Impact of Latency and Reliability on Separation Assurance with Remotely Piloted Aircraft in Terminal Operations

Vishwanath Bulusu*, Gano Chatterji†, Todd Lauderdale‡, Jordan Sakakeeny§ and Husni Idris¶
NASA Ames Research Center, Moffett Field, CA, USA

Remotely Piloted Aircraft (RPA) for cargo operations in the national airspace system will impact safety due to, among other factors, the latency and reliability of command & control, and of communication. This paper investigates the safety impact with increasing mix of RPA amidst manned traffic in a generic arrival pattern with three merging flows. Latency was modelled as the response time between air traffic control's determination of a resolution and the RPAs' initiation of the maneuver. Reliability was modelled as a message drop probability. The experiment was repeated with two different aircraft types having different performance characteristics as representatives of RPA for conducting automated cargo operations. Overall response time above thirty seconds and message drop probability over twenty percent caused losses of separation. Specific results depended on the RPA aircraft type. The detailed impacts of latency and reliability with increasing mix of RPA traffic are provided. Applications of the approach for further studies at increasing levels of automation are also discussed.

I. Introduction

The introduction of Remotely Piloted Aircraft (RPA) amidst manned traffic in the national airspace system is envisioned at scale for cargo operations. These operations could be limited by safety implications due to, among other factors, the latency and reliability of command and control (C2), and communication. Human-in-the-loop studies have shown significant impacts of these issues on controller workload [1] under limited automation. This paper investigates the impacts of these issues on separation assurance in terminal airspace.

Typical separation assurance functions are: predict/detect the conflict, determine a safe and efficient resolution, communicate the resolution and resolve the conflict by executing the resolution [2]. Where and by whom these functions and their sub-functions are performed depends on the type of operation and the level of automation involved. Future airspace concepts, such as the Next Generation Air Transportation System (NextGen) [3] and the Single European Sky ATM Research (SESAR) [4], generally feature a higher level of automation than current operations. Some of these separation assurance concepts propose a centralized ground-based control authority [5], while some envision limited and/or full delegation of control functions to the cockpit [6]. There is a comprehensive body of literature reporting investigations of such future concepts covering various aspects of separation assurance, e.g., conflict detection and resolution algorithms, integrated decision support tools, datalink communications, and the roles and responsibilities of humans and automation tools. From a survey of these, two of Bilimoria's [2] recommendations were to direct efforts towards sharper definition of pilot/controller roles and responsibilities and to determine the combinations of aircraft equipage mix that may yield tangible benefits. As the number of agents involved in separation assurance increases, this definition of roles and responsibilities becomes even more important.

In a typical scenario with RPA, separation assurance functions could be divided among three major agents: the Air Traffic Control (ATC) controller, the Remote Pilot (RP), and the RPA. Depending on the type of automation and delegation, there are several pairs of communication, like controller-RP and RP-RPA, and other intermediate agent level sub-functions. Each of these entails a potential response time (latency) and/or disruption (reliability) which would impact the overall performance of the separation assurance function. In an airspace, safety may decrease as the number of RPA increases. Additionally, it is expected that an increase in latency and decrease in reliability will also have a significant impact on safety. As a first step towards investigating this impact, this paper focuses on the time between a

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*Aerospace Research Scientist, Crown Consulting Inc., Aviation Systems Division, AIAA Member

†Senior Scientist and Lead, Crown Consulting Inc., Aviation Systems Division, AIAA Associate Fellow

‡Aerospace Engineer, Aviation Systems Division, AIAA Member

§Aerospace Engineer, Aviation Systems Division, AIAA Member

¶Aerospace Research Engineer, Aviation Systems Division, AIAA Associate Fellow controller determining the resolution and detecting that the RPA has begun the maneuver. This process is explained further in Section II.

Three mixes of RPA traffic amidst manned traffic are studied for each of two types of RPA. Two types of RPA are used to study the effect of flight characteristics. For a given RPA type and traffic mix, five values of response times and six values of message drop probability are used as surrogates for latency and reliability, respectively. Their impact is measured using metrics for safety and efficiency as the traffic mix and flight characteristics of the RPA are varied.

The rest of the paper is structured as follows. Section II discusses the overall experiment design, metrics, test scenarios and study assumptions. The results are presented in Section III. Section IV concludes the paper with a summary of the findings and a discussion of the relevance of this work to future studies.

II. Methodology

The first step is to understand what latency is modelled, what traffic is modelled, and how these are simulated. This is presented in the next section, followed by the definition of the metrics used to measure impact. Then, the test scenarios are described in detail, and the section concludes with a list of assumptions that also outlines the cases in the test matrix.

A. Experiment Design

Fig. 1 presents a timeline of the steps in detecting and resolving a conflict involving an RPA. As ATC monitors traffic, it will detect any potential conflicts, determine the necessary resolution, and relay it to the RP, who in turn will confirm it, feed in the command, and send it to the RPA, which will then begin the maneuver. Once the RPA begins the maneuver, ATC detects the beginning of the maneuver. Finally the RPA completes the maneuver which is also detected by the ATC on the monitor. Inter-agent communication latency is dependent upon the type of link, and individual agent pairs may use different types of links within the same chain of communication. For example, ATC-RP communication could be over a voice channel while the RP-RPA C2 communication could be over satellite communication (SatComm). There is also latency associated with steps each individual agent has to take before communicating with the next agent. For a manned aircraft, since the pilot is on board, the pilot-aircraft communication and the related intermediate steps are not present.

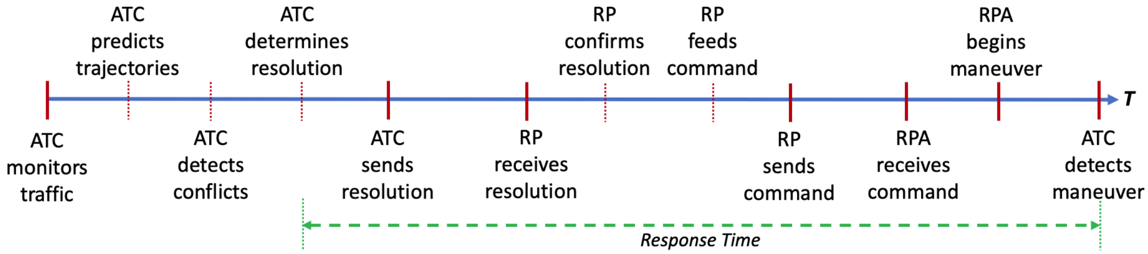

Fig. 1 A timeline of ATC, RP and RPA functions in separation assurance.

In this paper, the overall response time (RT) between the ATC determining a resolution and detecting the RPA beginning the maneuver is modelled. Knowledge on RT is limited as most studies focus on latency of the individual inter-agent links or overall times with a pilot in a manned cockpit. The closest reference is the work by Askelson *et al.* [7] who used pilots flying a Predator B (MQ9) in a simulator in stick and rudder mode and measured the response times similar to the definition in this paper. They found values as high as a minute. A more realistic scenario would potentially add further small delays between the RP and RPA. Therefore, in this paper RT is varied between 0 and 120 seconds. Furthermore, disruption at any stage of this response timeline could prevent the message from reaching the RPA, thereby preventing initiation of the maneuver. Hence, reliability is captured as a Message Drop Probability (MDP) varying between 0 and 0.5. Any higher MDP is assumed to be akin to a lost C2 link which is beyond the scope of investigation in this paper.

Fig. 2 shows the experimental set up for the analysis. Historical traffic data for a nominal day in the National Airspace System (NAS) was obtained from NASA's Sherlock Data Warehouse [8]. Earliest automated cargo operations are expected to begin at regional airports. Hence, data on aircraft movements between regional airports was used to generate representative flight plans for both RPA traffic and legacy background manned traffic. The mix of aircraft types for the background traffic was also generated based on regional airport inbound traffic. Base of Aircraft Data (BADA) [9] models were used to simulate the aircraft. Conflict detection and resolution was modelled utilizing NASA's AutoResolver (AR) [10]. Simulations were run in the Autonomy Development Kit (ADK) environment, which is an implementation of AR on NASA's SMART NAS Test Bed (SNTB) [11]. A communication delay module was added to the ADK code base to model RT and MDP. Simulations were run for traffic with increasing mix of RPA (described in the next section) and by varying the RT and MDP. Although the focus was on terminal operations, entire flight plans were simulated, with AR being active in both the terminal area and the enroute airspace prior to top of descent. This was done to capture any advanced strategic resolutions that would be issued by ATC in a realistic scenario. Entire flight plans of the aircraft Metrics were derived from the simulated trajectories as described in the next section.

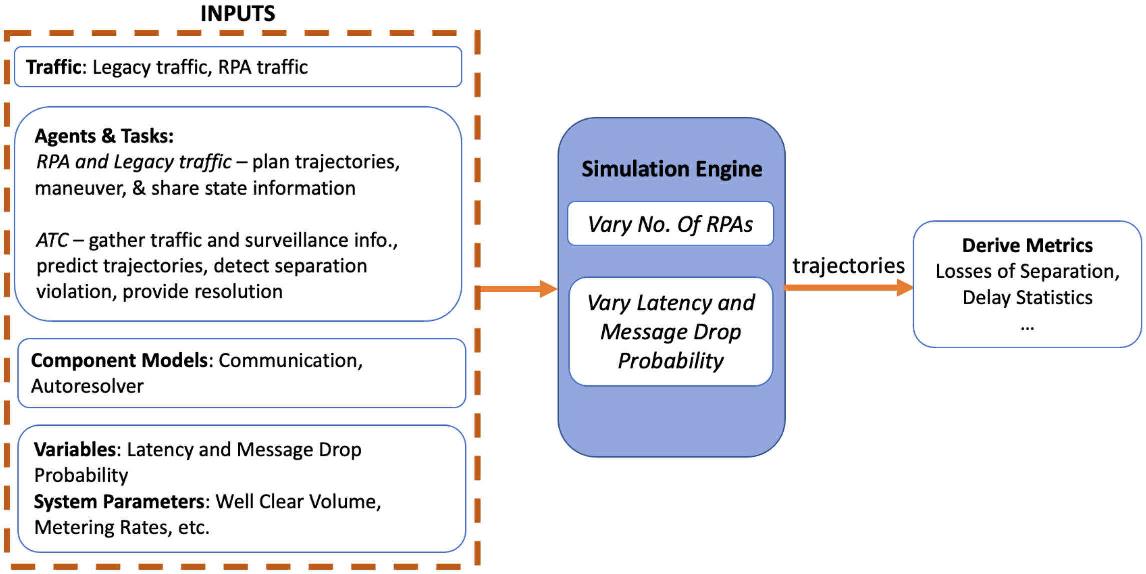

Fig. 2 A flow chart describing the experimental set-up.

A route structure was created to model a generic traffic arrival pattern into an airport as shown in Fig. 3. Traffic coming from three directions of arrival flows merges at the initial approach fix and then proceeds to the runway via the final approach fix. Distances used for the glide slopes and arrival paths were based on data from regional airports and their arrival patterns.

B. Metrics

The impact of latency and reliability on safety was measured using the *number of Losses of Separation (nLOS)* metric. nLOS is defined as the number of pairs of aircraft coming within 3 nautical miles (nmi) horizontally and 1000 feet (ft) vertically inside the terminal airspace. Outside the terminal airspace the horizontal separation requirement is 5 nmi. Ensuring safe operation is expected to affect the system performance. The delays incurred by flights is a measurable way to understand the efficiency of operations. The *Average Arrival Delay* observed over all the flights in a given scenario was measured. Arrival delay is defined as the difference between the actual time of arrival and the scheduled time of arrival. A late arrival would therefore be a positive arrival delay.

C. Test Scenarios

Input data was produced with 100 flights in each scenario. The number of RPA among those 100 was varied to simulate increasing mix of RPA traffic. Three RPA traffic mix were tested: 10, 30 and 50 RPA. The aircraft type used as RPA were kept homogeneous while the aircraft types for background legacy traffic were selected based on traffic data into regional airports.

Two types of aircraft were considered to represent RPA, namely ATR-72 (AT-72) and Cessna 208 (C-208). For example, a test scenario would be 100 flights with 10 of them being C-208. Then the next traffic mix tested would be 100 flights with 30 of them being C-208. The AT-72 has a cargo capacity of 8500 kg, a maximum cruise speed of 280 knots

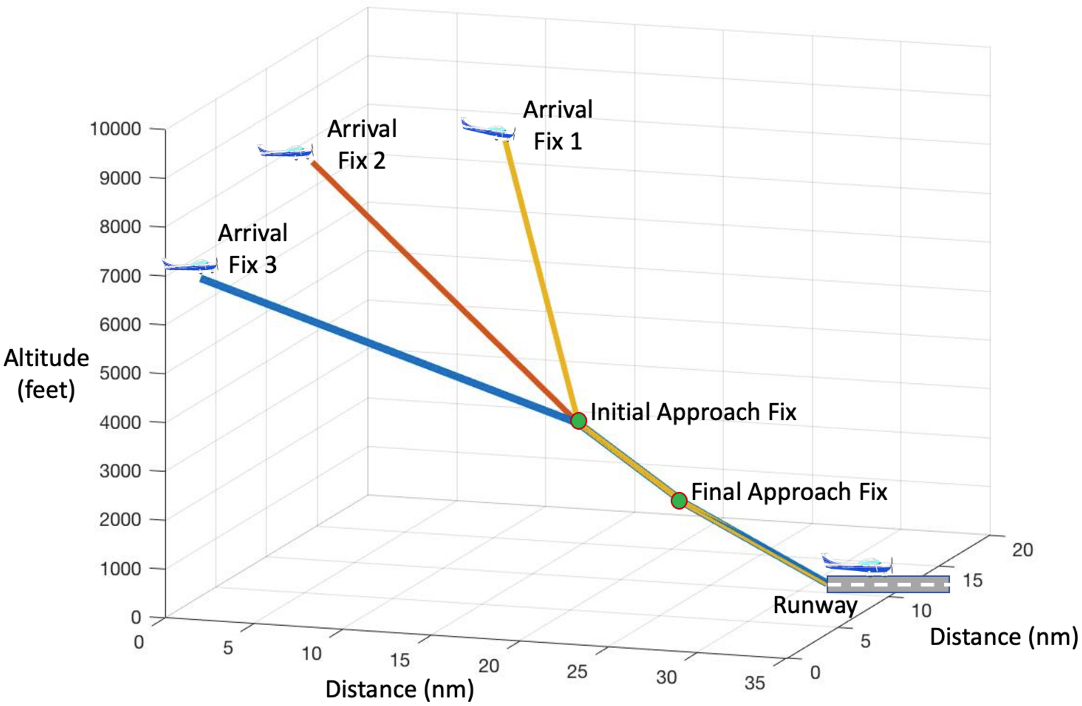

Fig. 3 Perspective view of the descent portion of the generic arrival pattern modelled.

and a range of 1500 nmi. The C-208 can carry 1600 kg, cruise at a maximum speed of 185 knots and fly up to 1000 nmi. These aircraft represent two types of aircraft that could potentially be leveraged for automated cargo operations.

Flights plans were generated entering the airspace within roughly 4 hours to simulate traffic flows that would ensure interaction between the aircraft without overwhelming ATC. The scenarios were designed such that, in the absence of any response time delays and no messages dropped, no losses of separation were produced. Then, these baseline scenarios were repeated, varying RT and MDP as indicated in Table 1.

Table 1 Test matrix showing the combinations of RT and MDP values used.

MDP	**0**	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**
RT (sec)						
0						
30						
60						
90						
120						

In the simulation, once a resolution was generated, the message was relayed to the aircraft after a certain response time period, per Table 1. Simultaneously, the message might have been dropped, depending on the MDP, also per Table 1. For example, in a test scenario with an RT of 30 seconds and MDP of 0.2, ATC generated resolutions would reach the RPA 30 seconds late and would be dropped 20% of the time. Once the message reached the aircraft, the aircraft implemented the maneuver at the next simulation step and ATC would also detect this. Hence, any response time and/or message drop would be detected by ATC as an unchanged state of the aircraft. ATC will then produce a new resolution based on new conflicts derived from the most recent state of the aircraft.

Fig. 4 shows the top view of merging flows from a sample scenario. The yellow lines are the planned trajectories of the flights overlaid on each other. Fig. 5 shows a later stage of the same sample scenario once AR has provided resolution maneuvers (shown as gray lines) to aircraft in conflict. It is to be noted that the ADK Traffic Viewer is

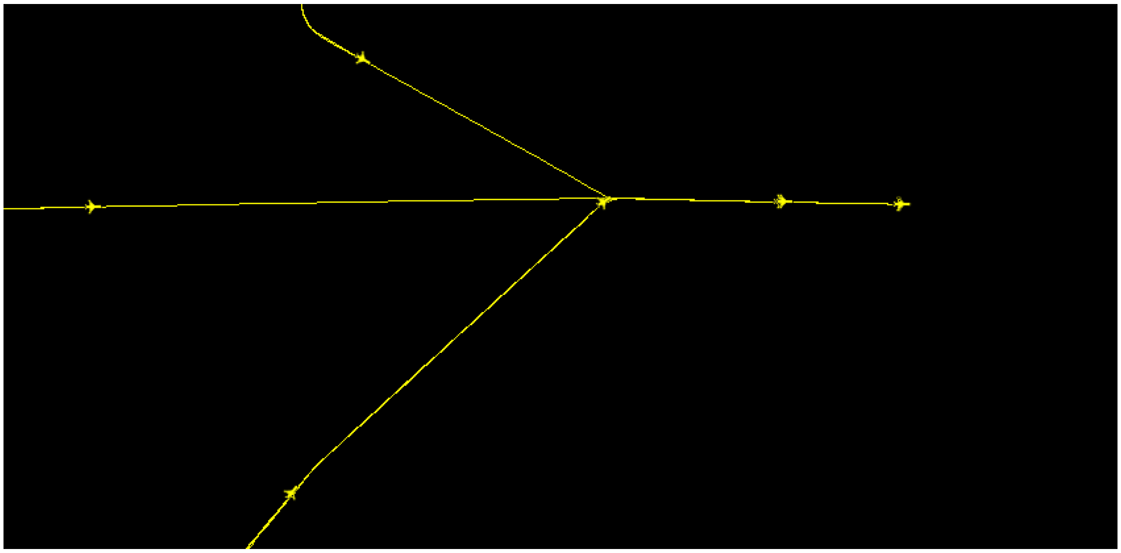

Fig. 4 Top view of a sample scenario from ADK showing three merging flows at arrival. Yellow lines are the planned trajectories.

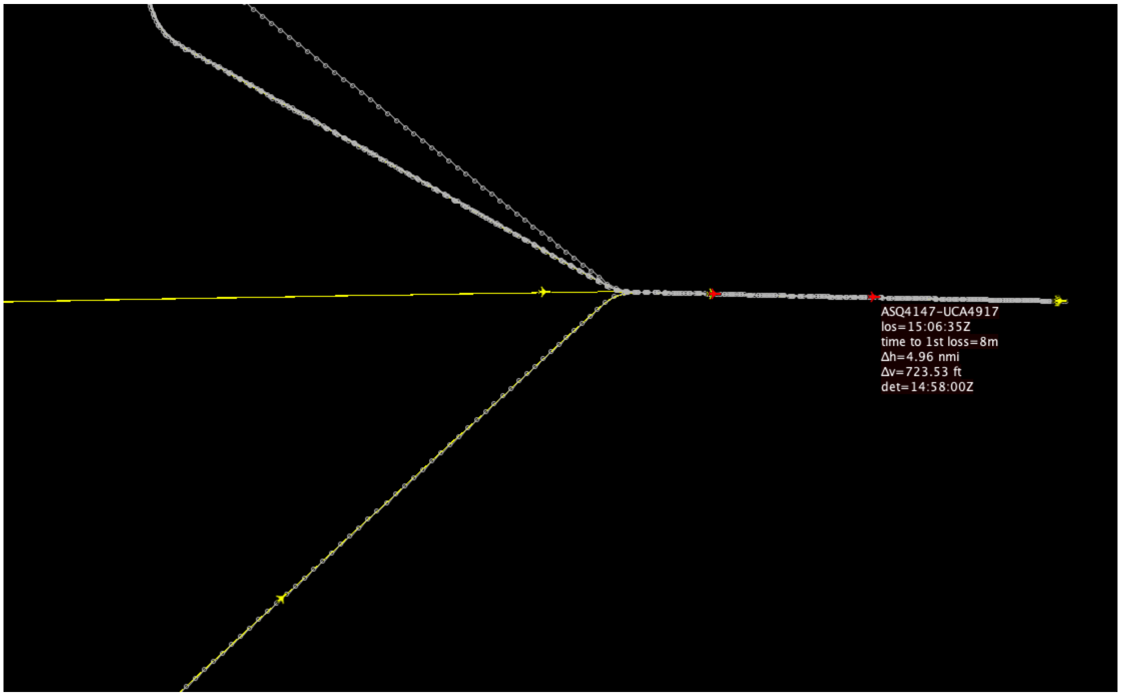

Fig. 5 Sample scenario with ATC resolutions shown as gray lines. Yellow lines are the planned trajectories. Aircraft in red are projected positions of aircraft at loss of separation.

designed to display any projected losses of separation based on en route separation standards of 5 nmi horizontal and 1000 ft vertical. Hence, the figure taken from the ADK Traffic Viewer displays a loss of separation at 4.96 nmi. Although this separation distance, as per the terminal area standards that would be used by ATC to separate the aircraft, would not be classified as a loss of separation in the simulation and therefore not counted in the evaluation of our safety metric.

D. Test Matrix and Assumptions

In addition to scenario assumptions stated earlier, the chosen values of different parameters are listed below:

- Two RPA aircraft were tested: AT-72 and C-208.
- For a given type of RPA, three traffic mix levels were tested: 10, 30 and 50 RPA out of the 100 flights in a scenario.
- Five values of RT were used: 0s, 30s, 60s, 90s and 120s.
- Six values of MDP were used: 0, 0.1, 0.2, 0.3, 0.4 and 0.5.

Hence, for a given type of RPA and a selected traffic mix, a total of 30 cases were tested - five values of RT for each of the six values of MDP as shown in Table 1. The aircraft performance parameters are determined by equivalent BADA models as implemented in the simulation software. Uncertainties introduced by winds and errors in navigation and surveillance were not modelled in the simulations.

For each test scenario, two metrics were computed: number of Losses of Separation (total pairs of aircraft that had a loss of separation at least once in the simulation), and Average Arrival Delay (average delay accrued by any flight in the test scenario).

III. Results

First, results are presented for the safety metric. Fig. 6 shows nLOS plotted as a function of RT and MDP. Each subplot is for a particular traffic mix of RPA. The left subplots are for AT-72, and the right subplots are for C-208. There is a high correlation between increase in nLOS and increasing MDP. Increasing RT also correlated with increased nLOS. Overall, for an RT of up to 30 seconds and an MDP under 0.2, no LOS occurred. At MDP higher than 0.2, LOS occurred at an RT over 30 seconds. At 120 seconds of RT and an MDP of 0.5, the total nLOS observed varied between 15 to 22 depending on the traffic mix and type of RPA.

Comparing the two types of RPA, ATC performed marginally better in C-208 scenarios than AT-72 scenarios. This difference was more pronounced at higher RT and MDP. For example, in the scenarios with 50 RPA, at an RT of 120 seconds and an MDP of 0.5, 15 LOS occurred with C-208 compared to 22 with AT-72. Furthermore, closer inspection of the proximity during losses showed that AT-72 scenarios had an average of 0.75 nmi horizontal separation vs 1.6 nmi for losses in scenarios involving C-208. One potential explanation is that C-208 can maneuver more sharply and initiate that maneuver in a shorter distance, owing to its lower speeds, compared to its larger counterpart. This would also potentially make missed and delayed resolutions in AT-72 scenarios more risky.

As the safe operation of the system degrades, it is important to observe how the efficiency of the operations is affected. Results are presented next for the performance evaluation. The Average Arrival Delay plots are shown in Fig. 7 as a function of RT and MDP. Each subplot is for a particular traffic mix of RPA. The left subplots are for AT-72 and the right subplots are for C-208. Three general trends were observed. First, in most scenarios, the average delay decreased as RT increased and MDP increased. Second, the variation in average arrival delay was smaller as RT increased. In other words, MDP correlated more with efficiency than RT at lower RT values. Third, these trends were more pronounced at higher RPA traffic mix.

Between the two RPA types, C-208 scenarios had lower average arrival delays at all RPA traffic mix levels. However, AT-72 scenarios generally showed greater reduction in average arrival delays with increasing RT values compared to C-208 scenarios, especially at MDP values of 0.2 and less. For example, with 50 RPA out of 100 flights, at MDP of 0.2, the average arrival delay for the AT-72 scenario decreased from 96.5 seconds to 48.5 seconds as RT increases from zero to 120 seconds. While for the C-208 scenario, the average arrival delay decreased from 80.1 seconds to 43 seconds.

Decreased arrival delays seemed to improve efficiency, which is counter-intuitive, given that the safety of the system has degraded. However, there are two effects to be considered. First, several aircraft either delaying response or not responding at all to ATC initiated route changes, would progress faster to destination, albeit through unsafe interactions with other aircraft. This would therefore reduce the average arrival delay. However, in practice, some form of onboard Detect and Avoid (DAA) system would take over to ensure safety and hence such aircraft will end up getting delayed. This study doesn't consider DAA systems and therefore these effects could be explored further in future.

Second, when ATC sees that RPA hasn't responded, there is lesser time to respond with a new resolution while the conflict encounter geometry has become more severe (e.g. aircraft are closer). Consequently, one of the aircraft could be potentially sped up close to its maximum speed. This would get that aircraft to its destination earlier than the scheduled arrival time (as was observed in the simulation data) while keeping it safe. Average delay of the traffic scenario would again be reduced but the aircraft would pay for this in increased fuel consumption. Thus reductions in arrival times would come either at the cost of safety or losses in energy costs.

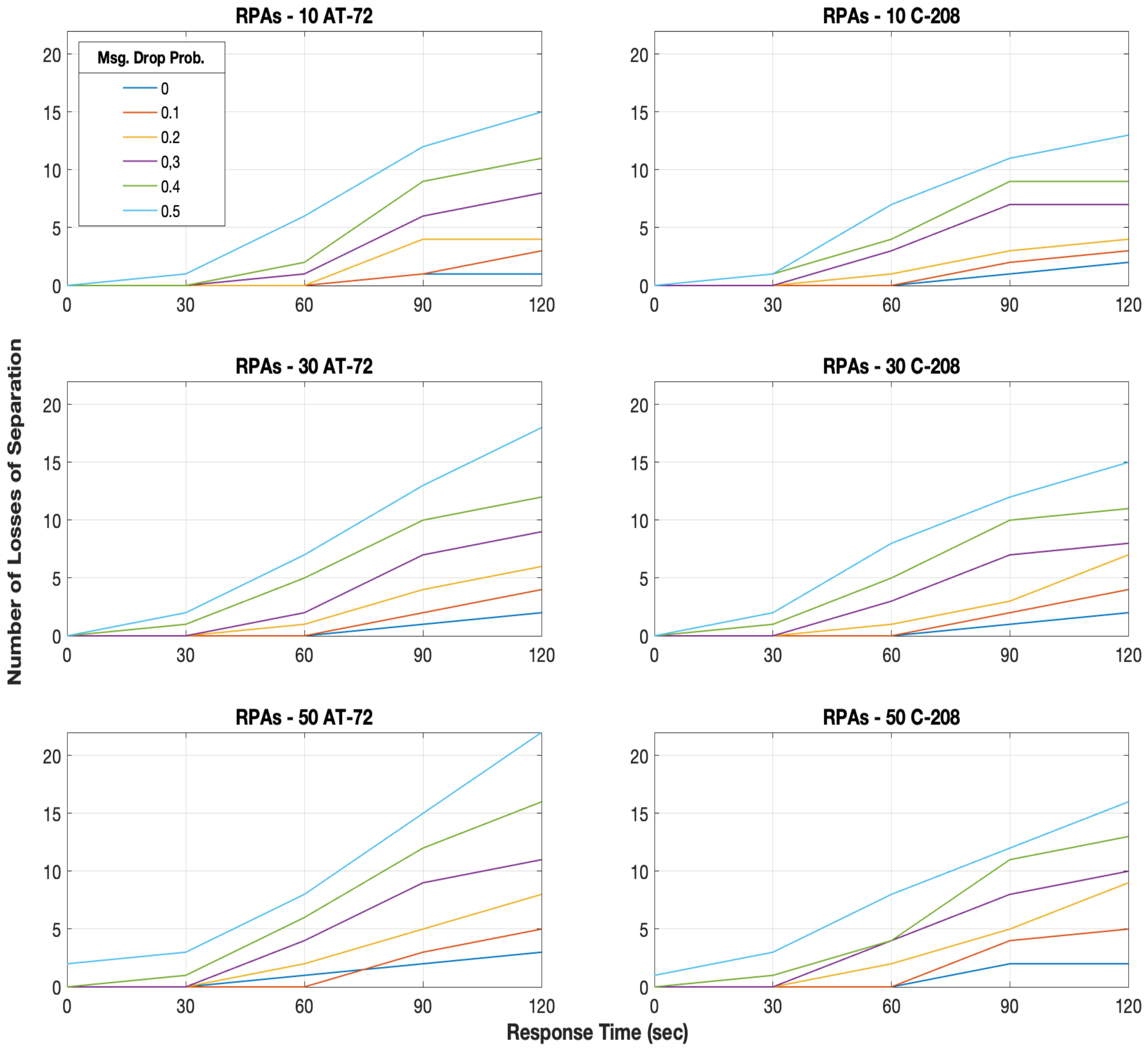

Fig. 6 Number of losses of separation as a function of response time (RT) and message drop probability (MDP). Each subplot is for a specific RPA traffic mix and type. Each colored line in a subplot is for one MDP value.

Furthermore, the performance behavior, like safety, may also be explained by the speed and maneuverability differences between the two RPA types. Since AT-72 has speeds comparable to other background traffic in the terminal area, extra delays for maintaining safety got evenly distributed. On the other hand, with a slower and more maneuverable C-208, delays were dispersed to slower flights potentially speeding up the faster flights. This is corroborated in part by the observation that in AT-72 scenarios, often the most and least delayed flights themselves did not change even though their delay values did. In contrast for the C-208 scenarios, the most and least delayed flight IDs were often different from scenario to scenario.

The results showed that based on both safety and performance impacts, a response time under 30 seconds and a message drop probability under 0.2 had no losses of separation even with half the traffic being RPA. In practice, performance requirements are expected to be tighter, indicating that high traffic mix of RPA could operate with low impact of latency and reliability on separation assurance in terminal operations. It was also evident that separation assurance depends on the type of RPA (i.e. its performance characteristics) and tighter bounds on latency and reliability are closely connected to the same.

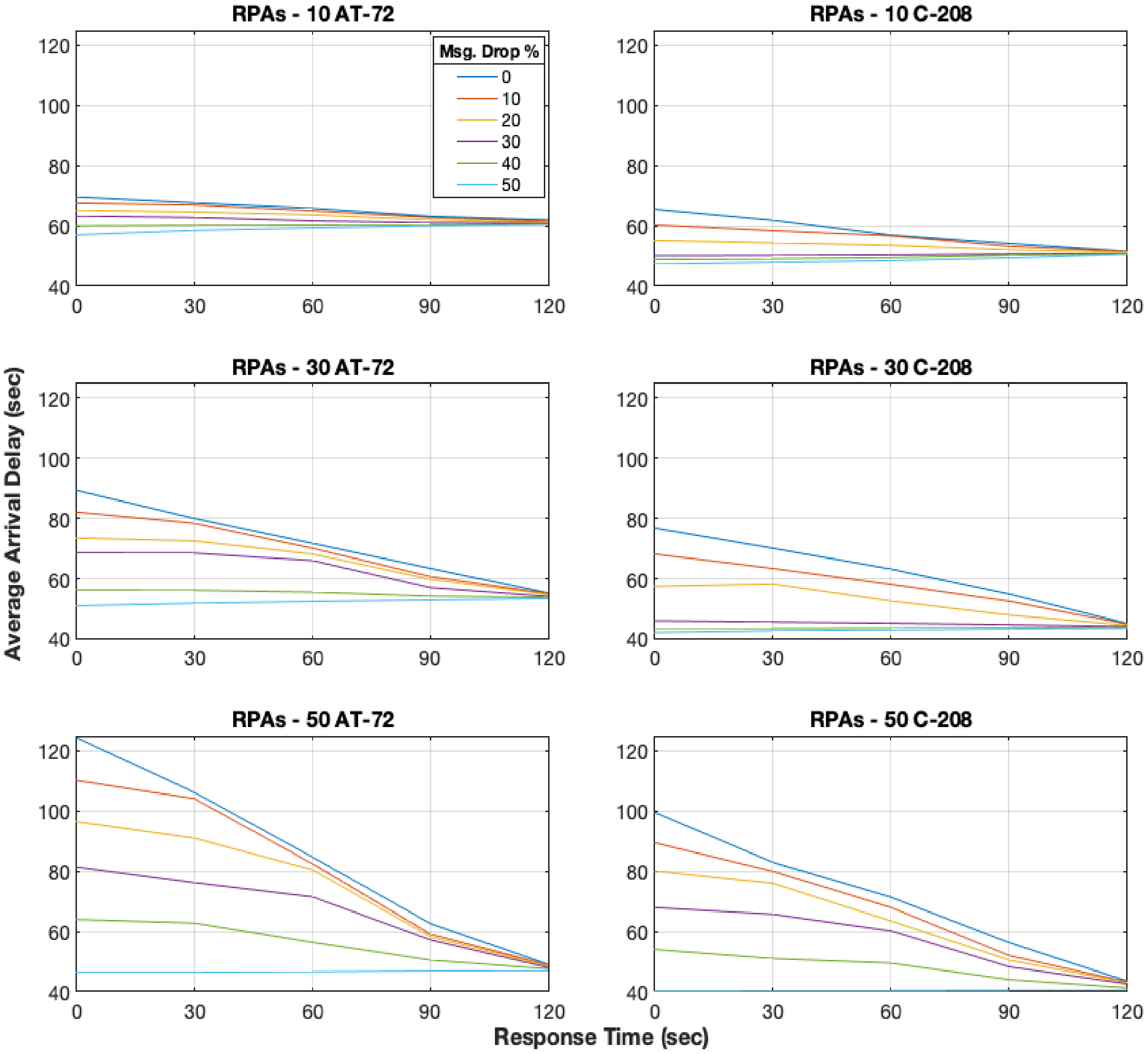

Fig. 7 Average arrival delay observed as a function of response time (RT) and message drop probability (MDP). Each subplot is for a specific RPA traffic mix and type. Each colored line in a subplot is for one MDP value.

IV. Conclusion

This paper explored the impact of latency and reliability on separation assurance with RPA operating amidst manned traffic in a generic terminal arrivals environment. Three mixes of RPA traffic were studied for each of two types of RPA: AT-72 and C-208. For a given RPA type and traffic mix, five values of response time and six values of message drop probability were studied, for a total of 180 simulations. A fast-time simulation methodology was developed and used to conduct the study. Losses of separation and arrival delays in each test scenario were measured.

Results showed that, as hypothesized, the safety of the system degraded as the response times and MDP values were varied. Overall response times under thirty seconds and messages dropped with a probability less than 0.2 exhibited the least impact on safety. The level of degradation depended on the type of RPA with C-208 scenarios generally performing better than AT-72 scenarios. The system efficiency measured by arrival delays observed, exhibited a counter-intuitive response with reduction in delays at high RT and MDP values. This provided further insights into the dependency on the aircraft flight characteristics and the effects of ATC-RPA interaction with delayed and missed messages. It is recommended that future efforts closely monitor such effects for further insights into the inter-operability of RPA with manned traffic.

This paper examined the effect of latency and reliability on separation assurance without any compensating measures and thus serves as a baseline for further studies that can examine alternative solution concepts (mitigation strategies) and their trade offs. Certain mitigation strategies, for example, could minimize the need for ATC-RPA communication with more separation responsibility on board. A higher fidelity breakdown of the response time with focus on individual communication links could be explored.

The work presented is also a first step towards developing both an understanding and a test environment to conduct more detailed studies that measure impact at increasing levels of autonomy in the airspace. These may include delegating separation responsibility to the RPA or RP from ATC. These could also include increased automation of RP and ATC tasks and increasing the number of RPA (N) that are managed by the number of remote pilots (m). While this paper focused on a RP:RPA ratio of 1:1, the test apparatus can be augmented to simulate m:N scenarios wherein a few RPs operate several RPA.

Acknowledgments

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