threshold is much lower. When the failure happens at high altitudes, the conflict may have already been resolved by the time the vehicles violate the horizontal distance condition, which usually occurs at lower altitudes as illustrated by Figs. 10 and 11. If, instead, the failure happens at lower altitudes, its propagation might simply be not fast enough, and therefore it would lead to no violation of the spatial separation at all. Differently from the undefined entries of Table 3, it is noteworthy to remember that zero values for these probabilities do not imply that a conflict did not occur; on the contrary, they indicate that the conflict has been cleared away from the considered critical points of lowest vertical and horizontal distance, respectively. These probabilities measure a conflict's severity by assessing the chance of its occurrence at those potentially critical conditions within this specific mixed-operation landing concept. To this end, a graphical sample of the results is given in Figs. 12–18, where the structure of the probability functions can provide insightful quantitative information on the intensity of spatial violation among vehicles.

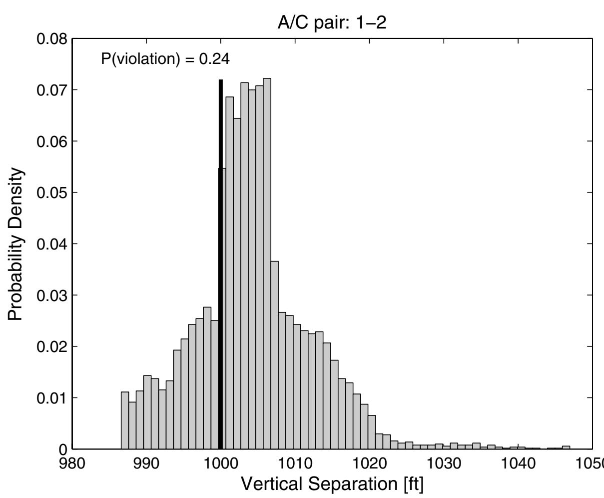


Fig. 12 Probability of violation $P(D_V|D_H^{\min})$ at 5000 ft with negative altitude bias.

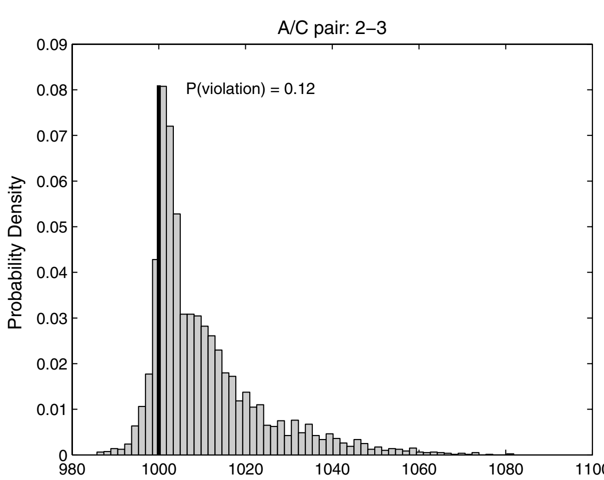


Fig. 13 Probability of violation $P(D_V|D_H^{\min})$ at 5000 ft with positive altitude bias.

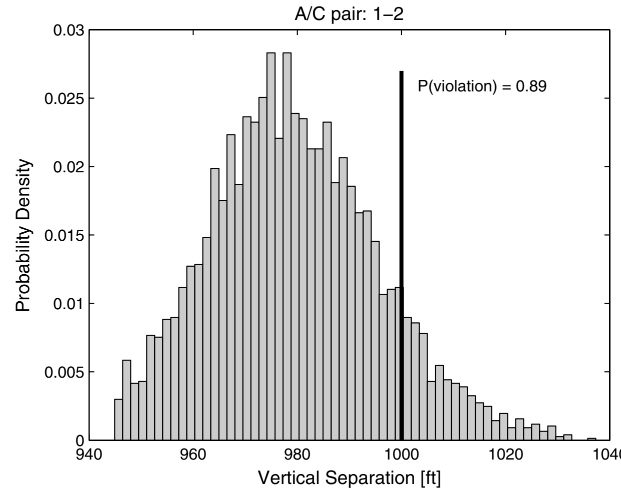


Fig. 14 Probability of violation $P(D_V|D_H^{\min})$ at 8000 ft with negative altitude bias.

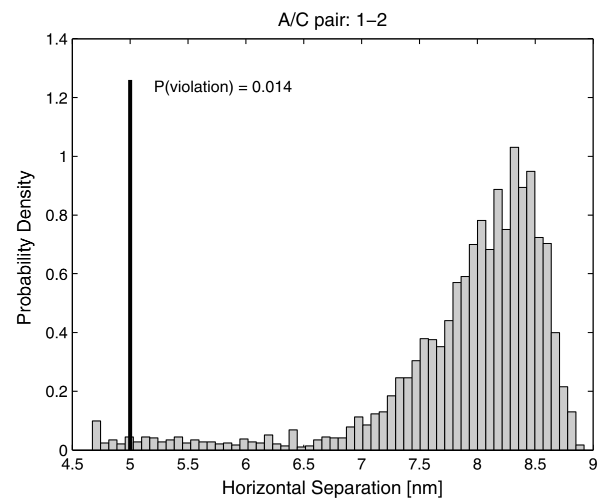


Fig. 15 Probability of violation $P(D_H|D_V^{\min})$ at 8000 ft with positive altitude bias.

As a final observation, the results presented above correspond to the VLJ being operated by two pilots ($\lambda(2) = 0.7$). The presence of one or two pilots did not show clear improvements in terms of how severe the conflict would become before being attended to and

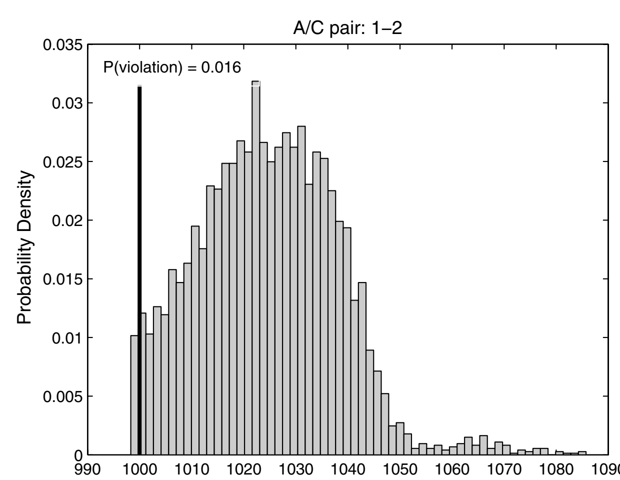


Fig. 16 Probability of violation $P(D_V|D_H^{\min})$ at 8000 ft with positive altitude bias.

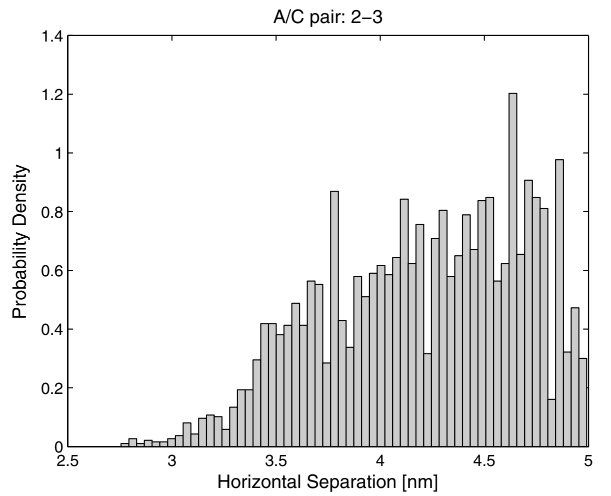


Fig. 17 Probability of violation $P(D_H|D_V^{\min})$ at 12,000 ft with positive altitude bias.

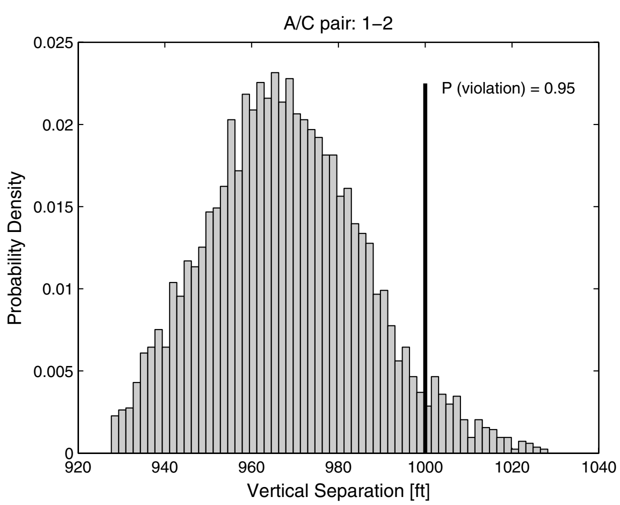


Fig. 18 Probability of violation $P(D_V|D_H^{\min})$ at 12,000 ft with negative altitude bias.

resolved. Other factors, such as bias intensity (and consequent rate of separation degradation) and ATC's idle times and monitoring frequency may damp out the benefits associated with load sharing among more than one pilot. Possibly, further advantages other than pilot redundancy may become more evident once additional or distinct capabilities are given to the copilot on the ground.

V. Conclusions

In the context of NextGen, two distinct novel concepts were evaluated together with possible hazards arising from their off-nominal operational modes. Both investigations were conducted using agent-based modeling, demonstrating that this approach provides a suitable framework to analyze the combined effects of new air traffic procedures and novel vehicles.

The first concept relates to a helical landing procedure for CESTOL aircraft that may give rise to safety hazards due to possible trajectory drifts and consequent intrusion into the air space dedicated to other incoming traffic. Results have shown that the combination of cross- and head winds provide the most adverse scenario for airspace invasion and intervehicle separation violation, since it may lead to very high probabilities of drifting away from the expected trajectory even in the presence of moderate wind velocities. Furthermore, any loss of safety margins may be exacerbated further depending on both the magnitude and the timing of the corrections applied by the pilots.

The second study investigated a mixed-operation concept aimed at increasing traffic volume by removing the limitations on throughput imposed by the slowest vehicle on an approach route. The very light jet, exhibiting a steeper than standard descent and traveling with low approach velocity, is paired with two regular aircraft in such a way that the aircraft must rely solely on the vertical separation during certain segments of the approach and landing. The analysis has shown that the hazards arising from a degradation of instrumentation capabilities will be more or less significant depending on the timing of the malfunction and its severity as well as any lagging of interaction among the various parties. Results at various failure-initiation points either indicated the lack of any loss of separation due to the vicinity of one of the involved aircraft to the runway, which called for no intervention, or that the lost safety margins could be recovered and further increased within the available time before the landing. Furthermore, for this type of failure, if a separation violation on the order of 100 ft were to be deemed acceptable for future operations, results seem to suggest that higher traffic operations could be envisioned even with moderately large response delays.

To isolate and investigate these off-nominal traffic conditions, several assumptions had to be made, and those assumptions are likely to change in the future. This uncertainty is inevitable due to the fact that the systems under consideration are still in the early phases of design. The model, however, can still provide valuable information for designing air traffic strategies capable of avoiding or mitigating the potential hazards, such as increasing the flexibility of the helix' exit condition or permitting some path deviation so that a correct position may be easily attained upon leaving the helical trajectory.

The main purpose of such created models is to provide quantitative input regarding not only the likelihood but also the timing of safety-critical events which can be used in subsequent system-level risk assessments (e.g., using stochastic Petri nets or discrete-event simulations). The results obtained from this agent-based simulation depend on the validity of the assumptions and inputs employed, and in this context sensitivity studies can help identify those parameters that are most critical from a safety standpoint. It is hoped that in the future this will direct more detailed discipline-specific research (such as human-in-the-loop simulations) focused on the evaluation of those key parameters.

Among other factors, further steps in the research shall account for more complex traffic configurations (e.g., multiple traffic streams) and aircraft interactions, missed approaches and go-around scenarios, a more sophisticated mapping between the model logics and human behavioral response, as well as any additional agents and sources of uncertainty or failure. The follow-up research will focus on efficient links between the agent-based or other relatively detailed physics-based simulations and more abstract system-level risk assessment tools (such as stochastic Petri nets, Markov chains, and Fault Trees).

Acknowledgments

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