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Drone Delivery: Nature of Traffic Conflicts in Constrained Urban Airspace Environments

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Abstract

Drone-based delivery is likely to reduce energy and greenhouse gas emissions associated with the transport of small express packages, fast-food meals and medicines, especially when deployed in large-scale in urban areas. However, it is an enormous challenge to facilitate such high traffic densities in constrained urban environments. A recent study applied the principles of traffic alignment and segmentation to the constrained urban airspace of Manhattan, New York, in an effort to mitigate conflict probability. In that study, two novel airspace concepts were proposed, namely, the two-way and one-way concept. Both concepts employed a heading-altitude rule to vertically segmented traffic with respect to their travel directions. In addition, the one-way concept also featured horizontal constraints to promote unidirectional traffic flow. These concepts bear resemblance to that of road-based traffic. Further, both concepts featured transition altitudes to accommodate turning flights that need to decelerate to safely perform turns at intersections. The comparative study showed the one-way airspace configuration to be more effective than the two-way concept in terms of safety. In the pursuit of demonstrating our understanding of the intricate differences between the two-way and one-way airspace configurations, this paper aims to explore and analyse salient conflict properties. By using fast-time simulation experiments, the different types of conflicts are captured and analysed for multiple traffic demand levels. Our results suggest that conflicts are largely caused by flights climbing or descending to their respective altitude layers. For both concepts, the merging conflicts consisted of in-trail and crossing conflicts, while the two-way also contained a high proportion of head-on conflicts.Our study therefore sheds light on the different categories of conflicts that could help guide future research in airspace design in constrained urban areas.

1 Introduction

Drones are likely to transform the transportation network of cities by offering time-saving services such as the delivery of express packages, fast-food meals, vital medical supplies as well as the transport of passengers within urban environments [1, 2, 3, 4]. Over the years, interest for these applications have mainly grown because drone-based delivery is expected to yield economic, environmental and societal benefits [5]. As a result, many drone delivery companies have been established, for example Zipline, which deliver life-saving medicines and vaccines to hospitals in rural areas [6]. Yet, the full potential of drone delivery might only materialise when large-scale drone-based delivery operations is deployed in dense urban areas [7, 8]. However, it is a challenge to safely facilitate high densities of drone traffic in such areas. Because the low-altitude urban airspace is highly constrained with physical landform structures and its existing street networks [9].

In order to cope with the future demand for urban drone delivery, a recent study proposed two novel airspace design concepts [10]. In that study, the fundamental principles of traffic segmentation and alignment ([11]) were applied to a constrained urban environment to generate the two-way and one-way airspace concepts in an effort to mitigate conflict probability [10]. For both concepts, a heading-altitude rule was used to vertically segment traffic to different altitude layers with respect to their travel directions. In addition, the one-way concept featured horizontal constraints to promote unidirectional traffic, while the two-way concept accommodated bidirectional traffic flow. Both concepts were implemented to the urban street network of Manhattan, New York in an attempt to simulate a constrained urban environment. Subsequently, the concepts were compared and evaluated using fast-time simulations for multiple traffic demand scenarios. The study concluded the one-way airspace configuration to be more effective than the two-way concept in terms of safety [10].

The current study extends the research of [10] with the goal of understanding the nature of conflicts and intrusions generated in the two-way and one-way airspace configuration. Characterising the statistics of merging, in-trail, crossing and head-on conflicts could help guide future research in urban airspace design and, conflict detection and resolution. Similar research has been done, albeit for air traffic management [12] and road traffic [13]. Therefore, using fast-time simulations, the performance of the two concepts are compared for multiple traffic demand levels with respect to the number of conflicts, intrusions, and their constitute properties.

The reminder of this paper is organised as follows. Section 2 describes the two-way and one-way urban airspace design concepts. Section 3 outlines the experimental set-up and section 4 presents the results of our experiments. We then discuss the main finding in section 5 and provide some concluding remarks in section 6.

2 Urban Airspace Concepts

This section presents the conceptual designs for the two-way and one-way airspace configurations. To simulate a constrained urban environment, both concepts are applied to an existing urban street network. As a result, the drone flight-routes conform to the urban street network, similar road vehicles, albeit also utilising the third dimension. Further, in both concepts, traffic is organised into different altitude layers with respect to the four cardinal directions: north, east, south and west. In this sense, the two-way and one-way concepts consist of multiple stacks of layers that span the altitudes of 75 ft to 1050 ft which accommodate traffic with respect to their travel directions [10]. In addition to this vertical distribution of traffic, the one-way concept contains horizontal constraints to create unidirectional flow of traffic, which bears resemblance to how road traffic is organised by one-way streets [14, 15, 16].

2.1 Preliminary Observations

2.1.1 Turning Flights

In our initial experiments, we defined a constant drone speed of 10.3 m/s and a maximum bank angle of 35°. Interestingly, the preliminary simulations showed a strong correlation between the turn radii at intersections of the street network and the drones' performance [10]. We observed that the drones would overshoot their original flight-path at intersections, especially when flying at a constant speed. Therefore, our initial experiments indicated the need for drones to decelerate to at least 5 m/s to safely execute turns at intersections.

2.1.2 Through and Turn Altitude Layers

To accommodate the turning traffic, turn altitude layers are incorporated in the two-way and one-way concepts [10]. As a result, the turn-layers separate turning traffic from through traffic and thus reduces the likelihood of disruption to the flow of through traffic. A similar design scheme is used in road design to differentiate slow and fast traffic [16]. Note that through traffic is defined as traffic that passes at least one intersection, while turn traffic is identified by traffic that requires to turn at an intersection.

2.2 Design Concepts

In this study, the two-way and one-way airspace design concepts have 40 altitude layers that consist of 20 turn-layers and 20 through-layers (see illustrations in [10]). Each layer has a vertical separation of 25 ft. This section summarises the two airspace concepts.

2.2.1 Two-Way

The traffic in the two-way airspace concept is assigned with respect to a heading range of 90°. This division of traffic with flight headings, ψ, creates four quadrants: north bound layers, which are defined within $315° < \psi \leq 045°$; east bound layer, for $045° < \psi \leq 135°$; south bound layers, within $135° < \psi \leq 225°$; and flight headings

$225° < \psi \leq 315°$ to west bound layers. The two-way concept contains multiple altitude layers that range from 75 ft to 1050 ft that encapsulate a total of 40 altitude layers. These layers are equally segmented to include 20 through and 20 turn layers. Moreover, 10 altitude layers are allocated to north, east, south and westbound directions. Using the heading-altitude rule of Equation (1), we allocate short distance flights to the low altitudes and longer distance flights to higher portions of the altitude.

$$h_{TW,i} = h_{min} + \zeta \left[\left[\frac{d_i - d_{min}}{d_{max} - d_{min}} \kappa \right] \beta + \left[\frac{\psi_i}{\alpha} \right] \right] \tag{1}$$

Note that the above heading-altitude rule is a function of the flight heading ψ_i, its shortest path distance, d_i and the minimum and maximum threshold distances (d_{min} and d_{max} which is defined between 1 km and 10 km, respectively). The remaining constants include the heading range per flight level, α, which is equal to 90°; the minimum altitude of the through-layer, h_{min} (i.e., 100 ft); β, which is equal to 4 (i.e., 360°/ α); κ as 5 and; the vertical distance (ζ) between through-through-layers is equal to 50 ft.

2.2.2 One-Way

The one-way concept consist of 40 altitude layers, which consist of 20 through and 20 turn traffic layers. Here, horizontal constraints are imposed to the direction of travel in order to promote one-way traffic flow. This generates uni-directional traffic flow over a single street. As a result, a street can either accommodate north, east, south, or westbound traffic. Note that the prohibition of opposite flow of traffic in a single streets enables in an additional set of layers. Therefore, compared to the two-way concept that has 10 altitude layers per cardinal direction, the one-way concept has 20 altitude layers per cardinal direction. Similar to the two-way concept, the layering in the one-way design is organised with respect to the heading range of 90° with flight headings ψ: $315° < \psi \leq 045°$, for north bound layers; $045° < \psi \leq 135°$, for east bound; $135° < \psi \leq 225°$, south bound; $225° < \psi \leq 315°$, to west bound layers. To compute the respective cruising altitudes ($h_{OW,i}$), we employ the following heading-altitude rule:

$$h_{OW,i} = h_{min} + \frac{h_{max} - h_{min}}{d_{max} - d_{min}} (d_i - d_{min}) \tag{2}$$

Equation 2 ensures that short distance flights is assigned to the lower portions of the airspace while longer distance flights is allocated to higher altitudes. In addition to the above heading-altitude rule, we also use a simple heuristic (from [10]) to align flight to their altitudes with respect to their flight heading.

3 Experimental Design

A set of fast-time simulation experiments were performed to compare the safety of the two-way and one-way concepts. This section describes the experiment conducted in this study.

3.1 Experimental Methods

3.1.1 Simulation Platform

In this study, fast-time simulations are conducted using the open-source Air Traffic Management simulator, BlueSky [17]. The simulation platform's auto pilot module and its drone model database was expanded to feature characteristics of urban drone-based delivery. In this work, we employ the DJI Matrice 600 Pro hexacopter drone model since it is a popular delivery prototype. The characteristics of this drone model include: a speed range between 5-10.3 m/s; a mass of 15 kg; a maximum bank angle of 35° and; an acceleration/deceleration of ± 1.5 m/s^2.

3.1.2 Experimental Area

We examine the performance of the two-way and one-way concept by overlaying them over the urban street network of Manhattan, New York City (Fig. 1). Manhattan represents an orthogonal or grid-like network which is ideal for this study [10]. The red shaded circles in Fig. 1 represent three drone hubs or depots where drones depart to deliver packages to customers.

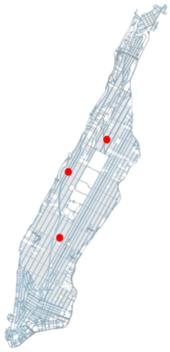

Figure 1: Urban street network of Manhattan, New York City, which consist of an area of approximately 59.1 km^2. The three circles shaded in red represent the location of the drone depots.

3.1.3 Conflict Detection and Resolution

The two-way and one-way concepts relied on a state-based conflict detection method and a basic 1-D speed control algorithm (tactical conflict resolution) to identify and resolve potential separation violations in a pair-wise manner [10]. In this study, we adopted a horizontal and vertical separation requirement of 164 ft and 25 ft, respectively. These requirements were chosen based on its suitability in initial test simulations [10].

3.1.4 Airspace Concept Implementation

The street network of Manhattan (4091 nodes and 9453 edges) was obtained from OpenStreetMap using the Python library OSMNX [18]. Subsequently, a undirected and directed graph was generated for the two-way and one-way concept, respectively. The directed graph ensures the direction of the streets in the one-way concept to be unidirectional. While the undirected graph ensures the streets in the two-way concept to be bidirectional.

In both concepts, we used three drone depots where drones depart to randomly assigned destinations by flying their respective shortest path [10]. To account for the drones' limited range, a minimum and maximum distance of 1 km and 10 km was defined. Based on the generated shortest paths, consisting of a set of latitude and longitudinal coordinates, the flight headings and the location of turns were computed for each and every street along its respective shortest path. Similarly, the cruise altitudes were found using heading-altitude rule. Then using the turn locations, the transition altitudes are computed for the respective flights.

3.2 Independent Variables

For this experiment, we used three independent variables, namely; the urban airspace concepts, which consist of the two-way and one-way concept; the airborne separation conditions, i.e., when conflict resolution is enabled and disabled; and the traffic demand level, which consist of low, medium and high densities of traffic. Note that the three traffic demand scenarios are based on a potential scenario of fast-food meal delivery via a fleet of autonomous drones [8]. The traffic demand used in this study includes: 3240 drones/hr (low); 3600 drones/hr (medium); 4320 drones/hr (high), respectively [10].

The simulations here contain 12 experimental conditions, which consist of two airspace concepts, two conditions of conflict resolution and three traffic demand levels. To improve the accuracy of the experiments, three repetitions were performed for each experimental condition. Furthermore, in each simulation run, uniformly random destinations between $1km$ and 10 km were used in order to have different drone trajectories.

3.3 Dependent Measures

In this study, we analyse the dependent measure of safety and its constitute properties for the two-way and one-way urban airspace concept.

3.3.1 Safety

The safety of two urban airspace concepts is defined by the number of conflicts and intrusions. An intrusion is defined when the vertical and horizontal separation requirements have been violated. While a conflict is denoted as a predicted intrusion within the prescribed look-ahead time of 30 s [10]. In this study, a safer airspace concept is reflected by fewer number of conflicts and intrusions.

3.3.2 Nature of conflicts and intrusions

To better understand the intricate differences between airspace concepts in terms of safety, we measured the number of drones involved in a conflict and intrusion. In addition, we also assessed the different conflict and intrusion categories: in-trail, head-on, crossing conflicts and intrusions, for level and non-level flights (i.e., merging flights).

4 Results

The experimental results are presented in this section. The effect of the independent variables on safety is illustrated using box-and-whisker plots and stacked bar plots. The box-and-whisker plot depict the median line; the interquartile range (IQR), which is marked by the boundary of the box; the minimum and maximum distribution of the data, which is denoted by the whiskers; and the outliers, which is represented by points greater than $\pm 1.5\times$ IQR. Furthermore, the different categories of conflicts and intrusions is presented using stacked bar plots.

4.1 Total Number of Conflicts and Intrusions

Fig. 2 and 3 show the total number of pairwise conflicts and intrusions for the two-way and one-way concept for low, medium and high traffic demand levels. Of note, a pairwise conflict and intrusion is accounted only once, independent of its duration, during the simulation, while a recurring conflict and intrusion is recounted.

Across both concepts, the total number of conflicts and intrusions increased with traffic demand (Fig. 2 and 3). The figures indicate the one-way concept has lower number of conflicts and intrusions compared to the two-way concept. Fig. 2 and 3 also demonstrate the effect of tactical conflict resolution for the two-way and one-way concept. When conflict resolution is disabled, the one-way concept has better intrinsic safety and thus it is able to reduce the occurrence of conflicts when compared to the two-way concept. Furthermore, both concepts showed a marked decrease in the number of intrusions when conflict resolution was enabled. On the other hand, the number of conflicts displayed a reverse effect. In both concepts, the number of conflicts increased when conflict resolution was switched on. This behaviour could be a consequence of the heavily constrained urban airspace, which limits the flexibility for resolution manoeuvres thereby forming conflict chains.

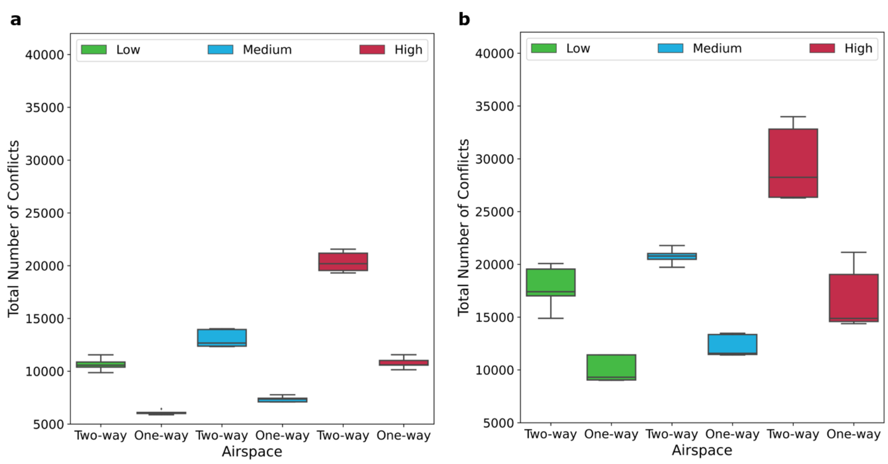

Figure 2: The total number of pairwise conflicts for the two-way and one-way urban airspace concept for low, medium and high traffic demands. (**a**) Without conflict resolution. (**b**) With conflict resolution.

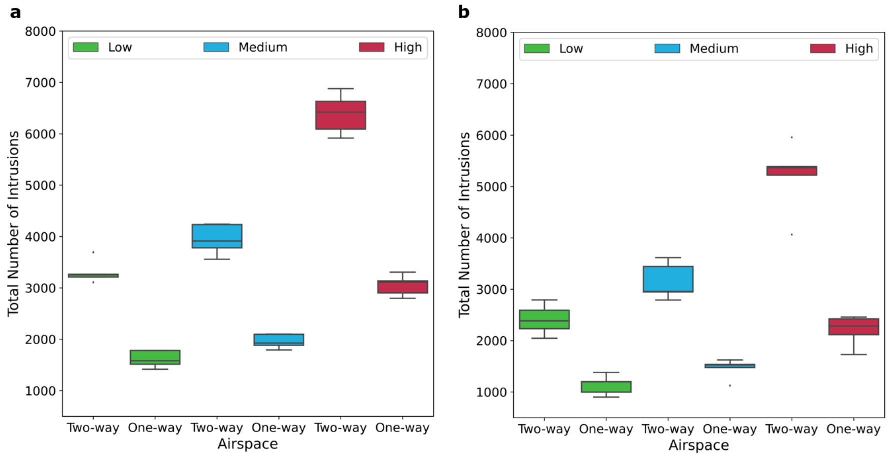

Figure 3: The total number of pairwise intrusions for the two-way and one-way urban airspace concept for low, medium and high traffic demands. (**a**) Without conflict resolution. (**b**) With conflict resolution.

4.2 Nature of Conflicts and Intrusions

Fig. 4 and 5 presents the different types of conflicts and intrusions for the two-way and one-way concepts. The bar graphs show that conflicts and intrusions are mainly generated by flights that are climbing or descending (i.e., merging) to their respective altitude layers. We see that the majority conflicts is triggered by in-trail and crossing flights. Notably, the charts highlight a significant difference between the two-way and one-way concept. The charts show that a large proportion of head-on conflicts in the two-way concept, while no head-on conflicts is recorded in the one-way concept. This difference could be explained by the structure of the one-way concept which spatially distributes opposite traffic flows and thus reduces the probability of head-on conflicts and intrusions. Moreover, most head-on conflicts triggered in the two-way appear to be short-term since they are largely resolved, as seen in Fig. 5.

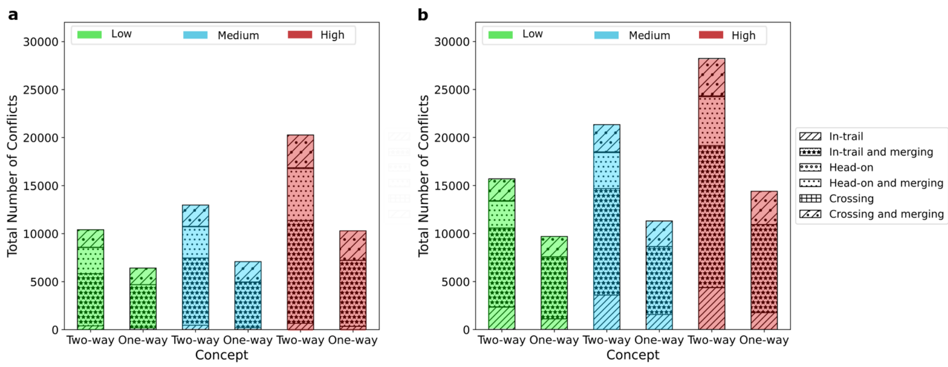

Figure 4: The total number of pairwise conflicts and their associated type for the two-way and one-way urban airspace concept for low, medium and high traffic demands. (**a**) Without conflict resolution. (**b**) With conflict resolution. The results show that a sustainable amount of conflicts is generated by merging flights.

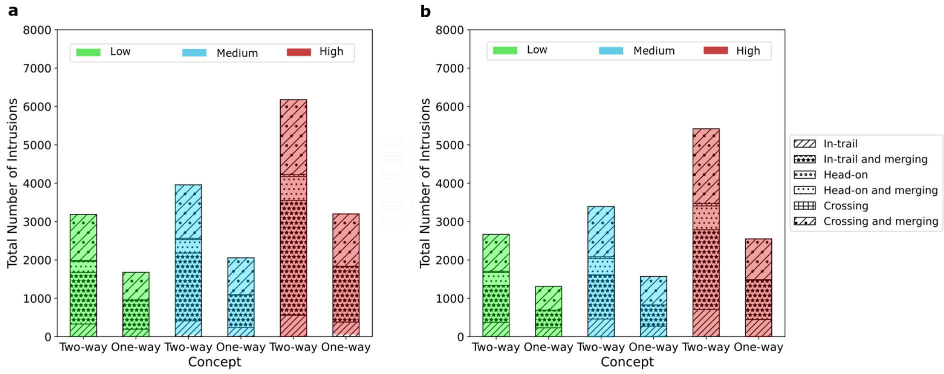

Figure 5: The total number of pairwise intrusions and their associated type for the two-way and one-way urban airspace concept for low, medium and high traffic demands. (**a**) Without conflict resolution. (**b**) With conflict resolution.

4.3 Spatial Distribution of Conflicts

Fig. 6 and 7 exhibit the location of instantaneous conflicts in both concepts without and with tactical conflict resolution. The left graph in Fig. 6 and 7 displays the conflict locations for the two-way concept, while the right plot depicts the location of conflicts for the one-way concept. Although a uniform traffic distribution is assumed, the maps indicate that some regions of the network have more conflicts than the rest. This effect may be explained by the network's high betweenness centrality of nodes which means that some nodes have higher number of shortest pathways passing through and thus it is used more often [19]. Note that this is a property of the employed urban street network.

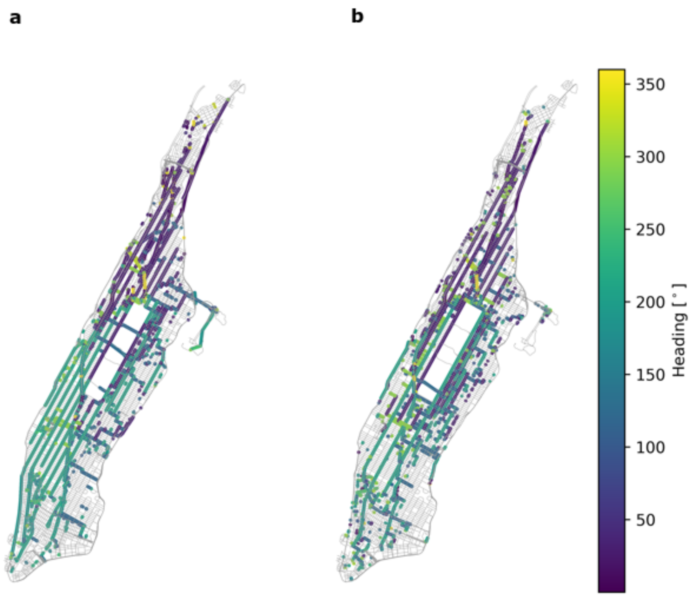

Figure 6: Geographical locations of instantaneous conflicts for low, medium and high traffic demand levels without conflict resolution. **a**, Instantaneous pairwise conflict locations in the two-way concept. **b**, Instantaneous pairwise conflict locations in the one-way concept.

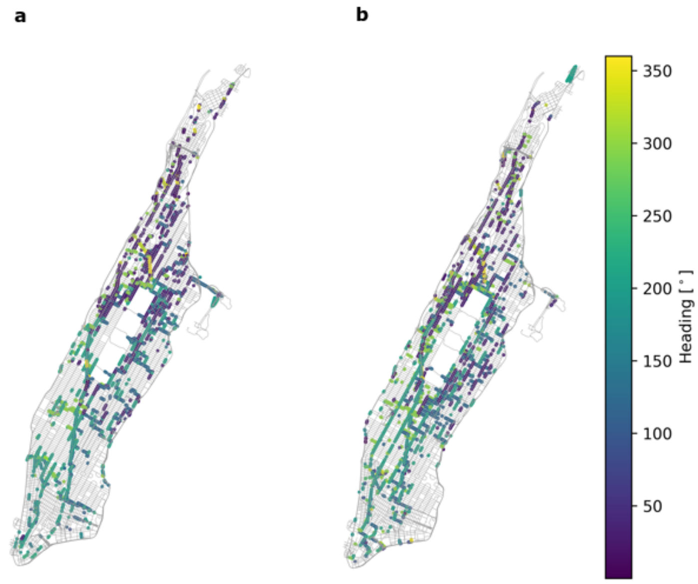

Figure 7: Geographical locations of instantaneous conflicts for low, medium and high traffic demand levels with conflict resolution enabled. **a**, Instantaneous pairwise conflict locations in the two-way concept. **b**, Instantaneous pairwise conflict locations in the one-way concept.

5 Discussion

Delivery drones are expected to operate in the low altitude airspace in high densities. This portion of the airspace is heavily constrained with physical structures and existing urban street networks and therefore, to safely facilitate large-scale drone traffic remains an enormous challenge. Prior studies have proposed solutions such as strategic deconfliction and tactical resolution measures [20]. However, they are not effective for high density traffic operations and thus may cause adverse affects to the safety of the airspace [21, 22]. What might be needed is a combination of airspace structure and tactical conflict resolution for the safe accommodation of large-scale drone traffic in constrained environments [10]. By employing the principles of traffic alignment and segmentation, the study proposed and evaluated two novel airspace designs, namely, the two-way and one-way concept. The study revealed the one-way airspace configuration to be more effective than the two-way concept in terms of safety [10]. To increase our understanding of the intricate differences between the two-way and one-way airspace designs, the current study investigates the nature of the conflicts and intrusions.

In this research, we apply the two-way and one-way airspace concepts to the urban street network of Manhattan, New York (which encapsulates an area of 59.1 km^2) in an effort to simulate a constrained environment. Using randomised fast-time simulations, we examined the safety of both airspace designs. Here, we compared safety in terms of the total number of conflicts and intrusions (i.e., losses of separation). To better understand the difference in safety, we measured four types of conflicts and intrusions. The results suggest that conflicts are predominately triggered when drones merge to their respective altitude layers. Our results indicate that the two-way concept contains a higher number of in-trail and crossing conflicts and intrusions than the one-way concept. Importantly, the merging conflicts in the two-way concept also largely consisted of head-on conflicts compared to the one-way concept, which did not experience any head-on conflicts. This notable difference could be a feature of the one-way airspace configuration for which opposite traffic flows are assumed to be spatially separated by the urban street network.

Our study shows that the one-way concept has fewer conflicts and intrusions than the two-way concept. This may be caused by the vertical segmentation of traffic with respect to travel direction and the imposed horizontal structure on the flow of traffic [10]. Fundamentally, these observations can be explained by the principles of segmentation and traffic alignment which reduces the relative velocities between cruising traffic [10].

In both concepts, conflicts and intrusions are largely caused by flights that are either climbing or descending to their respective altitude layers. These merge conflicts were expected since no measures were in-place to mitigate their likelihood. In road traffic, merge conflicts represent a large proportion of highway collisions [13]. Merge conflicts are commonly caused by insufficient gaps in the traffic flow due to high traffic density [23]. Therefore, as traffic demand increases, the amount of free airspace reduces for merging flights and thereby causing a higher number of conflicts. The fewer number of intrusions (relative to the number of conflicts) further justify that the majority of these conflicts are caused by transitory flights. This means that most of the merge conflicts would never occur since the drones will not be on the same altitude during the predicted conflict. One potential solution to this challenge could be to implement a predictive airborne separation assurance system [24].

In addition to the merging flights that trigger conflicts, a majority of cohort is comprised of in-trail crossing conflicts. Even though the probability of crossing conflicts is largely reduced due to the structure of the airspace, the relatively shorter distances of street edges in some parts of the network and the high density of traffic mean that merging flights have limited time and space to climb or descend to their respective layers. An example solution to circumvent such conflicts could be to implement a metering strategy or to impose variable speed limits [25].

Using conflict maps, we captured the location of conflicts in both concepts. The spatial distribution of conflicts indicates that conflicts probably occur at intersections due to flights reducing their speed to perform turns. Such conflicts may also exhibit continuous repeating conflict over time. The conflict maps also locate geographical hot spots regions in both concepts thus indicating that some street edges are utilised more than the rest. This spatial clustering of conflicts to specific swathes of the network could lead to local congestion and thus more conflicts. This effect, however, may be caused by a particular property of the urban street network and not necessarily the structure of airspace concepts. A recent study demonstrated that some street networks exhibit high betweenness centrality, which means that some intersections experience a disproportionately large number of traffic flow, due to a larger number of shortest paths going through the intersections [19]. In light of this, future research should investigate whether redistributing traffic flows to under-utilised portions of the network as a potential means to mitigate the probability of conflicts.

Our results are subject to some limitations. First, our airspace design concepts were applied to a test region that featured an orthogonal street network. Even though orthogonal street networks are largely represented in most cities [26], there still exist seven other types of street networks [27]. Recent studies have identified a growth in non-orthogonal street networks, which are inflexible and less connected street networks [27, 28]. These non-grid networks have different properties, such as high fraction of dead-ends and high dendricity (tree-like networks). For road traffic, lower connected urban street networks are associated with increased vehicle travel kilometres, energy use and emissions [27]. Hence, validating the airspace configurations for non-orthogonal street networks is an interesting research direction. Second, our research was limited to the number of conflicts and intrusions, its classification and the locations of conflicts. Road traffic studies have also examined temporal and spatial proximity measures, such as time and distance to conflicts, to better understand the severity of conflicts [29]. Therefore, it is worth analysing similar measures for the two-way and one-way airspace concepts. Third, the airspace configurations remain static with time and assume uniform distribution of traffic. However, to cope with the paradigm of on-demand transport, a dynamic airspace is required, that is, one that adapts with changing traffic demand [30]. Nevertheless, future research should investigate dynamic airspace designs for on-demand transport of goods and services.

6 Conclusions

This study investigated the properties of conflicts and intrusions of the two-way and one-way urban airspace design concepts for large-scale drone delivery traffic. Both concepts were applied to the street network of Manhattan, New York, in an attempt to simulate one example of a highly constrained urban environment. Using fast-time simulations, we compared the concepts with respect to the total number of pairwise conflicts and intrusions. Our results show that the one-way concept has fewer conflicts and intrusions thus indicating that vertical segmentation of traffic with respect to flight headings as well as horizontal constraints imposed on the flow of traffic is beneficial for the safety of the urban airspace. For both concepts, we observed that conflicts are predominately triggered by flights that require to climb or descend to their respective altitude layers. The majority of this cohort consist of in-trail and crossing conflicts, while head-on conflicts also represented a large proportion of the cohort in the two-way concept. Future studies should develop strategies to mitigate the likelihood of merge conflicts, possibly by extrapolating research from road-traffic.

References

[1] D. Floreano, R. J. Wood, Science, technology and the future of small autonomous drones, Nature 521 (2015) 460–466. doi:10.1038/nature14542.

[2] M. Francisco, Organ delivery by 1,000 drones, Nature Biotechnology 34 (7) (2016) 684. doi:10.1038/nbt0716-684a.

[3] C. Lin, K. Shah, C. Mauntel, S. Shah, Drone delivery of medications : Review of the landscape and legal considerations 75 (3) (2018) 153–158. doi:10.2146/ajhp170196.

[4] A. Kasliwal, N. J. Furbush, J. H. Gawron, J. R. Mcbride, T. J. Wallington, R. D. D. Kleine, H. C. Kim, G. A. Keoleian, Role of flying cars in sustainable mobility, Nature Communications 10 (1555) (2019). doi:10.1038/s41467-019-09426-0.

[5] J. K. Stolaroff, C. Samaras, A. S. Mitchell, D. Ceperley, E. R. O. Neill, A. Lubers, Energy use and life cycle greenhouse gas emissions of drones for commercial package delivery, Nature Communications (2018) 1–13doi:10.1038/s41467-017-02411-5.

[6] E. Ackerman, E. Strickland, Medical delivery drones take flight in east africa, IEEE Spectrum 55 (1) (2018) 34–35. doi:10.1109/MSPEC.2018.8241731.

[7] M. Doole, J. Ellerbroek, J. Hoekstra, Drone delivery: Urban airspace traffic density estimation, SESAR Innovation Days (8 December) (2018).

[8] M. Doole, J. Ellerbroek, J. Hoekstra, Estimation of traffic density from drone-based delivery in very low level urban airspace, Journal of Air Transport Management 88 (October 2019) (2020) 101862. doi:10.1016/j.jairtraman.2020.101862.

[9] A. Petrovsky, M. Doole, J. Ellerbroek, J. M. Hoekstra, F. Tomasello, Challenges with obstacle data for manned and unmanned aviation, in: International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives, Vol. 42, 2018, pp. 143–149. doi:10.5194/isprs-archives-XLII-4-W10-143-2018.

[10] M. Doole, J. Ellerbroek, V. L. Knoop, J. M. Hoekstra, Constrained Urban Airspace Design for Large-Scale Drone-Based Delivery Traffic, Aerospace 8 (2) (2021). doi:10.3390/aerospace8020038.

[11] J. M. Hoekstra, J. Maas, M. Tra, E. Sunil, How do layered airspace design parameters affect airspace capacity and safety?, In: Proceedings of the 7th International Conference on Research in Air Transportation, Philadelphia, PA (20-25, June) (2016).

[12] H. Lee, K. Bilimoria, Properties of air traffic conflicts for free and structured routing, in: AIAA Guidance, Navigation, and Control Conference and Exhibit. doi:10.2514/6.2001-4051.

[13] H. Yang, K. Ozbay, Estimation of traffic conflict risk for merging vehicles on highway merge section, Transportation Research Record 2236 (1) (2011) 58–65. doi:10.3141/2236-07.

[14] P. Chakroborty, A. Das, Principles of Transportation Engineering, 2005.

[15] M. Slinn, P. Matthews, P. Guest, Traffic Engineering Design: Principles and Practice, 2005. doi:http://dx.doi.org/10.1016/B978-075065865-2/50018-3.

[16] N. Garber, L. Hoel, Traffic & Highway Engineering, 2008.

[17] J. Hoekstra, J. Ellerbroek, BlueSky ATC Simulator Project: an Open Data and Open Source Approach, in: seventh International Conference for Research on Air Transport (ICRAT), no. June, 2016.

[18] G. Boeing, Computers , Environment and Urban Systems OSMnx: New methods for acquiring, constructing, analyzing , and visualizing complex street networks, Computers, Environment and Urban Systems 65 (2017) 126–139. doi:10.1016/j.compenvurbsys.2017.05.004.

[19] A. Kirkley, H. Barbosa, M. Barthelemy, G. Ghoshal, From the betweenness centrality in street networks to structural invariants in random planar graphs, Nature Commun 9 (2501) (2018). doi:10.1038/s41467-018-04978-z.

[20] C. Barrado, M. Boyero, L. Brucculeri, G. Ferrara, A. Hately, P. Hullah, D. Martin-marrero, E. Pastor, A. P. Rushton, A. Volkert, U-Space Concept of Operations : A Key Enabler for Opening Airspace to Emerging Low-Altitude Operations, Aerospace 7 (3) (2020) 1–18. doi:10.3390/aerospace7030024.

[21] E. Sunil, J. Hoekstra, J. Ellerbroek, F. Bussink, D. Nieuwenhuisen, A. Vidosavljevic, S. Kern, Analysis of airspace structure and capacity for decentralised separation using fast-time simulations, Journal of Guidance and Control Dynamics 40 (1) (2017) 38–51.

[22] E. Sunil, Analyzing and Modeling Capacity for Decentralized Air Traffic Control, Ph.D. thesis (2019). doi:10.13140/RG.2.2.20080.51208.

[23] V. L. Knoop, Introduction to Traffic Flow Theory, 2017, course textbook.

[24] J. Hoekstra, R. van Gent, R. Ruigrok, Designing for safety: the 'free flight' air traffic management concept, Reliability Engineering & System Safety 75 (2) (2002) 215–232. doi:10.1016/S0951-8320(01)00096-5.

[25] V. L. Knoop, A. Duret, C. Buisson, B. van Arem, Lane distribution of traffic near merging zones influence of variable speed limits, in: 13th International IEEE Conference on Intelligent Transportation Systems, 2010, pp. 485–490. doi:10.1109/ITSC.2010.5625034.

[26] G. Boeing, Urban spatial order: street network orientation, configuration, and entropy, Applied Network Science 4 (1) (2019) 1–19. arXiv:1808.00600, doi:10.1007/s41109-019-0189-1.

[27] C. Barrington-leigh, A. Millard-ball, A global assessment of street-network sprawl, PloS ONE 14 (11) (2019) 1–16. doi:10.1371/journal.pone.0223078.

[28] C. Barrington-leigh, A. Millard-ball, Global trends toward urban street-network sprawl, Proceedings of the National Academy of Sciences of the United States of America 117 (4) (2020). doi:10.1073/pnas.1905232116.

[29] L. Zheng, K. Ismail, X. Meng, Traffic conflict techniques for road safety analysis: open questions and some insights, Canadian Journal of Civil Engineering 41 (7) (2014) 633–641. doi:10.1139/cjce-2013-0558.

[30] J. M. Hoekstra, J. Ellerbroek, E. Sunil, J. Maas, Geovectoring: Reducing Traffic Complexity to Increase the Capacity of UAV airspace, In 2018 Proceedings of the International Conference on Research in Air Transportation (June) (2018).