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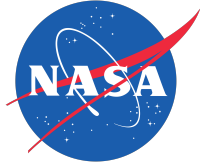
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Acknowledgments

The material is based upon work supported in part by NASA under award number NNA16BD14C and 80ARC024DA007 for NASA Academic Mission Services (NAMS-1 and NAMS-2) respectively.

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Summary

This research aims to study the trade-off between safety and efficiency of 4D volume-based pre-departure strategic deconfliction (SD) under wind uncertainty in the small unmanned aircraft systems (sUAS) traffic management (UTM) environment for beyond-visual-line-of-sight (BVLOS) flight operations, specifically considering unmanned aircraft (UA-to-UA) conflicts. In this research, simulation-based studies are performed using NASA's Flexible Engine for Fast-time Evaluation of Flight Environments (Fe³) simulator by varying operational volume block (OVB) sizing, wind uncertainty (magnitude and direction), sUAS package delivery demand rate, and air traffic complexity. The simulation results suggest that employing 4D volume-based pre-departure strategic deconfliction using relatively larger OVB sizing does not always ensure higher-level of safety when sUAS are flying in a constant airspeed mode under wind uncertainty. Therefore, safety in the UTM ecosystem under wind uncertainty is contingent upon additional conflict management services and the presence of flight control features, for example, the participating sUAS maintaining a constant groundspeed.

1 Introduction

Small unmanned aircraft systems (sUAS) are expected to provide socio-economic benefits by transforming operations in areas such as package delivery, precision agriculture, surveillance, support for first responders, and the inspection of critical infrastructure like railroads and bridges. These sUAS are anticipated to operate: i) much closer to each other (higher traffic density) than conventional aircraft, ii) exclusively in low-altitude airspace, i.e., less than 400 ft above ground level (AGL) (Ref. 1), and iii) beyond visual line-of-sight (BVLOS) in the National Airspace System (NAS) (Ref. 2–4).

The demand for various sUAS operations necessitates innovative Air Traffic Management (ATM) solutions to accommodate the anticipated dense sUAS BVLOS operations over densely populated urban areas and within complex airspace. Consequently, sUAS Traffic Management (UTM) aims to develop a scalable traffic management system that safely and efficiently integrates these low-altitude sUAS BVLOS operations into the NAS.

1.1 Background

In this section, definitions and concepts that are key to understanding the current studies and results are described.

1.1.1 Conflict Management Model

UTM has been envisioned to have multiple layers of a conflict management model for unmanned aircraft (UA-to-UA) conflicts to ensure the safe, efficient, and scalable operations of sUAS. These layers of the conflict management model are strategic deconfliction, tactical separation assurance, and collision avoidance (Ref. 3). At each layer, UA-to-UA conflicts are resolved through a series of maneuvers compatible with the operational environment. On one hand, the objective of the first layer of the conflict management model, i.e., pre-departure strategic deconfliction, is to i) minimize the likelihood of airborne conflicts between sUAS operations and ii) maximize the airspace usage, for example, by adjusting the departure times of sUAS (Ref. 2, 3). The strategic deconfliction may involve re-planning routes in some scenarios. On the other hand, the tactical separation assurance layer consists of executing one or more maneuvers (speed change, altitude change, and path-stretch) to avoid an airborne conflict promptly when strategic deconfliction was not executed or has failed due to uncertainties (Ref. 5–7). Finally, the last layer of protection is the onboard detect and avoid (DAA) system/traffic collision avoidance system (TCAS) (Ref. 2).

1.1.2 Pre-Departure Strategic Deconfliction Using Trajectory-Based Operational Volume Blocks

In the UTM ecosystem, a sUAS operator planning to fly BVLOS is required to share the trajectory-based operational intent (OI) with other sUAS operators/airspace users via the sUAS Supplier Service (USS) network (Ref. 2, 3). As shown in Figure 1, the trajectory-based operational intent includes a sequence of 4D (spatiotemporal) operational volume blocks (OVBs) that make up the intended flight profile (Ref. 2, 8, 9). In this research, each OVB is assumed to be fixed in space and has specified entry and exit times for the sUAS of an operator per NASA and the FAA’s UTM concept of operations (Ref. 2, 3, 8). In the operation planning phase, prior to departure, the sUAS operator or operator’s USS checks the OVBs against other sUAS operations for any 4D conflicts.

If any spatiotemporal overlapping of OVBs is detected, then negotiation and replanning of the operational intent of the sUAS are performed (Ref. 2, 10). For example, at a crossing waypoint, whenever there is a 4D spatiotemporal overlapping of two operational intents of different sUAS operators, then deconfliction of overlapping OVBs can be performed via temporal separation at the waypoint because of the 400 ft AGL upper bound constraint for the cruise altitude of sUAS operations (Ref. 1, 2).

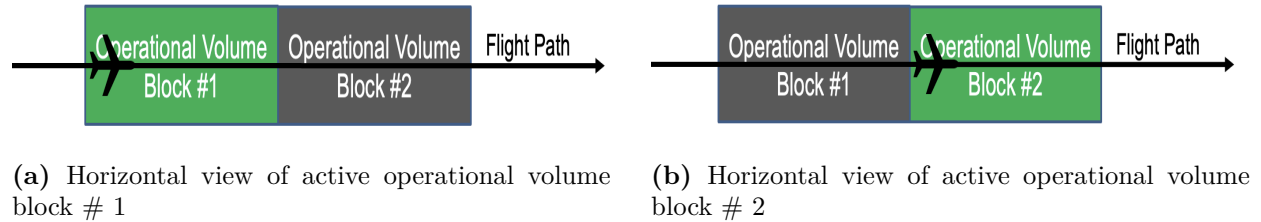


Figure 1.—Activation (Green) and Deactivation (Grey) of Operational Volume Block (OVB) as a sUAS Enters and Exits (Ref. 4)

1.1.3 Aggregate Conformance Monitoring (ACM)

Aggregate Operational Intent Conformance Monitoring, also known as Aggregate Conformance Monitoring (ACM), determines if flights of a sUAS operator are conforming to their operational intents over time (Ref. 11). Therefore, the ACM functionality determines if a sUAS of the operator is conforming with its active OVBs of the coordinated and active OI at least a minimum percentage of total flight time. If a sUAS operator is chronically in nonconformance, it could indicate a problem with the construction of OIs, characterization of sUAS performance, or the operating procedures (Ref. 11). However, to study the adverse impact of various factors such as OVB sizing, demand-rate, air traffic complexity, and wind uncertainty (magnitude and direction) (Ref. 6, 12), the % of aggregate nonconformance is used as one of the safety metrics in this research.

1.1.4 Near Mid-Air Collision (sNMAC) for UA-to-UA Conflict

Given the small size of various package delivery sUAS, UA-to-UA mid-air collision (sMAC) may be a rare event, i.e., loss of horizontal separation of 3 m (Ref. 13) from a safety metric perspective. Therefore, an alternative measure for UA-to-UA conflict, i.e., near mid-air collision (sNMAC), is defined as any loss of 15.24 m (50 feet) of horizontal separation between UA-to-UA for a safety metric (Ref. 13). This approach is based on scaled down format of a loss of separation (LOS) definition of 500 feet of horizontal separation and 100 feet of vertical separation in commercial aviation called a near-mid air collision - NMAC (Ref. 13, 14).

1.1.5 Fe³: Fast-Time Simulation Tool

NASA's fast-time simulation tool called "Flexible engine for Fast-time evaluation of Flight environments (Fe³)" provides the capability of statistically analyzing high-density, high-fidelity, and low-altitude traffic system without conducting flight tests. Using the fast-time simulation capability of Fe³, stakeholders can study the impacts of critical factors, define requirements, policies,

and protocols needed to support a safe and efficient traffic system, assess operational risks, and optimize flight schedules (Ref. 15). It consists of two main functions, i.e., trajectory generation and collision avoidance (Ref. 15). To keep the fidelity at a high level, 6-DOF vehicle trajectory models are implemented in the Fe³ simulator.

1.2 Motivation

The motivation of the current research is to understand the impact of OVB sizing, wind uncertainty (magnitude and direction), sUAS package delivery demand rate, and air traffic complexity on the safety (UA-to-UA conflicts) and efficiency (throughput) of 4D volume-based pre-departure strategic deconfliction (SD) in the UTM BVLOS ecosystem. The following four metrics are used to measure efficacy of 4D volume-based pre-departure SD under various conditions: i) sNMACs risk ratio, ii) sMAC per sUAS operation, iii) the percentage of nonconformance to active OVBs of approved operational intents, and iv) the departure throughput per operations depot.

The rest of the paper is organized as follows. In Section 2, the framework for simulation-based studies using the Fe³ simulator is presented. In Section 3, simulation results from this research are discussed. Finally, the main findings are summarized in Section 4.

2 Framework of Simulation-Based Studies

As stated earlier, fast-time simulation-based studies are conducted to understand the impact of uncertainties on the safety and efficiency of sUAS flights in the UTM ecosystem, as shown in Figure 2.

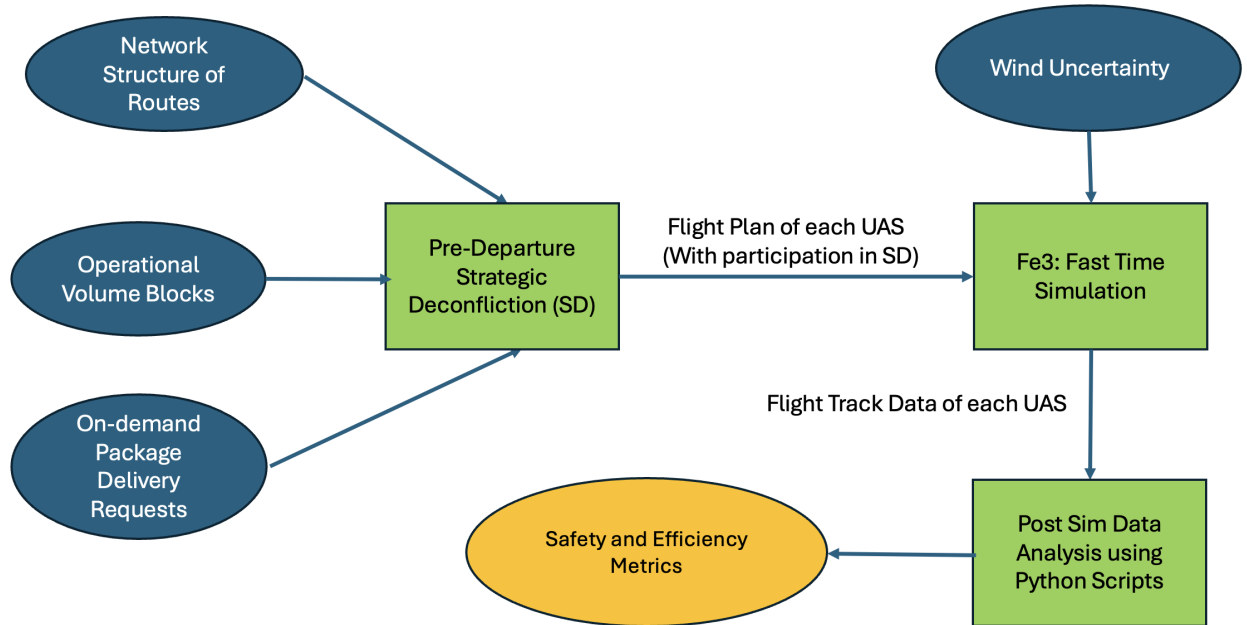


Figure 2.—Framework of Simulation-Based Studies

2.0.1 sUAS Trajectories

To study UTM BVLOS flight operations under uncertainties, a quadrotor aerial vehicle model (flight kinematics, flight dynamics, power required, and energy consumption) is incorporated in the Fe³ simulator to compute sUAS trajectories (Ref. 15, 16). In this research, the Fe³ simulator is used to generate sUAS trajectories. The tactical separation assurance functionality of the simulator is intentionally turned off to understand the need for conformance monitoring for situational awareness (CMSA) and tactical separation assurance services under uncertainties, even with 4D volume-based pre-departure strategic deconfliction of sUAS. Therefore, post-simulation flight track data of sUAS are analyzed to understand nonconformance and sNMACs risk ratio due to uncertainties in the environment. In various scenarios, sUAS are flown either in a constant airspeed mode or constant groundspeed mode.

2.0.2 UTM Scenarios

This research considers two different network structures of routes with varying levels of air traffic complexity of sUAS operations (Ref. 17), as shown in Figure 3. The traffic density of sUAS on each route is maintained the same irrespective of the number of routes originating from an operations depot so that the level of complexity increases with an increase in the number of routes and crossing waypoints, mainly to compare results from two different network structures of routes. The on-demand service request to deliver packages using sUAS on each route of an operations depot is simulated using a Poisson distribution (Ref. 4, 18).

In pre-departure strategic deconfliction problem formulation, three types of temporal separation constraints are imposed between sUAS flights. First, for each sUAS flight, a temporal separation constraint between on-demand package delivery request time (ODT) and scheduled time of departure (STD) is imposed for flight and package preparation time ($\Delta t_{\text{Flight Preparation}}$) (Ref. 4, 18):

$$\text{STD}(i) \geq \text{ODT}(i) + \Delta t_{\text{Flight Preparation}} \quad (1)$$

Next, a minimum temporal separation constraint ($\Delta t_{\text{Departure}}$) is imposed between STDs of a leading sUAS and trailing sUAS as follows (Ref. 4, 18):

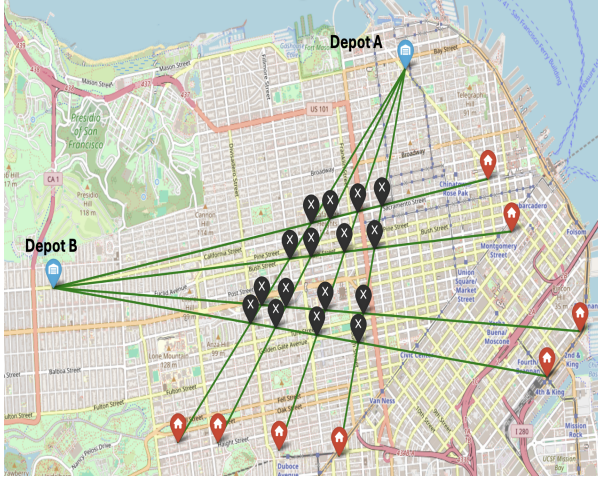
$$\text{STD}(i+1) \geq \text{STD}(i) + \Delta t_{\text{Departure}} \quad (2)$$

Finally, a minimum temporal separation ($\Delta t_{\text{Crossing Waypoint}}$) constraint imposed between scheduled time of arrival (STA)s of two sUAS belonging to different operators at the crossing waypoint is as follows (Ref. 4, 18):

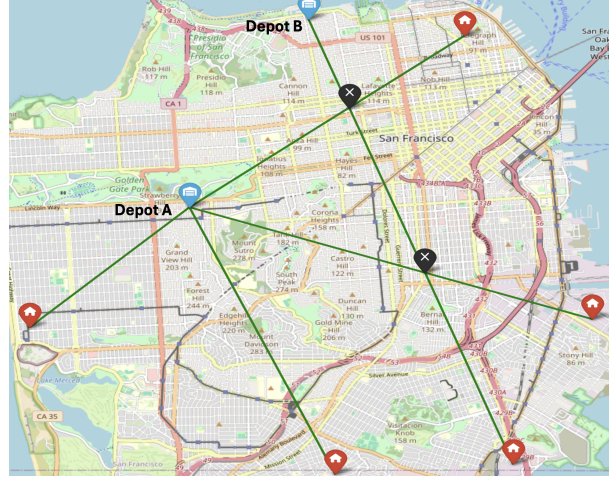
$$(\text{STA}(j) - \text{STA}(i))\omega(i, j) + (\text{STA}(i) - \text{STA}(j))(1 - \omega(i, j)) \geq \Delta t_{\text{Crossing Waypoint}} \quad (3)$$

where $\text{STA}(i)$ and $\text{STA}(j)$ are the scheduled times of arrival to the crossing waypoint of the i^{th} sUAS and j^{th} sUAS, respectively, and $\omega(i, j)$ is the binary decision variable to decide which sUAS will sequence the crossing waypoint first, i.e., i^{th} sUAS or j^{th} sUAS (Ref. 19):

$$\omega(i, j) = \begin{cases} 1, & \text{if } i^{\text{th}} \text{ sUAS sequences before } j^{\text{th}} \text{ sUAS,} \\ 0, & \text{if } j^{\text{th}} \text{ sUAS sequences before } i^{\text{th}} \text{ sUAS,} \end{cases} \quad (4)$$



(a) Scenario 1: top view of network structure of routes with sixteen crossing waypoints (higher air traffic complexity)



(b) Scenario 2: top view of network structure of routes with two crossing waypoints (lower air traffic complexity)

Figure 3.—Various Network Structures of Routes for Generating Simulated UTM Scenarios in San Francisco Metropolitan Area (Courtesy OpenStreetMap(Ref. 20))

2.0.3 Wind Uncertainty in the UTM Ecosystem

For various UTM scenarios, pre-departure strategic deconfliction of sUAS flights to resolve UA-to-UA conflicts is performed in the absence of wind uncertainty, i.e., in a deterministic environment. Then, the wind uncertainty (as shown in Table 1) is introduced in the fast-time simulation environment to study the impact on the chosen safety and efficiency metrics, such as sNMACs risk ratio, sMACs per sUAS operation, the percentage of nonconformance to active OVBs of sUAS flights, and throughput.

2.0.4 Operational Volume Block (OVB) Sizing

In a given scenario, size of OVBs for each sUAS is chosen based on the transit time (T_{OVB}) of the sUAS in the trajectory-based active OVB:

$$T_{OVB} = \int_0^L \frac{1}{V_{GS}} dl \quad (5)$$

where V_{GS} is the groundspeed of the sUAS, L is the length of the OVB, and dl is the infinitesimal length along the flight path. In this research, transit time of sUAS in all OVBs are assumed to be

Table 1.—Wind Uncertainty Used in Simulation-Based Studies

Definition	Value (%)	Wind Direction
Wind Magnitude Uncertainty Maximum Cruise Airspeed	[0, 5, 10, 15]	[North, South, East, West]

equal.

2.1 Safety and Efficiency Metrics

The following safety and efficiency metrics are computed for various scenarios post-simulation for UA-to-UA conflicts of sUAS in the cruise phase belonging to different operators:

2.1.1 sNMACs Risk Ratio

The number of sNMACs for UA-to-UA conflicts in a UTM scenario is computed based on the definition for NMAC per (Ref. 21), i.e., when the lateral separation between flight track of sUAS ≤ 50 ft and vertical separation between flight track of sUAS ≤ 50 ft at any instance of simulation time. Therefore, for a given UTM scenario, the number of sNMAC instances is computed as follows:

$$\# \text{ of sNMACs} = \sum_{i=1}^{N_A} \sum_{j=1}^{N_B} d_{ij} \quad (6)$$

where N is the total number of sUAS flights in a given UTM scenario, N_A and N_B are the total number of sUAS flights departing from depot A and depot B, and d_{ij} is the binary variable for a pairwise conflict between sUAS(i) and sUAS(j) departing from different depots, defined as follows:

$$d_{ij} = \begin{cases} 1, & \text{pairwise sUAS, i.e., (i,j) are in sNMAC,} \\ 0, & \text{otherwise,} \end{cases} \quad (7)$$

The sNMAC risk ratio is computed as follows (Ref. 22):

$$\text{sNMACs Risk Ratio} = \frac{(\# \text{ of sNMACs})_{\text{with SD}}}{(\# \text{ of sNMACs})_{\text{without SD}}} \quad (8)$$

where the numerator in Equation 8 signifies the number of sNMAC computed in the presence of the pre-departure strategic deconfliction and the denominator signifies the number of sNMACs computed in the absence of the 4D volume-based pre-departure strategic deconfliction for the same scenario. If the ratio is less than one, then the pre-departure strategic deconfliction reduces the risk of sNMACs. For example, a risk ratio of 0.1 indicates a 90 % reduction in risk, therefore, small values are desirable (Ref. 22).

2.1.2 UA-to-UA Mid-Air Collisions (sMACs)

As the pairwise UA-to-UA mid-air collision (sMAC) event is always triggered after each UA-to-UA sNMAC event. Therefore, the number of mid-air collisions ($\#$ of sMACs) per scenario is estimated as follows (Ref. 13):

$$\# \text{ of sMACs} = P(\text{sMAC} \mid \text{sNMAC}) * (\# \text{ of sNMACs}) \quad (9)$$

where $P(\text{sMAC} \mid \text{sNMAC})$ is assumed to be a constant (0.1) per (Ref. 23).

2.1.3 Percentage of Nonconformance of sUAS Flights

Nonconformance is computed by comparing a sUAS's flight track position data with the associated active OVB. If the position data indicates the sUAS is within the active OVB, the flight track data point is considered in conformance; if the position data indicates the sUAS is not within the active OVB, the flight track data point is considered in nonconformance (Ref. 11). Therefore, the percentage of nonconformance of each sUAS flight is calculated based on flight track data points as follows:

$$\% \text{ of nonconformance of } sUAS_i = \frac{\sum_{f=1}^{n_f} \text{nonconf}_f}{n_f} 100 \quad (10)$$

where n_f is the total number of flight track data points related to $sUAS_i$ and binary variable nonconf_f is defined as follows:

$$\text{nonconf}_f = \begin{cases} 1, & \text{nonconformance of flight track position data point w.r.t associated active OVB,} \\ 0, & \text{otherwise,} \end{cases} \quad (11)$$

The percentage of nonconformance of sUAS flights in a UTM scenario is calculated using Equations 10 and 11 as follows:

$$\% \text{ of nonconformance of sUAS Flights in a UTM Scenario} = \frac{\sum_{i=1}^N \% \text{ of nonconformance of } sUAS_i}{N} \quad (12)$$

2.1.4 Departure Throughput

The following equation calculates the departure throughput of sUAS flights at depot X:

$$\text{Throughput} = \frac{N_X}{ATD(N_X) - ATD(1)} \quad (13)$$

where X is either A or B, N_X is the number of sUAS departing from the depot A or depot B, $ATD(N_X)$ is the actual time of departure of the last flight from the depot, and $ATD(1)$ is the actual time of departure of the first flight from the same depot in a given scenario.

3 Results

3.1 Case Study I

In this case study, the sUAS traffic for each route is modeled using a Poisson distribution, with a mean inter-departure interval of 120 seconds. Case study 1a is based on scenario 1a (Subfigure 3a), i.e., a 4-by-4 routes structure, and case study 1b is based on scenario 2 (Subfigure 3b), i.e., a 4-by-1 routes structure. There are in total 1000 sUAS flights per scenario, with 500 sUAS flights scheduled from each operations depot. On each route, the minimum temporal separation between STDs of sUAS equals 120 seconds to maintain approximately the same traffic density irrespective of the OVB sizing. Three OVB lengths have been chosen based on the transit time (T_{OVB}), i.e., 30 seconds, 60 seconds, and 120 seconds of a sUAS in the active OVB based on the

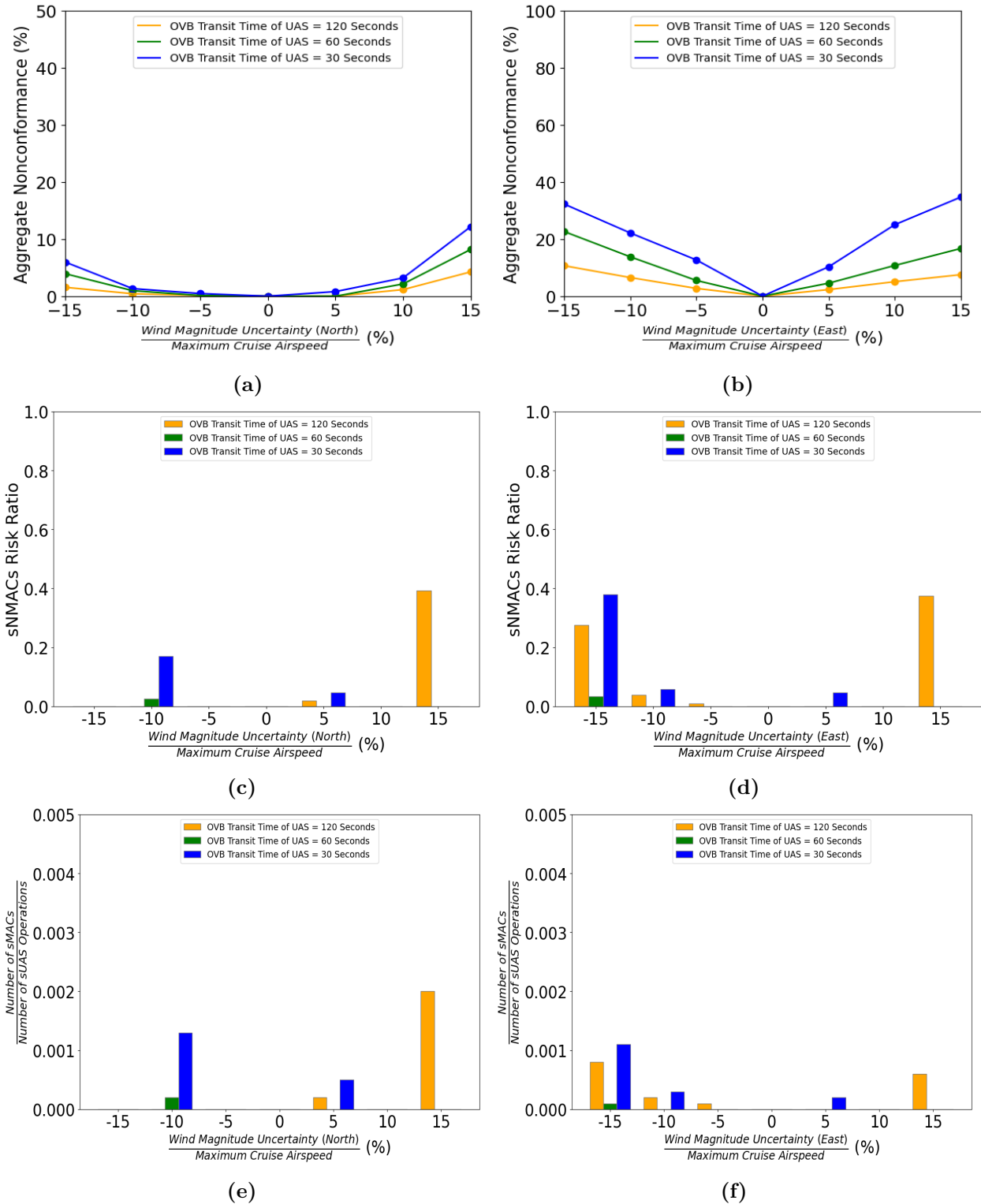


Figure 4.—Case Study 1a (Higher Air Traffic Complexity Scenario): Impact of Wind Uncertainty on i) Aggregate Nonconformance (%), ii) sNMAs Risk Ratio, and iii) sMAs per sUAS Operation

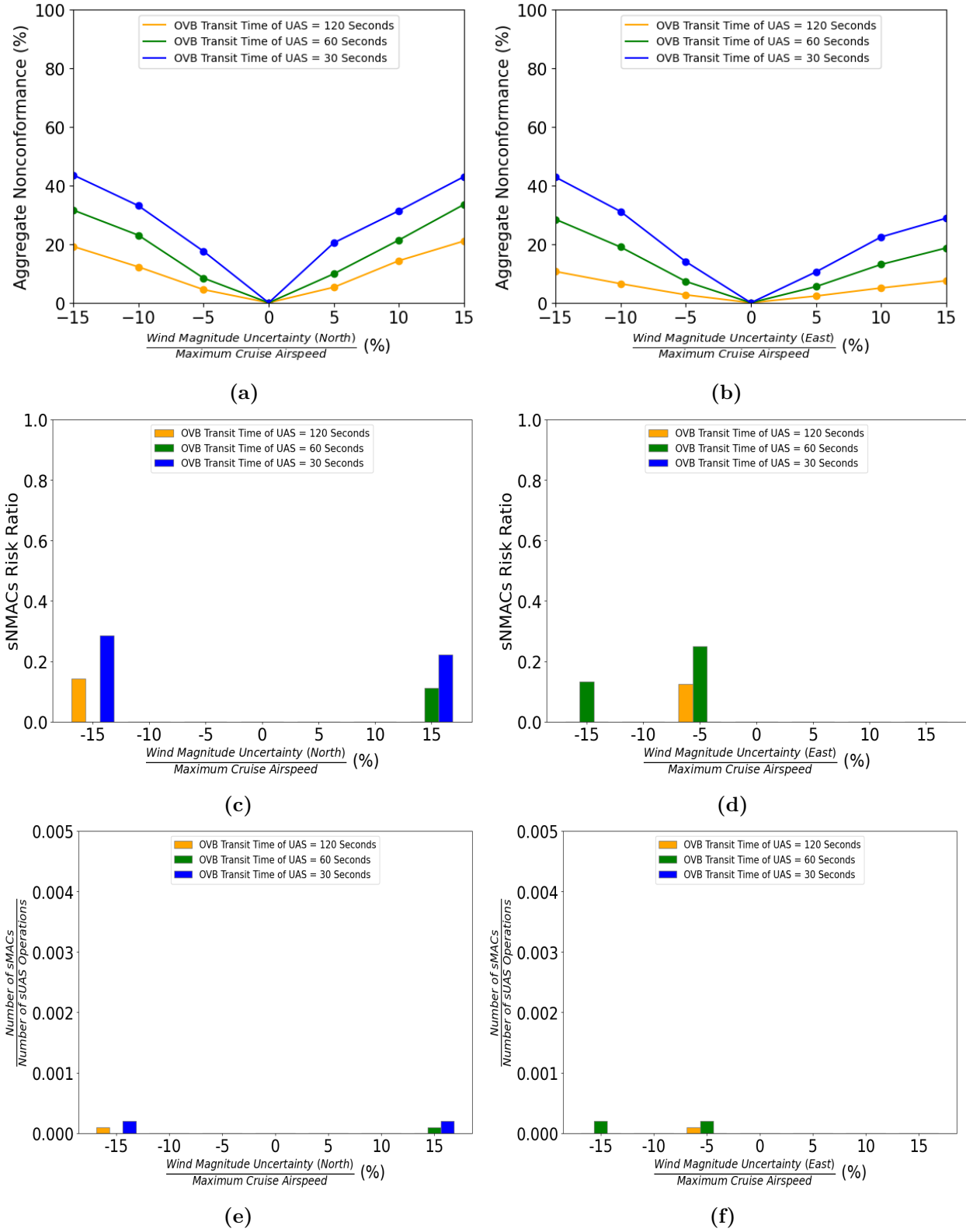


Figure 5.—Case Study 1b (Lower Air Traffic Complexity Scenario): Impact of Wind Uncertainty on i) Aggregate Nonconformance (%), ii) sNMAs Risk Ratio, and iii) sMACs per sUAS Operation

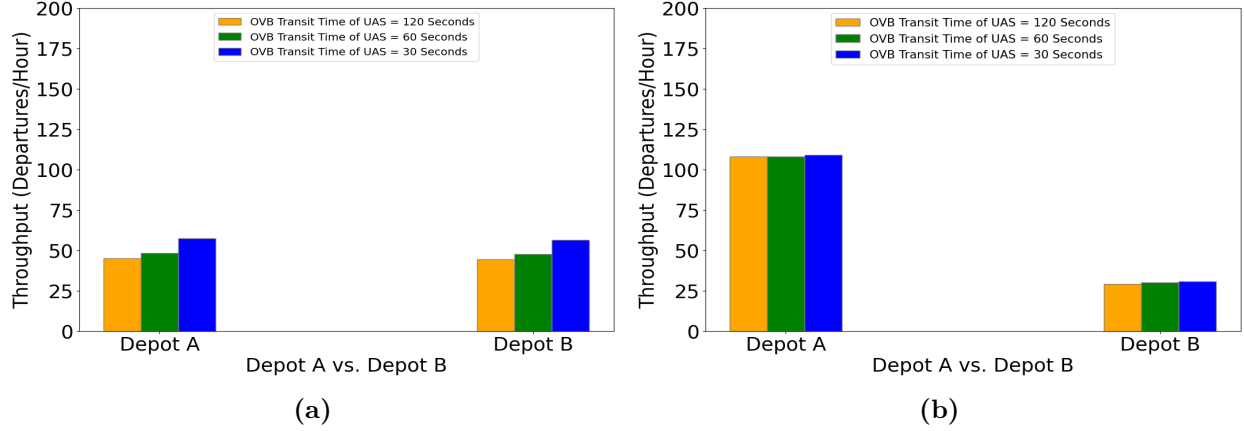


Figure 6.—Case Study 1a vs Case Study 1b: Departure Throughput per Operations Depot
 groundspeed of 20 m/s in the absence of wind (Ref. 16). The OVB width has been fixed to 200 m. The wind uncertainty for various scenarios is considered per Table 1. Furthermore, the airspeed of sUAS flights during the cruise phase is simulated to remain constant at 20 m/s. Therefore, the groundspeed of each sUAS is modified during the simulation based on the wind uncertainty (magnitude and direction) imposed on the scenario by the simulator and route of the sUAS. Each data point, i.e., combination of scenario, wind uncertainty (magnitude and direction), OVB sizing, and demand-rate in the following figures, corresponds to a single simulation iteration. The results suggest the following:

- As illustrated in Subfigures 4a and 4b, as well as Subfigures 5a and 5b, the percentage of aggregate nonconformance to active OVBs is influenced by wind magnitude uncertainty and its direction relative to the network structure of routes. Generally, a higher uncertainty in wind magnitude along the track leads to greater aggregate nonconformance.
- From Subfigures 4c and 4d, along with Subfigures 5c and 5d, it can be observed that the risk ratio of sNMACs for a given scenario does not necessarily decrease with a relative increase in OVB sizing under specified wind uncertainty (magnitude and direction) when sUAS are operating at a constant airspeed mode.
- As shown in Subfigures 4e and 4f, along with Subfigures 5e and 5f, the values of sMACs per sUAS operation around the order of magnitude of 10^{-3} for some cases indicate that sUAS operations at a constant airspeed mode under wind uncertainty are risky from a safety (UA-to-UA collision) perspective.
- As shown in Subfigures 6a and 6b, since the minimum temporal separation and demand rate at depots are fixed across all scenarios, the throughput is determined by the minimum temporal separation at the crossing waypoints (Ref. 18) and the air traffic complexity related to the network structure of routes, i.e., the number of crossing waypoints in this case. Therefore, the higher the air traffic complexity and the longer the OVB, the lower the departure throughput.

3.2 Case Study II

In this case study, the sUAS traffic for each route is simulated using a Poisson distribution, with a mean inter-departure interval of 75 seconds on higher complexity network structure of routes

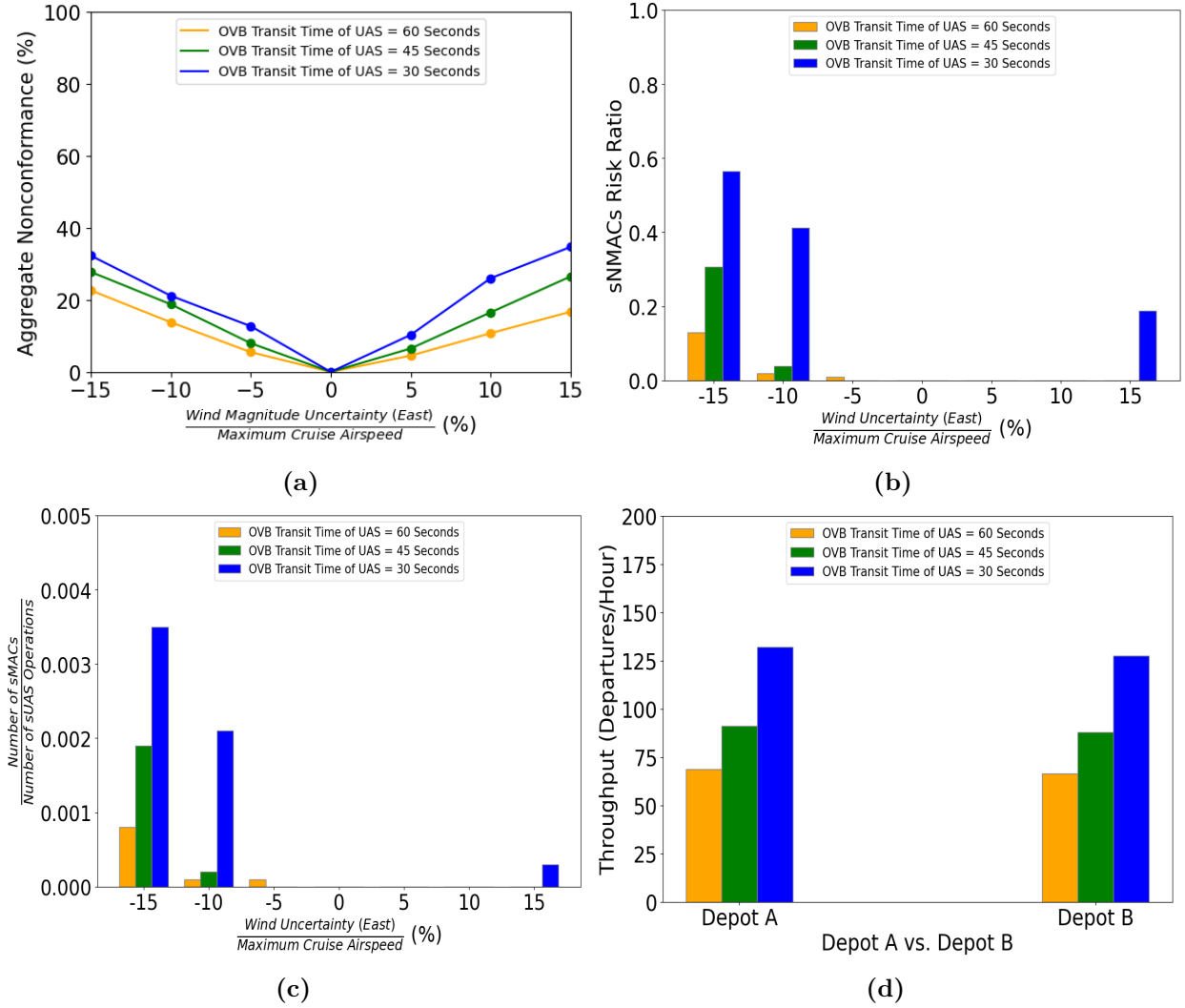


Figure 7.—Case Study IIa (Higher Air Traffic Complexity Scenario): Impact of Wind Uncertainty on i) Aggregate Nonconformance (%), ii) sNMACs Risk Ratio, iii) sMACs per sUAS Operation, and iv) Departure Throughput per Operations Depot

(Subfigure 3a). There are in total 1000 sUAS flights per scenario with 500 sUAS flights scheduled from each operations depot. Three OVB lengths have been chosen based on the transit time (T_{OVB}), i.e., 30 seconds, 45 seconds, and 60 seconds of a sUAS in the active OVB and groundspeed of 20 m/s in the absence of wind. On each route, the minimum temporal separation between STDs of sUAS is chosen to equal the OVB transit time in the absence of wind. Therefore, the traffic density on each route is function of length of the OVB, i.e., longer the OVB length, lower the traffic density. The OVB width has been fixed to 100 m. Only, the east and west wind uncertainties are considered from Table 1. Each data point, i.e., combination of scenario, wind uncertainty (magnitude and direction), OVB sizing, and demand-rate in following figures, corresponds to a single simulation iteration.

- For case study IIa, the airspeed of sUAS flights during the cruise phase is simulated to remain

constant at 20 m/s. From Subfigures 7a, 7b, 7c, and 7d, it can be observed that the smaller the OVB sizing, i.e., the higher the air traffic density, the greater the safety risk (sNMACs risk ratio and sMACs per sUAS operation).

- For case study IIb, the groundspeed of sUAS flights during the cruise phase is simulated to remain within $\pm 5\%$ of 20 m/s. The simulation results showed zero sNMACs and aggregate nonconformance (%) less than 0.5 % for all simulation runs based on case study IIa. Therefore, results show maintaining aggregate conformance % greater than 99 % significantly improves safety under wind uncertainty.

3.3 Discussions

The simulation results concerning aggregate nonconformance, the sNMAC risk ratio, and the number of mid-air collisions (sMACs) per operation across different scenarios indicate that even after using 4D volume-based pre-departure strategic deconfliction, participating sUAS flying at a constant airspeed remain vulnerable to mid-air collisions even with a small degree of wind magnitude uncertainty (≤ 3 m/s). The primary reason for this is the modifications in groundspeed of various sUAS due to wind uncertainty, which leads to changes in actual times of arrival at crossing waypoints.

Consequently, a potential mitigation strategy for sUAS operating on routes with high traffic density and air traffic complexity would be to maintain a constant groundspeed. Such an approach could significantly reduce the risk of sMACs. Additionally, the simulation results show that depending solely on 4D volume-based pre-departure SD for safety when sUAS are flying in a constant airspeed mode under wind uncertainty is insufficient for sUAS package delivery operations in UTM. So, it's important to combine 4D volume-based pre-departure strategic deconfliction with other services, like conformance monitoring for situational awareness (CMSA), airborne strategic deconfliction, or tactical separation assurance.

4 Conclusions

This research aimed to study the trade-off between safety and efficiency of 4D volume-based pre-departure strategic deconfliction (SD) under wind uncertainty in the small unmanned aircraft systems (sUAS) traffic management (UTM) environment for beyond-visual-line-of-sight (BVLOS) flight operations, specifically considering UA-to-UA conflicts. In this research, simulation-based studies were performed using NASA's Flexible Engine for Fast-time Evaluation of Flight Environments (Fe³) simulator by varying parameters such as operational volume block (OVB) sizing, wind uncertainty (magnitude and direction), sUAS package delivery demand rate, and air traffic complexity.

First, the simulation results showed that using 4D volume-based pre-departure strategic deconfliction with larger OVB sizing doesn't always ensure better safety when sUAS are flying in a constant airspeed mode under wind uncertainty, depending on the level of air traffic density and complexity. Next, the simulation results indicated that the safety risk increases with air traffic density and air traffic complexity. Finally, the simulation results showed that maintaining aggregate conformance greater than 99 percent by flying in a constant groundspeed mode significantly improves safety under wind uncertainty. Therefore, the safety of the UTM ecosystem under wind uncertainty depends on the availability of additional conflict management services and the presence

of flight control features, such as the participating sUAS maintaining a constant groundspeed.

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