Sensitivity Analysis of Key Factors in High Density Unmanned Aerial System Operations

Min Xue*
NASA Ames Research Center, Moffett Field, CA 94035

The interest in air passenger and cargo transportation within an urban area is growing rapidly. Safely and efficiently managing high-density operations in low-altitude airspace still faces great challenges. The new concept of air transportation revolutionizes the paradigm of the existing air traffic system due to the variety of vehicle characteristics, high-density operations, urban operational environments, and complex atmospheric condition in low-altitude airspace. In order to gain a better understanding of how individual components affect high-density safe operations, this work analyzes the effects of a list of critical factors, including communication latency, position accuracy, wind, separation buffer, and traffic density under a specific system setup. Experiments showed that these sensitivity studies can help define system requirements. For instance, with the default conflict management setup, 20 vehicles can safely operate in an area of three square nautical miles with zero losses of separation if the intruder's position error is less than 40 feet. Furthermore, a 5% energy reserve should be adequate to deal with the position uncertainty. Experiments also revealed that increasing the separation buffer within the conflict management model improved the safety robustness to position errors, but did not improve the tolerance to communication latency and wind. Overall, this work demonstrated that the proposed sensitivity studies based on fast-time simulation results can be used to quantify the relationships among key factors in a high-density unmanned aerial system traffic management system and help define requirements for these factors for a given safety threshold.

I. Introduction

In recent years, driven by the rapidly growing interest in air passenger and cargo transportation within an urban area, the concepts of unmanned aircraft system traffic management (UTM) [1] and urban air mobility (UAM) [2] have been proposed to enable safe and efficient aerial vehicle operations. These new concepts change the paradigm of existing air traffic systems because of a variety of factors, including various vehicle characteristics, increased density of operations, urban terrain environments, and complex atmospheric condition in low-altitude airspace. How to safely and efficiently handle high-density operations in low-altitude airspace faces great challenges.

Because of the above characteristics, many minor factors in conventional aviation and large Unmanned Aerial System (UAS) operations may play important roles in the new operational environments. For instance, the communication update rate becomes critical as vehicles fly much closer to each other than in conventional aviation. When vehicle density gets high, the communication signal interference becomes severe due to the high communication channel load [3, 4]. Moreover, while new vehicle types (e.g., multicopters) can execute agile operations in urban areas, they also impose complexity on analyzing airspace operation capacity. As vehicles operate closely, the effects of position accuracy and wind on a UAM/UTM traffic system need to be investigated. Although there were many studies on complexity or capacity for conventional aviation [5–9] and some initial studies on small UAS (sUAS) operations [10, 11], the understanding of key factors that affect the high-density UAM and UTM operations is still limited. In-depth studies must be conducted to help stakeholders understand and derive requirements for these factors, including equipages, conflict management models, and wind conditions. These studies can be used to help enable safe and efficient high-density air traffic operations.

This work analyzed five factors that can impact the traffic system: position accuracy, communication latency, wind uncertainty, traffic density, and separation buffers. To analyze the impact of these factors on safety and efficiency in high density operations, hundreds of experiments were conducted using the Fe^3 simulation tool [12]. Section II introduces the experimental setup in this work, including the conflict resolution model and test scenarios. Section III presents sensitivity study results and analyses. Section IV summarizes the findings in this work.

*Aerospace Research Engineer, Aviation Systems Division. Mail Stop 210-15. AIAA senior member.

II. Experiment Setup

The Fe[3] simulation tool incorporates many models that are involved in low-altitude air traffic operations, such as six degrees of freedom (DOF) vehicle aerodynamic and control models, conflict resolution models, wind, communication, navigation, and energy consumption. A description of these models can be found in previous research [12]. To understand experimental results and analyses in this work, the experiment setup is presented in this section to provide necessary context, including the conflict management model and test scenarios.

A. Conflict Management Model

According to the UTM conflict management model published by the NASA UTM research transition team (RTT) sense and avoid (SAA) working group [13], a three-phase confliction management model was proposed to resolve predicted conflicts between two sUASs: strategic conflict management, separation provision, and collision avoidance. The strategic conflict management changes flight plans to resolve conflicts and normally occurs prior to departure. The separation provision is a tactical process for conflicts predicted while airborne to prevent well-clear violations. The collision avoidance is triggered when the well-clear definition is violated and serves as the last layer of conflict resolution. Because the strategic separation phase occurs prior to departure and will be handled by scheduling and re-routing flight plans through the UAS Service Supplier (USS) and/or Supplemental Data Service Provider (SDSP), the conflict management model in this work only covers separation provision and collision avoidance phases when sUASs are aloft after departure.

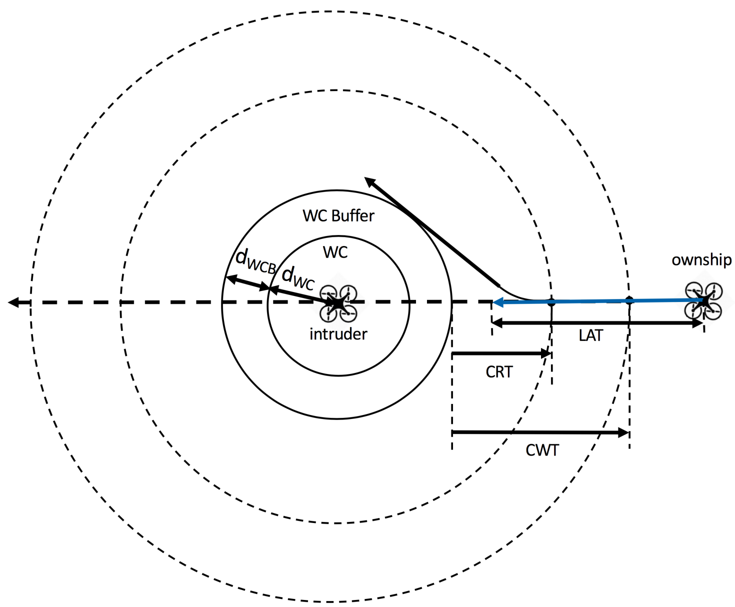


Fig. 1 Structure used in the conflict resolution algorithms

Since the RTT work package didn't specify the complete structure for the separation provision, a detailed framework is proposed to implement the conflict resolution algorithm for this work. Figure 1 shows the structure (not to scale) used in the simulator. The well-clear (WC) threshold d_{WC} provides minimal space for collision avoidance for which both ownship and intruder can take actions as the last effort before colliding with each other and serves as the boundary between the collision avoidance and separation provision phases. The well-clear buffer d_{WCB} defines the extra buffer used to improve error tolerance. The look-ahead time (LAT) t_{LAT} defines the time horizon for trajectory prediction. The conflict warning threshold (CWT) defines the time t_{CWT} when a conflict warning becomes effective. The conflict resolution threshold (CRT) defines the time t_{CRT} when the ownship can start to maneuver to resolve the conflict. Since developing the well-clear definition is still an open research question [11, 14], a distance of 30 feet is arbitrarily chosen for d_{WC} this study. The default settings of these parameters are: t_{LAT} = 50 seconds, t_{CWT} = 50 seconds, t_{CRT} = 30 seconds, d_{WC} = 30 feet, and d_{WCB} = 50 feet.

The model used in this work utilizes discrete heading changes as the only resolution maneuver option. Vehicles are assumed to fly cooperatively following a set of predefined conflict resolution logics to decide the right of the way and the preferred resolution maneuver when there are multiple solutions. While defining a safe and efficient set of conflict resolution logic remains as a challenging problem [15, 16], this work adopts the following simple logics to decide the right of way and the resolution maneuver preference:

- If the intruder is on the right side of the ownship, the intruder has the right of way and the ownship shall take a conflict resolution maneuver.
- If it's a head-on conflict, both the ownship and intruder shall take right turns.
- If the ownship and intruder are in-trail, the front vehicle has the right of the way and the trailing vehicle shall take an avoidance maneuver.
- If the well-clear definition is violated, both ownship and intruder need to take maneuvers to avoid collision.
- When there are multiple resolutions, the maneuver with minimum deviation from its planned trajectory is chosen.

The conflict resolution model uses the constant-velocity ("dead-reckoning") trajectory projection with a maximum turn rate when producing trial trajectories corresponding to various heading change options. The update rate of the conflict resolution model is set to 500 milliseconds, which is assumed to be the approximated computational time needed for a conflict resolution algorithm [17]. For reference, the update rate of ACAS-X is expected at 1Hz [18] and the same is expected for the Detect And Avoid (DAA) algorithms in the Java Architecture for Detect and Avoid Extensibility and Modeling (JADEM) [19].

B. Test Scenarios

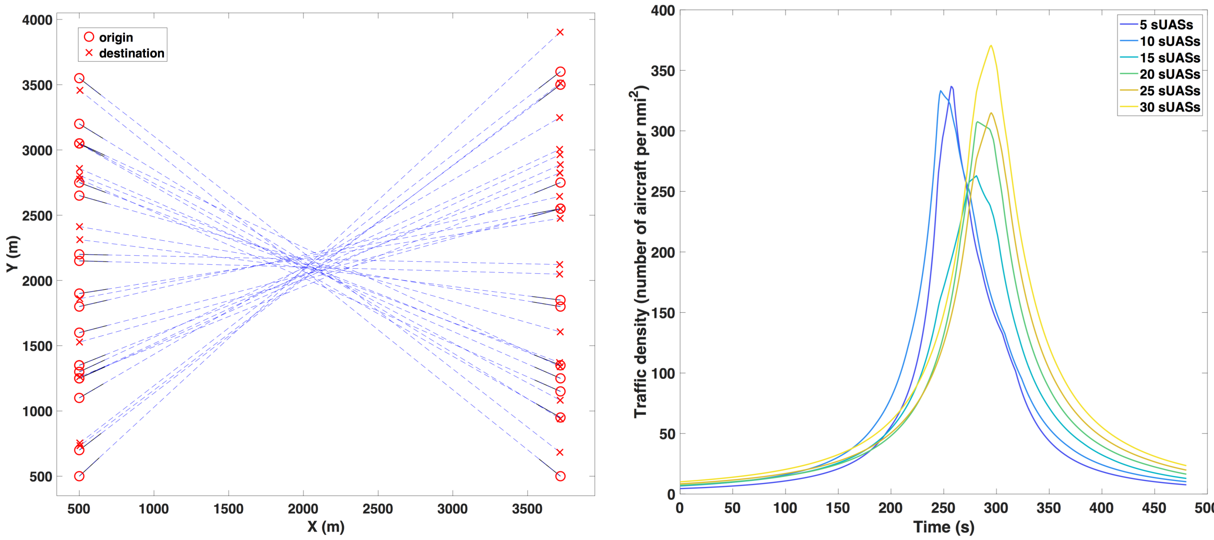
Pairwise encounter scenarios are typically used in analyzing the performance of DAA algorithms. Despite their popularity, pairwise encounter scenarios are not enough for systematic analyses in medium and high density operational environments (e.g., >1 aircraft/nmi^2), where aircraft operate much closer to each other and multi-aircraft encounters are common. Previous work [12] showed that even though a conflict resolution algorithm resolved all conflicts in thousands of pairwise encounter scenarios with varied relative speeds and encounter angles, it still could not prevent losses of separation in multi-aircraft encounter scenarios, where a loss of separation happens when the well-clear threshold is violated. Apparently, multi-aircraft encounter scenarios serve the purpose better in systematic analyses.

The traffic density is a simple and intuitive metric commonly used to describe the airspace operation complexity. It's usually defined by the number of aircraft divided by the operating area over a given period (e.g., number of aircraft per nmi^2). However, this definition is not an accurate complexity measurement, especially when comparing a scenario of multiple aircraft flying in parallel against a scenario of multiple aircraft flying towards each other with potential conflicts. In this work, six multiple-aircraft scenarios were created, not only with increased traffic density but also with increased number of potential conflicts (when no conflict resolution maneuver is used) to ensure increased complexity. Because quantifying the complexity is still an ongoing research topic, it's not clear if the complexity of these scenarios increases proportionally with the aircraft count or with the number of potential conflicts.

Table 1 Test Scenarios

Scenario	I	II	III	IV	V	VI
Aircraft count	5	10	15	20	25	30
Traffic density over the entire simulation period (aircraft/nmi^2)	1.6	3.2	4.8	6.5	8.1	9.6
Average of instantaneous traffic density (aircraft/nmi^2)	59	69	63	68	72	85
Number of potential conflicts	1	2	2	5	7	10

Flights in these scenarios are planned to fly direct routes, which means that each flight flies directly from its own origin to destination without any planned turns as shown in Fig. 2(a). The target ground speeds of all sUASs are 22 fps (or 15 mph) and approximated flight times are around 450 seconds. The operation area is about 3 nmi^2. In this study, a quad-rotor vehicle model is used for all vehicles. Table 1 lists some attributes of these six scenarios. As presented in the table, the aircraft count varies from 5 to 30 aircraft and the number of potential conflicts (without any conflict resolution maneuver) increases from 1 to 10. Convex hull was used to create a boundary around all sUASs (with each sUAS wrapped with separation buffers). This boundary represents the current operating area. The history of instantaneous traffic density (over one second) is calculated and shown in Fig. 2(b) to provide some insight on the complexity of these test scenarios. The averages of these instantaneous traffic densities are presented in Table 1.



(a) Flight plans in Scenario VI

(b) Time histories of traffic densities

Fig. 2 Test Scenarios

III. Experiments

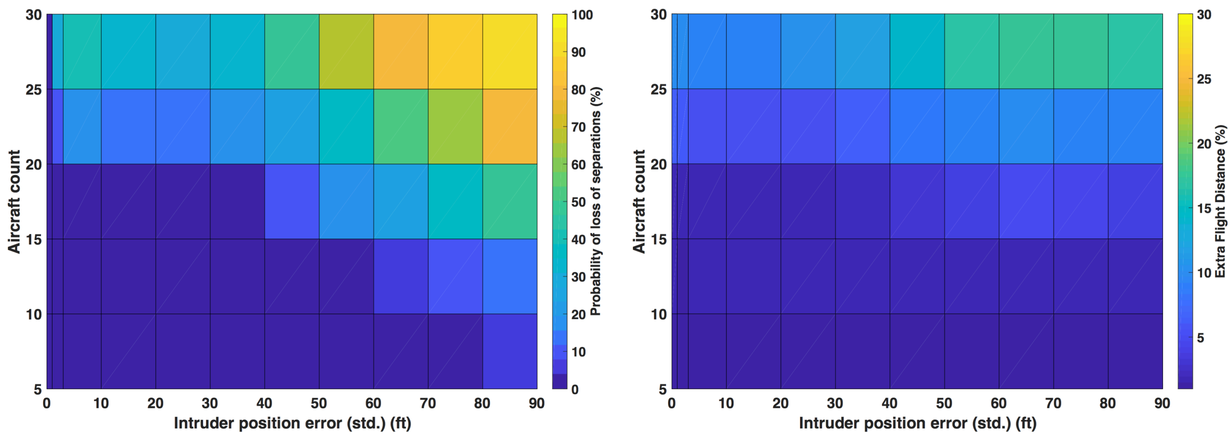
Five factors including traffic density, position accuracy, communication latency, wind, and separation buffer, are investigated in this work. To identify their individual effects, only one parameter is varied. The probability of loss of separation and average percentage of extra flight distance are measured and used to represent safety and efficiency measurement, respectively. The percentage of extra flight distance is the percentage of additional flight distance divided by the unimpeded flight distance where no resolution maneuver is involved. Because the flight distance is highly correlated to the energy consumption, the percentage of extra flight distance can be used to approximate required energy reserve. For simplicity, the aircraft count is used to represent the six test scenarios in the following sections.

A. Position accuracy

An intruder's position can be obtained through sensors (on-board or ground-based) or shared by the intruder via various communication approaches. This section examines the effect of intruder position error despite the means of obtaining the information. It assumes that each vehicle's own position is known accurately, whereas intruder positions include errors that follow a normal distribution with a zero mean. Position errors are introduced purely by the standard deviation. With a specified standard deviation, the Fe^3 simulator can generate random errors to simulate intruder positions received by the ownship and feed them into the conflict management algorithm. About 1,000 Monte Carlo simulations are performed for each position accuracy level defined by standard deviation to obtain the probability of loss of separation and the percentage of extra flight distance.

Figure 3(a) presents the probability of loss of separation under various density levels and intruder position accuracy levels. The cold colors denote low probability of loss of separation whereas the warm colors represent high possibility of loss of separation. It is noted that the dark blue grids are safe operational regions where no losses of separation are expected. According to this plot, one may derive requirements for safe operations given the default setup in this work: At the density level with 5 vehicles, the standard deviation of intruder position received by the ownship must be less than 80 feet; when the number of operating vehicles increases to 20, the intruder position error must be less than 40 feet; when the aircraft count is between 20 and 30 vehicles, no position error should be allowed for any safe operation.

Figure 3(b) shows the percentage of extra flight distance, which can be used to help define requirements for energy reserves. This metric is directly related to requirements for battery life. It is shown that within the region where there is a zero percent chance of loss of separation (the dark blue area in Fig. 3(a)), when the aircraft count is less than 15 vehicles, the percentage of extra flight distance is typically less than 5%, which implies that 5% energy reserve should be adequate. When the aircraft count is 20 and the position standard deviation is over 60 feet, the percentage of extra flight distance is over 10%, which indicates that the energy reserve has to be greater than 10% to deal with position uncertainties. It's clear that position uncertainty affects both safety and efficiency. Improving position accuracy not only increases the safety level but also helps improve operational efficiency.



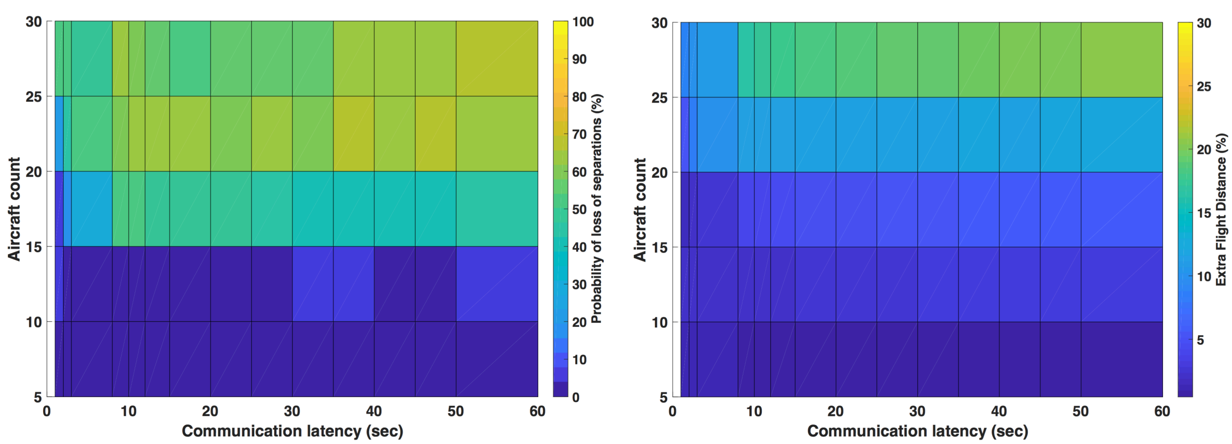
(a) Safety measure: probability of loss of separation (%)

(b) Efficiency measure: extra flight distance (%)

Fig. 3 Impact of Position Errors on Safety and Efficiency

B. Communication latency

Various communication techniques have been proposed and studied for UTM operations such as ADS-B [3, 20], DSRC [21], LDACS [22], LTE&5G [23]. While identifying appropriate communication techniques is still an active research area, this section provides a basic understanding of effects caused by communication latency regardless of communication technologies. A communication latency of 5 seconds means that the ownship vehicle can only receive one complete and accurate package of intruder's information every 5 seconds, which can be translated to a reception probability of 10% at each time step (half a second) of the Fe^3 simulator. Similar to the position accuracy study, once the communication latency is specified, the simulator can then simulate the package reception probability using the uniform distribution.



(a) Safety measure: probability of loss of separation (%)

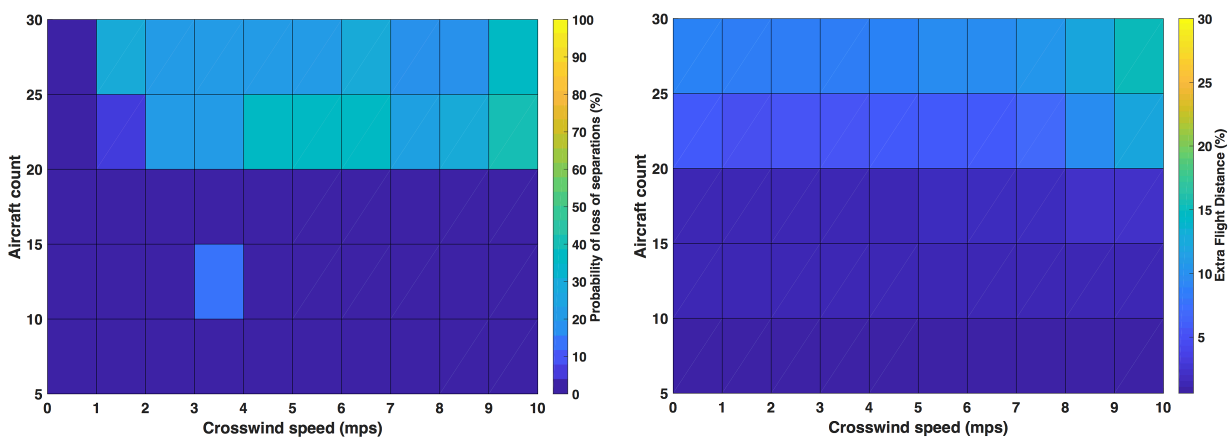
(b) Efficiency measure: extra flight distance (%)

Fig. 4 Impact of Communication Latency on Safety and Efficiency

Figure 4(a) presents the probability of loss of separation under various communication latencies. It is interesting to see that when the aircraft count is lower than 15, these data suggest that it is safe to operate even with a 60 second communication latency. This requirement on communication latency is generous. Whereas, at an aircraft count of 20, the communication delay has to be less than 1 second for safe operation. Unlike the gradual transition in experiments with position error, the probability of loss of separation increases suddenly once the aircraft count is higher than 15. Figure 4(a) shows that the safety measurement (based on loss of separation) is more sensitive to the traffic density, or aircraft count, than the communication latency. Comparing these results to position accuracy, when there are 20 vehicles, the safety measurement is less tolerant to communication latency than to position error (where the operations were still safe within a 40-foot position error). Figure. 4(b) presents the percentage of extra flight distance and shows that within the safe operation zone (i.e., the dark blue region in Fig. 4(a)), the inefficiency caused by communication latency is close to 10%, which is slightly higher than what was seen within the safe region for the position uncertainty case.

C. Wind

Wind disturbance becomes a major concern for UAS operation, especially when these small and lightweight UASs operate in low-altitude airspace where the wind gust is much less predictable within the Atmospheric Boundary Layer (ABL). Experiments with different crosswind conditions are explored in this section. The wind condition at any location is defined as a statistical distribution with a mean and standard deviation (intensity). The mean of the crosswind is limited to 0 to 10 mps because the quadrotor vehicle model used in this work cannot conform to its trajectory once the crosswind is higher than 12 mps. The wind intensity is simply defined as one tenth of the mean [12, 24]. Figure. 5(a) shows the probability of loss of separation at various crosswind speeds. It is noticed that crosswind is not an issue when the aircraft count is lower than 20 (assuming the crosswind is under the 12 mps maximum operational limit). The hypothesis is that the vehicle control system mitigated the trajectory disturbance by applying tight controls to make sure each vehicle conforms to its planned trajectory as much as possible. Therefore, the disturbance caused by crosswind didn't reduce the trajectory projection accuracy enough to affect the performance of the conflict resolution algorithm. Figure 5(b) confirms that the extra distance is relatively low due to the tight control law utilized by the vehicle. The percentage of extra distance is typically around 2% when the aircraft count is lower than 20. It should be noted that the extra flight distance may not represent the extra energy in this case. Due to the increase of the drag force caused by wind, extra energy will be consumed to produce extra forces, which is not reflected by the extra flight distance in Fig. 5(b).



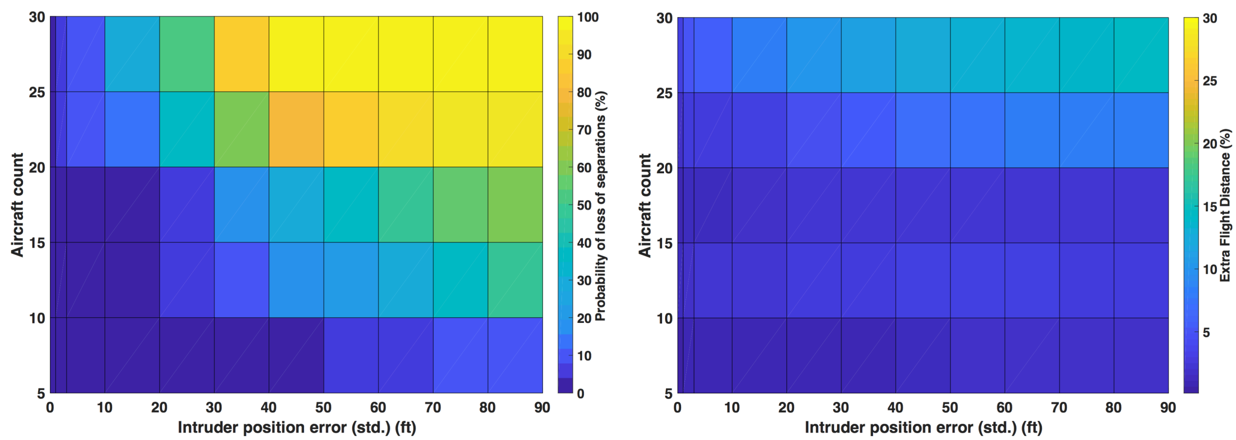
(a) Safety measure: probability of loss of separation (%)

(b) Efficiency measure: extra flight distance (%)

Fig. 5 Impact of Cross Wind on Safety and Efficiency

D. Separation buffer

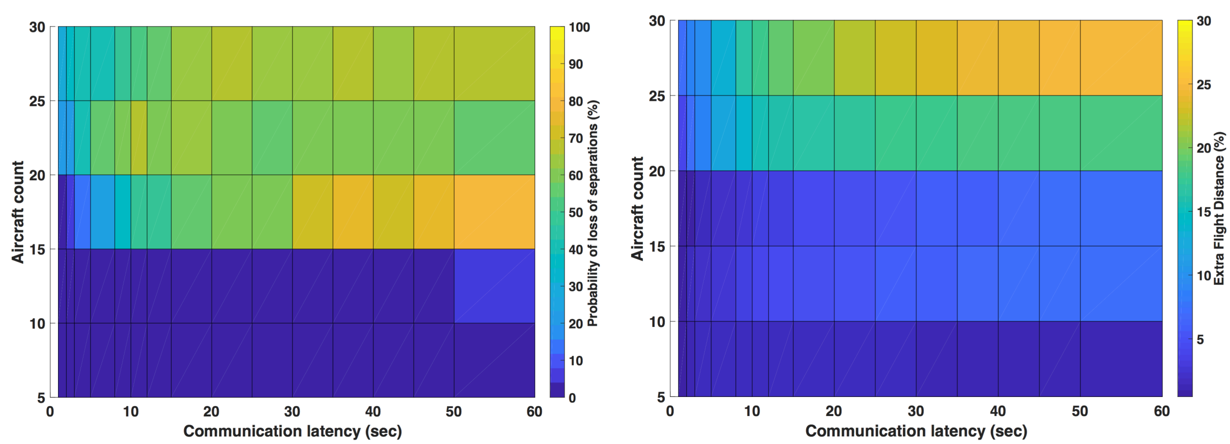
As a core component, the conflict management model plays an important role in the low-altitude traffic system. The model, which includes structure, parameters, and logics/rules, greatly affects the outcome in terms of safety and efficiency. To better understand its impact, this section investigates one parameter in the conflict management model: separation buffer, which is defined as an extra buffer around the well-clear threshold. The separation buffer d_{WCB} is changed to 10 feet instead of 50 feet. Figure 6(a) and 6(b) present results for various position errors as a comparison. When comparing Fig. 6(a) to Fig. 3(a), the safe operation area (dark blue area with zero losses of separation) is much smaller. Even at the traffic density level with 5 vehicles, to guarantee zero losses of separation, the position errors is required to be less than 50 feet. Meanwhile, comparing Fig. 6(b) to Fig. 3(b), the efficiency has been slightly increased due to the low extra flight distance that resulted from the small separation buffer.



(a) Position errors: probability of loss of separation (%)

(b) Position errors: extra flight distance (%)

Fig. 6 Impact of Separation Buffer on Safety and Efficiency: Position Errors

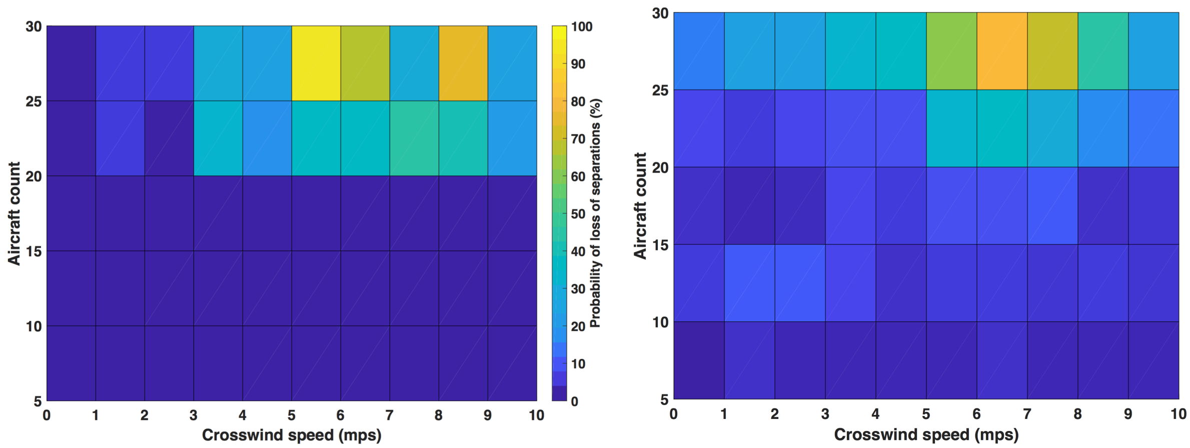


(a) Comm. latency: probability of loss of separation (%)

(b) Comm. latency: extra flight distance (%)

Fig. 7 Impact of Separation Buffer on Safety and Efficiency: Communication Latency

Figure 7(a) and 7(b) provide results for communication latency with this reduced separation buffer. Comparing against the previous section, there are not many differences in terms of safe operation area and efficiency, especially at low traffic density levels. However, the safety and efficiency measurements become a bit more sensitive to communication latency when the aircraft count is higher than 15. Similar trends hold for the wind study. As shown in Fig. 8(a) and 8(b), reducing the separation buffer didn't affect safety and efficiency very much. According to this study, it seems that increasing the separation buffer makes the traffic system more robust to position errors, while improving the robustness to communication latency and crosswind less noticeably.



(a) Wind: probability of loss of separation (%)

(b) Wind: extra flight distance (%)

Fig. 8 Impact of Separation Buffer on Safety and Efficiency: Wind

E. Discussion

Given a specific conflict management model, the above experiments showed that sensitivity analyses of key factors could be examined through the Monte Carlo simulation capability in Fe^3. Experiments on position accuracy showed that intruder's position accuracy not only affected the safety of a sUAS traffic system but also its efficiency. Data suggest that a sUAS traffic system can safely operate up to 20 vehicles with zero losses of separation if position errors can meet corresponding requirements. The extra energy reserve, derived from extra flight distance, is less than 5%. Studies in communication latency showed two extreme conclusions that high density operations are vulnerable to communication latency, whereas, low density operations are robust to it. Extra energy consumed due to communication latency can reach 10 % within the safe operation zone. Although there may exist a maximum crosswind that a sUAS can tolerate, with an appropriate control system, the crosswind should not be a major concern for maintaining safety and extra flight distance, especially at a relatively low traffic density. However, extra energy may be consumed due to extra drag force caused by wind, even though the extra flight distance is very low. Studies in separation buffer showed that increasing the separation buffer improved the robustness to position errors, whereas it did not drastically improve the robustness to communication latency and wind.

Findings in this work may change if the conflict management model (including structure, parameters, and logics) changes. However, given a safety and efficiency threshold, these types of studies (using Fe^3 simulations) can be used to derive and evaluate requirements for a high-density traffic system including equipages and conflict management models.

IV. Summary

This paper presented a systematic sensitivity analysis of key contributors effects on safety and efficiency in high density UAS operations. The structure and model of the conflict resolution algorithm used in the simulator are presented first to setup the context for experiments in this work. The test scenarios with increasing complexity are then introduced. The probability of loss of separation and the percentage of extra flight distance are used in this work to represent safety and efficiency measurements, respectively. Five key factors including position accuracy, communication latency, wind, separation buffer, and traffic density, were then investigated. Experiments showed that requirements on these factors can be easily derived. For instance, 20 sUASs can safely operate in the given area under the default setup with zero losses of separation as long as the position error is less than 40 feet. For this configuration, the energy reserve must be higher than 5%. Studies also reveal relationships among those factors. For example, increasing the separation buffer improved the system robustness to position errors but doesn't improve its tolerance to communication latency and wind. This type of Fe^3-based study can be used to define requirements for a high-density traffic system.

Future work will extend to sensitivity analyses with conflict management models that are more comprehensive and realistic. Parameters and logics will be studied for evaluating and developing a safe and efficient conflict management model. Meanwhile, different concept of operations, like route structure based operations, will also be investigated to find out if and when route structure based operations are beneficial. Mixing vehicle types and their performance characteristics will also be considered. In addition, using these sensitivity analyses will allow a real-time model to be developed to quickly assess the airborne risk in terms of metrics like the probability of loss of separation and minimum energy reserve.

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